Contemporary Research in Theorectical and Applied Mechanics

PROCEEDINGS

Program and Abstracts for the 14th US National Congress of Theoretical and Applied Mechanics

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June 23-28, 2002

Blacksburg, VA

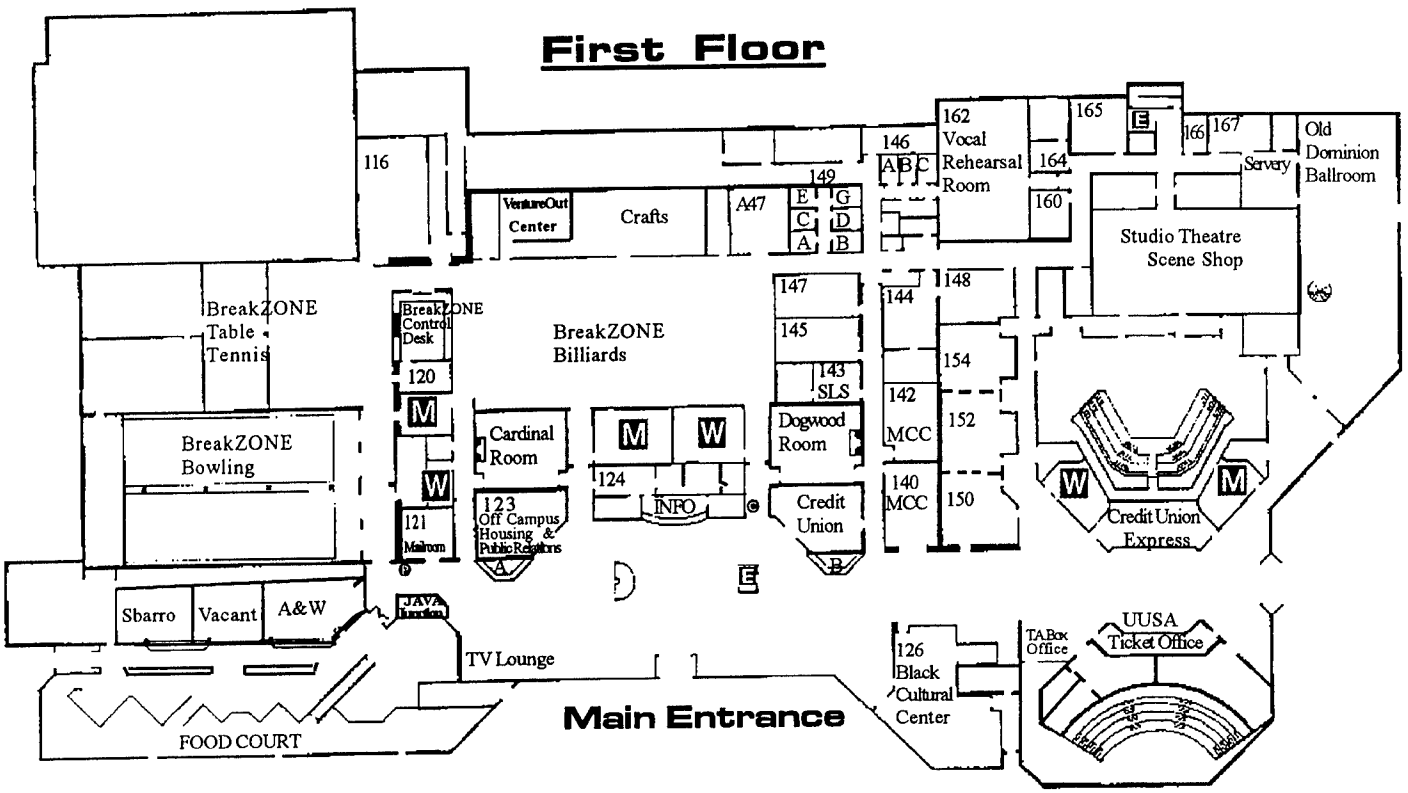
Editors: R.C. Batra, E. G. Henneke

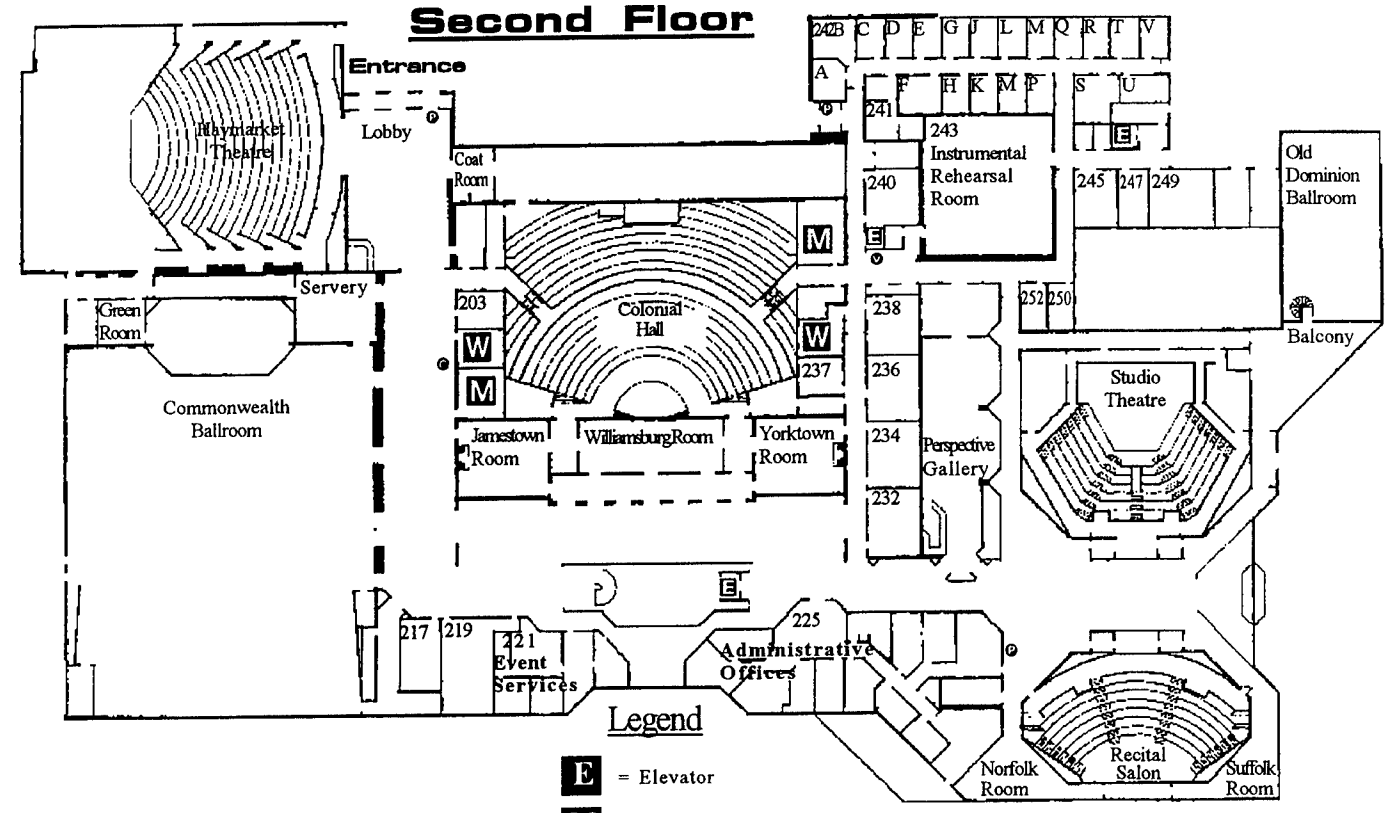
Department of Engineering Science and Mechanics, MC 0219
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Virginia Tech

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13. ABSTRACT (Maximum 200 words)

A part of travel expenses of nineteen graduate students to participate in the 14th US National Congress of Theoretical and Applied Mechanics were paid from the grant. The Congress was held at Virginia Polytechnic Institute and State University, Blacksburg, June 23-28, 2002. The congress attracted over one thousand participants from 5 continents, 32 countries and 46 US states. Besides presenting their research findings, participants discussed future directions of research in Mechanics. Graduate students had the opportunity to present their research work, listen to some of the leading researchers, and interact with their peers and persons more established in research.

14. SUBJECT TERMS
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Contemporary Research in Theoretical and Applied Mechanics

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ISBN 0-9721257-0-1

Virginia Polytechnic Institute and State University
Blacksburg, VA

June 23-28, 2002

Editors: R. C. Batra, E. G. Henneke

Department of Engineering Science and Mechanics, MC 0219
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Under the aegis of the
U. S. National Committee for Theoretical and Applied Mechanics
and its participating societies:

- Acoustical Society of America
- American Academy of Mechanics
- American Institute of Aeronautics and Astronautics
- American Institute of Chemical Engineers
- American Mathematical Society
- American Physical Society
- American Society of Civil Engineers
- American Society of Mechanical Engineers
- American Society for Testing and Materials
- Society of Engineering Science
- Society for Experimental Mechanics
- Society for Industrial and Applied Mathematics
- Society for Naval Architects and Marine Engineers
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FORWARD

The U.S. National Congresses of Theoretical and Applied Mechanics (USNCTAMs) are quadrennial meetings held under the aegis of the U.S. National Committee on Theoretical and Applied Mechanics (USNC/TAM). The Committee, established in 1949 by the National Academy of Sciences, represents the United States in international mechanics related activities. It is the focal point for the U.S. engineering, scientific, and mathematical communities which have common interests in research, technology, and education. It proposes strategies in areas of mutual interests and concerns, and stimulates appropriate actions. A representative from each one of the fourteen professional socieites listed on the first page of this book serves on the USNC/TAM.

Virginia Polytechnic Institute and State University, also known as Virginia Tech, is honored to host the USNCTAM14, June 23-28, 2002. Over 1100 papers authored by researchers from all around the world are scheduled for presentation at the Congress.

ACKNOWLEDGEMENTS

Drs. E. G. Henneke and R. C. Batra, Co-Chairs of the Congress are deeply indebted to Ms. Norma Guynn for her devotion and immense help with the organization of the Congress. Without her help, this event would not have been possible. She cheerfully corresponded with thousands of potential participants, answered their emails and other enquiries, and catalogued the abstracts and edited them for incorporation into the book. We sincerely thank Ms. Vanessa McCoy for her help with the preparation of the Preliminary and the Final Program, Ms. Lisa Smith for her help in corresponding with graduate students who requested travel support, Ms. Susan Hilton for her dedication to taking care of all phases of the organization of the Congress, and Ms. Terry Sadler for her help with the registration. We owe a debt of gratitude to Dr. E. L. Nelson of the Office of Continuing Education whose expertise and dedication played a key role in making all arrangements for running the Congress smoothly.

Our most sincere debt of gratitude goes to the Symposium Organizers for their immense help in organizing special symposia, and freely devoting their time to this very important activity. A majority of the Congress Program is made up of papers presented at these special symposia. We are grateful to members of the Scientific Program Committee for their invaluable advice and help with the organization of minisymposia made up of key-note lecturers.

Papers received by the Organizing Committee were reviewed by Professor R. C. Batra to see if they will fit in one of the special symposia. Those found suitable for incorporation in a symposium were forwarded to the symposium organizer(s); others were also reviewed by a member of the Scientific Program Committee.

Professor F. Hussain, co-chair of the Scientific Program Committee, graciously provided advice, reviewed papers in the fluids area and arranged them in sessions. Professor M. W. Hyer, co-chair of the Scientific Program Committee, and Professor E. G. Henneke, reviewed papers in the solids area and arranged them in sessions. Professors M. W. Hyer and R. C. Batra prepared the final schedule of presentation. Batra modified the preliminary program in response to requests from authors, symposia organizers and also necessitated by the cancellation of papers. He accepts full responsibility for errors, scheduling of papers at undesirable times and in inappropriate sessions and rooms, and for not incorporating all requests to modify abstracts and change the scheduled time of presentation.

Grants from the NSF, the ARO, the ONR and the AFoSR enabled us to provide travel fellowships to several graduate students; this financial support is gratefully acknowledged.

We are also indebeted to Mrs. Sandra Morris, Mrs. Gloria Henneke and Mrs. Manju Batra for their planning, organizing and executing the accompanying person's program.

Of course, there are no words to thank you, the participants, who made the Congress a success.

R.C. Batra
E. G. Henneke

ABSTRACTS

Abstracts are listed in the following order: plenary lectures, keynote lectures, symposia in memory of Professors Cole, Speziale and Truesdell; symposia honoring persons; special symposia; and general sessions. In each category, they are listed alphabetically according to either the last name of the person being honored or the symposium organizer. Abstracts in the general session are listed in the order of the title of the symposium.

The first ten pages of the book summarizing the program can be used to find the time, the day, the page number in the program where the session is listed, and the page number in the book where abstracts for that session begin.

Program

14th U.S. National Congress of Theoretical and Applied Mechanics

June 24-28, 2002

Virginia Tech

Blacksburg VA

The following ten pages provide a day-by-day schedule of sessions. There are two pages per day for each of the five days. Session times are on the left of each page. Session titles and the *(honoree)* or (organizer) are listed in the block representing each session. Also listed in each block is the page number where titles of the papers in that session may be found. Those pages follow the ten-page session schedule. In the block for each session is the building and room where the session is to be held. At present this entry is meaningless, and Torg 233 (meaning room 233 in Torgersen Hall) is used strictly as a place holder. A keynote session is denoted by (kn). Use the **Find** feature under **Edit** or **Tools** and the **Go To Page** feature in Acrobat to move around in the Program. When the rooms are scheduled, that information will be updated. Though significant changes to this Program are unlikely, if papers are withdrawn the schedule will be modified. Check the schedule periodically.

Monday, June 24, 2002

Registration: 7:30 am-5:00 pm, SQ, Commonwealth. Accompanying persons welcome, DB Committee Rm: 8-9:45 am

	A	B	C	D	E	F	G	H	I	J
M1 8:00-9:05am	Bones Have Ears, *S. C. Cowin* SQ, Colonial Hall									
9:05-9:30am	**BREAK: SQ Commonwealth**									
M2 9:30-11:45am	Mechanics, Continuum Thermo & Kinetic Theory I *(Truesdell)* p.12/109 SQ, Colonial	MEMS (kn) (Sharpe) p. 15/97 SQ, Haymarket	Material Failure at High Strain Rates (kn) (Rajapakse) p. 15/94 Torg 3100	Deformation, Fracture & Mass Transport I (Suo, Huang) p. 15/448 Torg 2150	Experimental Mechanics: Optical Methods *(Daniel)* p 19/185 DB, Front Aud.	Developments in Composites Materials & Structures (kn) (Hyer) p 22/87 SQ, Brush, A	Complex Fluids I *(Speziale)* p. 22/104 SQ 234	Plasticity I p. 27/576 DB, Rm C	Material Behavior I p 23/553 DB, Rm F	Dynamics I p. 34/503 DB, Exec.
	LUNCH: On Your Own									
M3 1:00-3:05pm	Mechanics, Continuum Thermo & Kinetic Theory II *(Truesdell)* p 12/110 SQ, Colonial	Contemporary Issues in Mechanics I *(Beatty)* p. 39/131 SQ, Haymarket	Fluid Mechanics & Multiphase Flow I *(Joseph)* p. 41/227 SQ 219	Turbulent Flows (Mahesh) p. 42/426 SQ, Brush B	Advances in 3-Dimen-sional Flow Modeling I (Khalil) p. 42/396 SQ 236	Complex Fluids II *(Speziale)* p. 23/107 SQ 234	Microelec-tronics, MEMS and Coatings I (Suo, Huang) p. 16/450 Torg 2150	Experimental Mechanics: Mechanical Behavior of Materials I *(Daniel)* p. 19/187 DB, Front Aud.	Visco-elasticity in Composites I *(Schapery)* p. 43/330 DB, Rear Aud.	Advances in Composite Materials I *(Dvorak)* p. 44/210 DB, Rm D
3:05-3:30	**BREAK: SQ, Commonwealth.**									
M4 3:30-5:35pm	Mechanics, Continuum Thermo & Kinetic Theory III *(Truesdell)* p. 12/112 SQ, Colonial	Contemporary Issues in Mechanics II *(Beatty)* p. 39/133 SQ, Haymarket	Fluid Mechanics & Multiphase Flow II *(Joseph)* p. 41/229 SQ 219	Turbulent Flows (Mahesh) p. 42/428 SQ, Brush B	Advances in 3-Dimen-sional Flow Modeling II (Khalil) p. 43/398 SQ 236	Perturbation Theory & Computa-tions I *(Cole)* p. 57/100 SQ 234	Nano-structures & Nano-mechanics I (Suo, Huang) p. 16/451 Torg 2150	Experimental Mechanics: Mechanical Behavior of Materials II *(Daniel)* p. 19/188 DB, Front Aud.	Visco-elasticity in Composites II *(Schapery)* p. 43/332 DB, Rear Aud.	Advances in Composite Materials II *(Dvorak)* p. 44/213 DB, Rm D
6:00-7:30 pm	**RECEPTION: SQ, Commonwealth**									

Key: (*honoree* or organizer); page with schedule of presentations/page where abstracts begin; building and room no., DB=Donaldson Brown Hotel & Conf. Center, SQ=Squires Student Center, Torg=Torgersen Hall; kn=keynote lecture

MONDAY IS CONTINUED ON NEXT PAGE

Monday, June 24, 2002 (cont.)
Registration: 7:30 am-5:00 pm; SQ, Commonwealth

	K	L	M	N	O	P	Q	R	S	T
M1 **8:00-9:05am**	Bones Have Ears, *S. C. Cowin* SQ, Colonial Hall									
9:05-9:30am	**BREAK: SQ, Commonwealth**									
M2 **9:30-11:45am**	Friction & Wear I p. 27/547 SQ 232	Elasticity I p. 28/510 SQ, Brush B	Heat Transfer & Thermo-dynamics p. 23/551 SQ 341	Material Modeling & Optimization p. 23/565 SQ 345	Metal Working & Metallurgy p. 23/573 DB, Rm A	Turbulence p. 36/605 SQ 236	Nonlinear Dynamics & Control I (kn) (Junkins) p. 38/87 DB, Rear Aud.	Flow Control p. 36/515 SQ 219	Fracture Mechanics I p. 25/532 DB, Rm D	
	LUNCH: On Your Own									
M3 **1:00-3:05pm**	Low Vel. Impacts I (Abrate) p. 45/349 SQ 341	Thin Films & MEMS (Espinosa, Ballarini, Knauss) p. 47/370 Torg 3100	Optical Methods I *(Dally)* p. 49/169 SQ 232	Instability in Solids & Structures I (Kyriakides) p. 50/411 SQ 345	Plasticity & Cyclic Plasticity *(Mroz)* p. 51/272 DB, Rm F	Magneto-elasticity I (Shindo) p. 54/433 DB, Exec.	Mechanics Education I *(McNitt)* p. 55/267 DB, Rm C	Advances in Computa-tional Mechanics I *(Oden)* p. 55/304 SQ, Brush A	Fracture Mechanics II p. 25/534 DB, Rm A	
3:05-3:30	**BREAK: SQ, Commonwealth**									
M4 **3:30-5:35pm**	Low Vel. Impacts II (Abrate) p. 45/352 SQ 341	Computa-tional Modeling of MEMS (Espinosa, Ballarini, Knauss) p. 47/373 Torg 3100	Optical Methods II *(Dally)* p. 48/172 SQ 232	Instability in Solids & Structures II (Kyriakides) p. 50/413 SQ 345	Crystal Plasticity *(Mroz)* p. 51/276 DB, Rm F	Coupled Problems (Shindo) p. 54/435 DB, Exec.	Mechanics Education II *(McNitt)* p. 55/269 DB, Rm C	Advances in Computa-tional Mechanics II *(Oden)* p. 55/306 SQ, Brush A	Fracture Mechanics III p. 26/537 DB, Rm A	
6:00-7:30 pm	**RECEPTION: SQ, Commonwealth**									

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Tuesday, June 25, 2002
Registration: 7:30 am-5:00 pm; SQ, Commonwealth

	A	B	C	D	E	F	G	H	I	J
T1 8:00-9:05am	Cutting of Materials, *B. von Turkovich* SQ, Colonial Hall									
9:05-9:30am	**BREAK**									
T2 9:30-11:45am	Mechanics, Continuum Thermodynamics, Kinetic Theory IV *(Truesdell)* p. 12/114 SQ, Colonial	MEMS (kn) (Sharpe) p. 15/98 SQ, Haymarket	Material Failure at High Strain Rates (kn) (Rajapakse) p. 15/95 Torg 3100	Deformation, Fracture & Mass Transport II (Suo, Huang) p. 16/453 Torg 2150	Recent Advances in Experimental Mechanics: Nondestructive Evaluation *(Daniel)* p. 20/189 DB, Front Aud.	Compressible Flow with Chemical Reaction I (kn) (Hornung) p. 57/84 SQ, Brush A	Arterial Flows: in Health & Disease I (kn) (Berger) p. 57/78 SQ 341/45	Plasticity II p. 28/578 DB, Rm C	Material Behavior II p. 24/555 DB, Rm F	Structures I p. 30/592 DB, Exec.
	LUNCH: SQ, Commonwealth									
T3 1:00-3:05pm	Mechanics, Continuum Thermodynamics, Kinetic Theory V *(Truesdell)* p. 13/116 SQ, Colonial	Contemporary Issues in Mechanics III *(Beatty)* p. 39/135 SQ, Haymarket	Fluid Mechanics & Multiphase Flow III *(Joseph)* p. 41/231 SQ, 219	Computational Fluid Dynamics p. 36/501 SQ, Brush B	Flow Instabilities p. 37/517 DB, Rm C	Perturbation Theory & Computations II *(Cole)* p. 57/102 SQ 234	Arterial Flows in Health & Disease II (kn) (Berger) p. 58/80 SQ 236	Experimental Mechanics: Composite Materials I *(Daniel)* p. 20/192 DB, Front Aud.	Visco-elasticity in Composites III *(Schapery)* p. 43/335 DB, Rear Aud.	Advances in Composite Materials III *(Dvorak)* p. 44/214 DB, Rm D
3:05-3:30	**BREAK: SQ, Commonwealth.**									
T4 3:30-5:35pm	Mechanics, Continuum Thermodynamics, Kinetic Theory VI *(Truesdell)* p. 13/118 SQ, Colonial	Contemporary Issues in Mechanics IV *(Beatty)* p. 40/137 SQ, Haymarket	Fluid Mechanics & Multiphase Flow IV *(Joseph)* p. 41/232 SQ 219	Turbulent Flows & Instabilities p. 37/607 SQ, Brush B	Liquid/Solid Interface I *(Davis)* p. 58/207 SQ 236	Flow in Porous Media p. 37/523 SQ 234	Analysis and Durability of Adhesive Bonds *(Brinson, Cardon)* p. 59/156 DB, Rm C	Experimental Mechanics: Composite Materials II *(Daniel)* p. 20/193 DB, Front Aud.	Mechanics of Plasticity I *(Tomita)* p. 60/337 DB, Rear Aud.	Advances in Composite Materials IV *(Dvorak)* p. 44/216 DB, Rm D

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TUESDAY IS CONTINUED ON NEXT PAGE

Tuesday, June 25, 2002 (cont.)
Registration: 7:30 am-5:00 pm; SQ, Commonwealth

	K	L	M	N	O	P	Q	R	S	T
T1 8:00-9:05am	Cutting of Materials, *B. von Turkovich* SQ, Colonial Hall									
9:05-9:30am	**BREAK: SQ, Commonwealth**									
T2 9:30-11:45am	Dynamics II p. 35/505 SQ, 232		Elasticity II p. 29/513 DB, Rm A			Flow & Modeling p. 36/520 SQ 219	Nonlinear Dynamics & Control II (kn) (Junkins) p. 38/89 DB, Rear Aud.	Fluid Flows p. 37/525 SQ 234		
	LUNCH: On Your Own									
T3 1:00-3:05pm	Impacts on Sandwich Structures & Fiber-Metal Laminates (Abrate) p. 45/355 SQ 341	Design of MEMS (Espinosa, Ballarini, Knauss) p. 47/375 Torg 3100	Dynamic Fracture I *(Dally)* p. 49/175 SQ 232	Instability in Solids and Structures III (Kyriakides) p. 51/416 SQ 345	Visco-plasticity *(Mroz)* p. 52/278 DB, Rm F	Piezoelec. Fracture & Damage Mechs. (Shindo) p. 54/438 DB, Exec.	Micro-electronics, MEMS & Coatings II (Suo, Huang) p. 16/455 Torg 2150	Advances in Computa-tional Mechanics III *(Oden)* p. 55/308 SQ, Brush A	Fracture Mechanics V p. 26/539 DB, Rm A	
3:05-3:30	**BREAK: SQ, Commwealth**									
T4 3:30-5:35pm	Dynamic Properties of Composite Materials and Ceramics (Abrate) p. 45/358 SQ 341	Computa-tional Approaches for Modeling Nanodevices (Espinosa, Ballarini, Knauss) p. 47/376 Torg 3100	Dynamic Fracture II *(Dally)* p. 49/177 SQ 232	Instability in Solids and Structures IV (Kyriakides) p. 51/417 SQ 345	Gradient Plasticity *(Mroz)* p. 52/279 DB, Rm F	Modeling Piezoelectric Systems (Shindo) p. 54/440 DB, Exec.	Nanostruc-tures & Nano-mechanics II (Suo, Huang) p. 17/456 Torg 2150	Advances in Computa-tional Mechanics IV *(Oden)* p. 55/310 SQ, Brush A	Fracture Mechanics VI p. 26/542 DB, Rm A	

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Wednesday, June 26, 2002
Registration: 7:30 am-5:00 pm, SQ Commonwealth

	A	B	C	D	E	F	G	H	I	J
W1 8:00-9:05am	On the Structure of Vorticity in the Inertial Range of Turbulence , *A Leonard* SQ, Colonial Hall									
9:05-9:30am	**BREAK: SQ, Commonwealth**									
W2 9:30-11:45am	Mechanics, Continuum Thermody-namics, Kinetic Theory VII *(Truesdell)* p. 13/119 SQ, Colonial	Contemporary Issues in Mechanics V *(Beatty)* p. 40/139 SQ, Haymarket	Soft Actuators & Sensors I (kn) (Nemat-Nasser) p. 61/90 Torg 3100	Deformation, Fracture & Mass Transport III (Suo, Huang) p. 17/459 Torg 2150	Experimental Mechanics: Composite Structures *(Daniel)* p. 20/195 DB, Front Aud.	Compressible Flow with Chemical Reaction II (kn) (Hornung) p. 57/86 SQ, Brush A	Arterial Flow: In Health & Disease III (kn) (Berger) p. 58/82 SQ 341/45	Structural Mechanics I *(Leissa)* p. 61/249 DB, Rm D	Material Behavior III p. 24/558 DB, Rm F	Structures II p. 31/594 DB, Exec.
	LUNCH: On Your Own									
W3 1:00-3:05pm	Mechanics, Continuum Thermody-namics, Kinetic Theory VIII *(Truesdell)* p. 13/122 SQ, Colonial	Contemporary Issues in Mechanics VI *(Beatty)* p. 40/142 SQ, Haymarket	Fluid Mechanics & Multiphase Flow V *(Joseph)* p. 42/233 SQ 219	Turbulence in Chemical Processing I *(Brodkey)* p. 63/164 SQ, Brush B	Liquid/Solid Interface II *(Davis)* p. 58/209 SQ 236	Time Dependence in Polymers *(Brinson, Cardon)* p. 58/158 DB, Rm C	Arterial Flow: in Health & Disease IV (kn) p. 58, 37/83,486 SQ 345	Experimental Mechanics: Hybrid Methods I *(Daniel)* p. 21/197 DB, Front Aud.	Mechanics of Plasticity II *(Tomita)* p. 60/340 DB, Exec.	Fluid Mechanics p. 35/528 SQ 234
3:05-3:30	**BREAK: SQ, Commonwealth**									
W4 3:30-5:35pm	Mechanics, Continuum Thermodyna mics, Kinetic Theory IX *(Truesdell)* p. 14/124 SQ, Colonial	Contemporary Issues in Mechanics VII *(Beatty)* p. 40/144 SQ, Haymarket	Fluid Mechanics & Multiphase Flow VI *(Joseph)* p. 42/236 SQ 219	Turbulence in Chemical Processing II *(Brodkey)* p. 64/166 SQ, Brush B	Constitutive & Damage of Polymers *(Garrett)* p. 74/387 SQ 234	Analysis and Durability of Composites *(Brinson, Cardon)* p. 59/160 DB, Rm C	Dynamic Fracture (Nishioka) p. 65/430 SQ 236	Experimental Mechanics: Hybrid Methods II *(Daniel)* p. 21/198 DB, Front Aud.	Mechanics of Plasticity III *(Tomita)* p. 60/342 DB, Exec.	

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WEDNESDAY IS CONTINUED ON NEXT PAGE

Wednesday, June 26, 2002, (cont.)
Registration: 7:30 am-5:00 pm, SQ Commonwealth

	K	L	M	N	O	P	Q	R	S	T
W1 8:00-9:05am	On the Structure of Vorticity in the Inertial Range of Turbulence , *A Leonard* SQ, Colonial Hall									
9:05-9:30am	**BREAK: SQ, Commonwealth**									
W2 9:30-11:45am	Plasticity III p. 28/580 SQ 232	Wave Motion I p. 33/615 SQ, Brush B	Dynamics III p. 35/507 DB, Rm A	Composite Materials I p. 29/489 SQ 236	Theory & Modeling of Fluids p. 38/602 SQ 234	Analysis of Piezoelectric Materials p. 27/475 SQ 219	Nonlinear Dynamics & Control III (kn) (Junkins) p. 39/89 DB, Rear Aud.		Fracture Mechanics VII p. 26/544 DB, Room C	
	LUNCH: On Your Own									
W3 1:00-3:05pm	Impact Damage (Abrate) p. 46/361 SQ 341	Mechanics of Nano-materials and Nano-structures (Espinosa, Ballarini, Knauss) p. 47/379 Torg 3100	Micro-mechanics *(Dally)* p. 49/180 SQ 232	Composite Materials II p. 29/491 DB Rm A	Damage Mechanics I *(Mroz)* p. 52/281 DB, Rm F	Structural Mechanics II *(Leissa)* p. 62/250 DB, Rm D	Micro-electronics, MEMS & Coatings III (Suo, Huang) p. 17/460 Torg 2150	Advances in Computa-tional Mechanics V *(Oden)* p. 56/313 SQ, Brush A	Stress Analysis of Composites *(Herakovich)* p. 64/218 DB, Rear Aud.	
3:05-3:30	**BREAK: SQ, Commonwealth**									
W4 3:30-5:35pm	Ballistic Impacts (Abrate) p. 46/363 SQ 341/45	Scale Effects in Plasticity & Elasticity (Espinosa, Ballarini, Knauss) p. 48/380 Torg 3100	Education in Experimental Mechanics *(Dally)* p. 49/183 SQ 232	Continuum Mechanics & Thermo-dynamics *(Müller)* p. 65/291 DB, Rm A	Damage Mechanics II *(Mroz)* p. 52/283 DB, Rm F	Structural Mechanics III *(Leissa)* p. 62/253 DB, Rm D	Nano-structures & Nano-mechanics III (Suo, Huang) p. 17/462 Torg 2150	Advances in Computa-tional Mechanics VI *(Oden)* p. 56/315 SQ, Brush A	Experimental Mechanics of Composites *(Herakovich)* p. 64/219 DB, Rear Aud.	

Key: (*honoree* or organizer); page with schedule of presentations; building and room no., DB=Donaldson Brown Hotel & Conf. Center, SQ=Squires Student Center, Torg=Torgersen Hall; kn=keynote

Thursday, June 27, 2002
Registration: 7:30 am-5:00 pm, SQ Old Dominion

	A	B	C	D	E	F	G	H	I	J
R1 8:00-9:05am	Influence of Surfaces on the Mechanics of Thin Films, *R. C. Cammarata*					Coherent Structures to 10:35 am *(Roshko)* p. 67/319 SQ 341/45				
9:05-9:30am	**BREAK: SQ, Old Dominion**									
R2 9:30-11:45am	Mechanics, Continuum Thermody-namics, Kinetic Theory X *(Truesdell)* p. 14/126 SQ, Colonial	Extended Thermodyna mics & Kinetic Theory I *(Müller)* p. 65/293 SQ, Haymarket	Soft Actuators & Sensors II (kn) (Nemat-Nasser) p. 61/92 Torg 3100	Deformation, Fracture & Mass Transport IV (Suo, Huang) p. 18/465 Torg 2150	Structural Testing & Analysis *(Daniel)* p. 21/199 DB, Front Aud.	Bluff Body & Cavity Flows *(Roshko)* p. 67/321 SQ 341/45	General Mechanics *(Boley)* p. 68/146 SQ, Brush A	Structural Mechanics IV *(Leissa)* p. 62/255 DB, Rm D	Material Behavior IV p. 24/560 SQ 236	Structures III p. 31/596 SQ 219
	LUNCH: On Your Own									
R3 1:00-3:05pm	Mechanics, Continuum Thermody-namics, Kinetic Theory XI *(Truesdell)* p. 14/128 SQ, Colonial	Shape Memory Alloys I-Theory *(Müller)* p. 66/295 SQ, Haymarket	Electrohydro-dynamics I (Khusid) p. 72/400 SQ 234	Multiphase & Suspension Flows p. 38/574 SQ, Brush B	Structural Dynamics I p. 32/585 SQ 236	Vortex Aero-dynamics *(Roshko)* p. 67/323 SQ 219	Design & Structural Issues *(Brinson, Cardon)* p. 59/162 DB, Rm C	Experimental Mechanics: Fracture and Fatigue I *(Daniel)* p 21/201 DB, Front Aud.	Mechanics of Plasticity IV *(Tomita)* p. 60/344 DB, Rear Aud.	Granular Mechanics *(Boley)* p. 68/147 DB, Rm A
3:05-3:30	**BREAK: SQ Old Dominion**									
R4 3:30-5:35pm	Mechanics, Continuum Thermodyna mics, Kinetic Theory XII *(Truesdell)* p. 14/129 SQ, Colonial	Application of Thermo-dynamics *(Müller)* p. 66/297 SQ, Haymarket	Electrohydro-dynamics II (Khusid) p. 72/403 SQ 234	Bifurcation & Nonlinear Dynamics in Fluids p. 38/487 SQ, Brush B	Structural Dynamics II p. 33/587 SQ 236	Mixing & Combustion *(Roshko)* p. 67/325 SQ 219	Material Behavior V p. 24/563 DB, Rm C	Experimental Mechanics: Fracture and Fatigue II *(Daniel)* p. 22/202 DB, Front Aud.	Mechanics of Plasticity V *(Tomita)* p. 61/347 DB, Rear Aud.	Finite & Boundary Element Methods *(Boley)* p. 68/149 DB, Rm A
6:00-7:00 pm	**Cash Bar; SQ Old Dominion**									
7:00-9:00 pm	**BANQUET: SQ Commonwealth**									

Key: (*honoree* or organizer); page with schedule of presentations/page where abstracts begin; building and room no., DB=Donaldson Brown Hotel & Conf. Center, SQ=Squires Student Center, Torg=Torgersen Hall; kn=keynote lecture

THURSDAY IS CONTINUED ON NEXT PAGE

Thursday, June 27, 2002, (cont.)
Registration: 7:30 am-5:00 pm; SQ Old Dominion

	K	L	M	N	O	P	Q	R	S	T
R1 8:00-9:05am	Influence of Surfaces on the Mechanics of Thin Films, *R. C. Cammarata*									
9:05-9:30am	**BREAK: SQ Old Dominion**									
R2 9:30-11:45am	Constitutive Modeling of Shape Memory Alloys I (Lagoudas & Levitas) p. 70/419 DB, Rm A	Wave Motion II p. 33/618 SQ 234	Topics in Mechanics of Materials I *(Knauss)* p. 70/238 SQ, Brush B	Composite Materials III p. 29/493 DB, Rm F		Vibration & Control p. 34/613 DB, Exec.	Contemp. Issues Mechs. (kn) (Batra) p. 73/76 DB, Rear Aud.			
	LUNCH: On Your Own									
R3 1:00-3:05pm	Crash Impact & Blast Loading (Abrate) p. 46/366 SQ 341	Nano-tribology/ Nano-machining (Espinosa, Ballarini, Knauss) p. 48/382 Torg 3100	Topics of Mechanics of Materials II *(Knauss)* p. 71/240 SQ 232	Structural Mechanics V *(Leissa)* p. 62/257 DB, Rm D	Fracture Mechanics *(Mroz)* p. 53/286 DB, Rm F	Piezoelectric Buckling, Stability & Vibration (Shindo) p. 55/.443 DB, Exec	Micro-electronics, MEMS & Coatings IV (Suo, Huang) p. 18/467 Torg 2150	Advances in Computa-tional Mechanics VII *(Oden)* p. 56/317 SQ, Brush A	Micro-mechanics of Fibrous Compsites *(Herakovich)* p. 64/222 SQ 345	
3:05-3:30	**BREAK: SQ Old Dominion**									
R4 3:30-5:35pm	Impact on Composites & Graded Materials (Abrate) p. 46/368 SQ 341	Mechanics of Nano-structures (Espinosa, Ballarini, Knauss) p. 48/384 Torg 3100	Topics in Mechanics of Materials III *(Knauss)* p. 71/242 SQ, Brush A	Structural Mechanics VI *(Leissa)* p. 63/259 DB, Rm D	Composite Material Behavior *(Mroz)* p. 53/288 DB, Rm F	Smart Sensors & Actuators (Shindo) p. 55/445 DB, Exec.	Nano-structures & Nano-mechanics IV (Suo, Huang) p. 18/469 Torg 2150	Applications of Finite Element Methods I p. 32/478 SQ 232	Damage in Composites *(Herakovich)* p. 65/225 SQ 345	
6:00-7:00 pm	**Cash Bar; SQ Old Dominion**									
7:00-9:00 pm	**BANQUET: SQ Commonwealth**									

Key: (*honoree* or organizer); page with schedule of presentations/page where abstracts begin; building and room no., DB=Donaldson Brown Hotel & Conf. Center, SQ=Squires Student Center, Torg=Torgersen Hall; kn=keynote lecture

Friday, June 28, 2002
Registration: 8:00 am-12:00-noon, SQ, Old Dominion

	A	B	C	D	E	F	G	H	I	J
F1 **8:00-9:05am**	Some Structural Mechanics Research Experiences at NASA Langley Research Center, *J. H. Starnes, Jr.*					Flow Control to 10:35 am *(Roshko)* p. 68/327 SQ 341/45				
9:05-9:30am	**BREAK: SQ Old Dominion**									
F2 **9:30-11:45am**	Mathematical Analysis of Continuua I p. 25/568 DB, Rm A	Shape Memory Alloys II-Applications *(Müller)* p. 66/299 Torg 3100	Soft Actuators & Sensors III (kn) (Nemat-Nasser) p. 61, 23/93.584 SQ, Brush A	Deformation, Fracture & Mass Transport V (Suo, Huang) p. 18/471 Torg 2150	Experimental Mechanics: Neutron Diffraction & Synchrotron Radiation Methods I *(Daniel)* p. 22/203 DB, Front Aud.	Jet Noise *(Roshko)* p. 68/329 SQ 341/45	Analytical Methods *(Boley)* p. 69/151 SQ 219	Structural Mechanics VII *(Leissa)* p. 63/261 DB, Rm D	Applications of Finite Element Methods II p. 32/481 DB, Rm F	Vibration Analysis p. 34/610 DB, Rm C
	LUNCH: On Your Own									
F3 **1:00-3:05pm**	Seismic Analysis p. 30/582 DB, Rm A	Solids I *(Müller)* p. 66/301 Torg 3100	Electrohydro-dynamics III (Khusid) p. 73/406 SQ 234	Microelec-tronics, MEMS & Coatings V (Suo, Huang) p. 19/473 Torg 2150	Experimental Mechanics: Neutron Diffraction & Synchrotron Radiation Methods II *(Daniel)* p. 22/205 DB, Front Aud.	Computa-tional Geo-mechanics II p. 73/391 SQ 236	Mechanics of Materials *(Boley)* p. 69/154 SQ 219	Structural Mechanics VIII *(Leissa)* p. 63/263 DB, Rm D	Applications of Finite Element Methods III p. 32/483 DB, Rm F	Structures IV p. 31/599 DB, Rm C
3:05-3:30	**BREAK: SQ Old Dominion**									
F4 **3:30-5:35pm**		Solids & Extended Thermo-dynamics/ Kinetic Theory II *(Müller)* p. 67/302 Torg, 3100	Electrohydro-dynamics IV (Khusid) p. 73/409 SQ 234			Compu-tational Geo-mechanics III p. 73/394 SQ 236.				

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FRIDAY IS CONTINUED ON NEXT PAGE

Friday, June 28, 2002 (cont.)
Registration: 8:00 am-12:00 noon, SQ Old Dominion

	K	L	M	N	O	P	Q	R	S	T
F1 **8:00-9:05am**	Some Structural Mechanics Research Experiences at NASA Langley Research Center, *J. H. Starnes, Jr.*									
9:05-9:30am	**BREAK: SQ, Old Dominion**									
F2 **9:30-11:45am**	Constitutive Modeling of Shape Memory Alloys II (Lagoudas & Levitas) p. 70/422 SQ 234	Wave Motion III p. 33/621 DB, Exec.	Topics in Mechanics of Materials IV *(Knauss)* p. 72/244 SQ 232	Composite Materials IV p. 30/495 SQ Brush B	Computa-tional Geo-mechanics I (Gutierrez) p. 73/389 SQ 236					
	LUNCH: On Your Own									
F3 **1:000-3:05pm**	Constitutive Modeling of Shape Memory Alloys III (Lagoudas & Levitas) p. 70/424 SQ 345	Mathematical Analysis of Continua II p. 25/570 DB, Exec.	Topics in Mechanis of Materials V *(Knauss)* p. 72/246 SQ, Brush A	Composite Materials V p. 30/498 SQ 341						
3:05-3:30	**BREAK: SQ, Old Dominion**									
F4 **3:30-5:35pm**		Wave Motion IV p. 34/624 SQ 232								

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Recent Advances and New Directions in Mechanics, Continuum Thermodynamics, and Kinetic Theory I

In Memory of Clifford A. Truesdell III

Organizer: C.-S. Man
Session: M2A, Mon., June 24, 9:30-11:50 am
Room: SQ, Colonial
Chair: R. L. Fosdick

9:30 Clifford Truesdell and Thermodynamics, *B. D. Coleman*

9:55 A Nonequilibrium Theory of Epitaxial Growth that Accounts for Surface Stress and Diffusion, *M. E. Gurtin, E. Fried*

10:40 The Lavrentiev Phenomenon in Nonlinear Elasticity, *M. Foss, W. Hrusa, V.J. Mizel*

11:25 Constitutive Relations of Textured Polycrystals, *C.-S. Man*

Recent Advances and New Directions in Mechanics, Continuum Thermodynamics, and Kinetic Theory II

In Memory of Clifford A. Truesdell III

Organizer: C.-S. Man
Session: M3A, Mon., June 24, 1:00-3:05 pm
Room: SQ, Colonial
Chair: E. Fried

1:00 Tensile Waves in a Rubberlike Material, *J. K. Knowles*

1:25 Kinetic Relations for Phase Boundaries- Computations and Proposed Experiments, *P. K. Purohit, K. Bhattacharya*

1:50 Non-Isothermal Kinetics of a Moving Phase Boundary, *A. Vainchtein*

2:15 Thermal Effects in Dynamics of Interfaces, *A. Umantsev*

2:40 Interface Evolution in Three-Dimensions with Curvature-Dependent Energy and Surface Diffusion, *M. E. Jabbour, M. E. Gurtin*

Recent Advances and New Directions in Mechanics, Continuum Thermodynamics, and Kinetic Theory III

In Memory of Clifford A. Truesdell III

Organizer: C.-S. Man
Session: M4A, Mon., June 24, 3:30-5:35 pm
Room: SQ. Colonial
Chair: D. E. Carlson

3:30 About Clapeyron's Theorem in Linear Elasticity, *R. Fosdick, L. Truskinovsky*

3:55 E. Frola (1906-62): An Attempt Toward an Axiomatic Theory of Elasticity, *S. Caparrini, F. Pastrone*

4:20 Complex Variable Displacement Method in Plane Isotropic Elasticity, *X.-L. Gao*

4:45 Anisotropic Elasticity and Multi-Material Singularities, *W.-L. Yin*

5:10 Constitutive Relation of Elastic Polycrystal with Quadratic Texture Dependence, *M. Huang, C.-S. Man*

Recent Advances and New Directions in Mechanics, Continuum Thermodynamics, and Kinetic Theory IV

In Memory of Clifford A. Truesdell III

Organizer: C.-S. Man
Session: T2A, Tues., June 25, 9:30-11:35 am
Room: SQ, Colonial
Chair: T. J. Healey

9:30 A Strain Averaged Statistical Mechanical Model for Rubber Elasticity, *M. F. Beatty*

9:55 An Elementary Molecular-Statistical Basis for the Mooney and Rivlin-Saunders Theories of Rubber-Elasticity, *E. Fried*

10:20 Rivlin's Approach to Rubber Elasticity is Ill-Suited for a Rational Experimental Method, *J. C. Criscione*

10:45 Analysis of J.F. Bell's Research on the Finite Twist and Extension of Cylindrical Tubes, *D. J. Steigmann*

11:10 Some New Advances in the Theory of Dynamic Materials, *K. A. Lurie*

Recent Advances and New Directions in
Mechanics, Continuum Thermodynamics, and Kinetic Theory
V

In Memory of
Clifford A. Truesdell III

Organizer: C.-S. Man
Session: T3A, Tues., June 25, 1:00-3:05 pm
Room: SQ, Colonial
Chair: M. F. McCarthy

1:00 Invariance, Computation, and Regularity, *S. S. Antman*

1:25 Generalized Hessian and External Approximations in Variational Problems of Second Order, *C. Davini, R. Paroni*

1:50 Equilibria of a Class of Tensegrity Structures, *W. O. Williams*

2:15 Identification of Crack by Boundary Measurement, *M. Ikehata, G. Nakamura*

2:40 On Cavitation, Configurational Forces and Implications for Fracture in Nonlinear Elasticity, *J. Sivaloganathan, S.J. Spector*

Recent Advances and New Directions in
Mechanics, Continuum Thermodynamics, and Kinetic Theory
VI

In Memory of
Clifford A. Truesdell III

Organizer: C.-S. Man
Session: T4A, Tues., June 25, 3:30-5:35 pm
Room: SQ, Colonial
Chair: Y. C. Chen

3:30 An Approach to Robust Structural Design, *E. Cherkaev, A. Cherkaev*

3:55 Minimum Elastic Energy Configurations of DNA Torus Knots and Catenanes, *D. Swigon*

4:20 Global Bifurcation of Barreling States of Cylindrical Columns, *E. L. Montes-Pizarro*

4:45 Global Bifurcation and Continuation in Nonlinear Elasticity, *T.J. Healey*

5:10 The Hanging Rope of Minimum Elongation for a Nonlinear Stress-Strain Relation, *P. V. Negron-Marrero*

Recent Advances and New Directions in
Mechanics, Continuum Thermodynamics, and Kinetic Theory
VII

In Memory of
Clifford A. Truesdell III

Organizer: C.-S. Man
Session: W2A, Wed., June 26, 9:30-11:35 am
Room: SQ, Colonial
Chair: J. T. Jenkins

9:30 The Augustinian Contuitus and its Relevance in Natural Philosophy, *G. Capriz*

9:55 Symmetries and Hamiltonian Formalism when Material Elements do not Behave Like Monads, *P. M. Mariano*

10:20 Smooth Categories and Microstructure, *F. W. Lawvere*

10:45 A Simple Class of Fit Regions for Continuum Mechanics, *G. Del Piero*

11:10 Cauchy's Theorem for Fluxes in Light of Geometric Integration Theory, *G. Rodnay, R.Segev*

Recent Advances and New Directions in
Mechanics, Continuum Thermodynamics, and Kinetic Theory
VIII

In Memory of
Clifford A. Truesdell III

Organizer: C.-S. Man
Session: W3A, Wed., June 26, 1:00-3:05 pm
Room: SQ, Colonial
Chair: C. Davini

1:00 Eshelby Tensor as Tensor of Free Enthalpy, *G. Buratti, Y. Huo, I. Müller*

1:25 Weak Phase Transitions in Multilattices, *M. Pitteri*

1:50 Kinetic Theory for Collisional Grain Flows, *J. T. Jenkins*

2:15 The Atomic Level Virial Stress is not a Valid Measure of Mechanical Stress, *M. Zhou*

2:40 Some Critical Experimental Results on Polymers, *A. S. Khan*

Recent Advances and New Directions in
Mechanics, Continuum Thermodynamics, and Kinetic Theory
IX

In Memory of
Clifford A. Truesdell III

Organizer: C.-S. Man
Session: W4A, Wed., June 26, 3:30-5:10 pm
Room: SQ. Colonial
Chair: W.-L. Yin

3:30 On the Equilibrium of Spherical Particles in a Vertical Shear Flow, *G.P. Galdi*

3:55 Minimum Free Energies for Materials with Finite Memory, *M. Fabrizio, J.M. Golden*

4:20 Exponential Decay in Materials with Memory, *D. W. Reynolds*

4:45 Universal Relations for Principal Acceleration Waves in Nonlinear Isotropic Viscoelastic Solids, *M. J. Scheidler*

Recent Advances and New Directions in
Mechanics, Continuum Thermodynamics, and Kinetic Theory
X

In Memory of
Clifford A. Truesdell III

Organizer: C.-S. Man
Session: R2A, Thurs., June 27, 9:30-11:35 am
Room: SQ, Colonial
Chair: F. Pastrone

9:30 Pseudo-Plasticity and Pseudo-Inhomogeneity Effects in Materials Mechanics, *G. A. Maugin*

9:55 Inhomogeneity of Generalized Media with Microstructure, *M. Epstein, I. Bucataru*

10:20 A Few Remarks on the Kinetic Energy in Continua with Structures, *C. Trimarco*

10:45 Mathematical Modeling of Mmesoscopic Elasticity, *L. G. Steinberg*

11:10 A Model of the Evolution of a Two-Dimensional Defective Structure, *M. Epstein, M. Z. Elzanowski*

Recent Advances and New Directions in
Mechanics, Continuum Thermodynamics, and Kinetic Theory
XI

In Memory of
Clifford A. Truesdell III

Organizer: C.-S. Man
Session: R3A, Thurs., June 27, 1:00-2:40 pm
Room: SQ, Colonial
Chair: R. G. Muncaster

1:00 Elasticity with Disarrangements as a Continuum Field Theory, *L. Deseri, D.R. Owen*

1:25 A Continuum Theory for Materials with Microstructures, *Y. C. Chen, G. Dui*

1:50 Modeling of Ferroelectric Liquid Crystals and Applications, *M. C. Calderer*

2:15 On Spontaneous Deformation and Internal Stress and Electric Fields, *Y. Zhang*

Recent Advances and New Directions in
Mechanics, Continuum Thermodynamics, and Kinetic Theory
XII

In Memory of
Clifford A. Truesdell III

Organizer: C.-S. Man
Session: R4A, Thurs., June 27, 3:30-5:35 pm
Room: SQ, Colonial
Chair: D. R. Owen

3:30 Rod Theories: Energy Formulations of the Theory of Slices, *R. G. Muncaster*

3:55 Unusal Buckling of Highly Anisotropic Elastic Materials and Rippling of Carbon Multiwalled Nanotubes, *Q.-S. Zheng, J.Z. Liu*

4:20 Equations for the Flexure, Twist and Extension of Fibre Networks, *C. Luo, D. J. Steigmann*

4:45 Theory of Linearly Elastic Residually Stressed Plates, *R. Paroni*

5:10 Higher Order Shear and Normal Deformable Thermopiezoelectric Plate Theory, *R.C. Batra*

Keynote Session
Microelectromechanical Systems (MEMS) I

Organizer: W. N. Sharpe, Jr.
Session: M2B, Mon., June 24, 9:30-11:45 am
Room: SQ, Haymarket
Chair: W. N. Sharpe, Jr.

9:30 A Twilight Zone in Fluid Mechanics - Nano and Micro Flows, *C.-M. Ho*

10:15 Data Storage using MEMS Technology, *A. P. Pisano*

11:00 Materials Issues in MEMS, *S. M. Spearing*

Keynote Session
Microelectromechanical Systems (MEMS) II

Organizer: W. N. Sharpe, Jr.
Session: T2B, Tues., June 25, 9:30-11:45 am
Room: SQ, Haymarket
Chair: W. N. Sharpe, Jr.

9:30 Gas and Vapor Bubbles in Microdevices, *A. Prosperetti*

10:15 The Strength of Polysilicon at the Micron and Submicron Levels, *W. G. Knauss*

11:00 Integrated Micromechanism Design, Fabrication, and Characterization, *D. L. DeVoe*

Keynote Session
Material Failure at High Strain Rates I

Organizer: Y. D. S. Rajapakse
Session: M2C, Mon., June 24, 9:30-11:45 pm
Room: Torg 3100
Chair: Y. D. S. Rajapakse

9:30 Dislocation Mechanics Based Description of Dynamic Deformation and Fracturing, *R. W. Armstrong, F. J. Zerilli*

10:15 Some Experimental Aspects of Dynamic Fracture Mechanics, *D. Rittel*

11:00 Analysis of Failure Mode Transition Speeds in an Impact Loaded Pre-Notched Plate, *R. C. Batra*

Keynote Session
Material Failure at High Strain Rates II

Organizer: Y. D. S. Rajapakse
Session: T2C, Tues., June 25, 9:30-11:45 pm
Room: Torg 3100
Chair: Y. D. S. Rajapakse

9:30 Intersonic Shear Rupture Along Weak Planes: From Earthquake Rupture to the Rupture of Atomic Planes, *A. J. Rosakis*

10:15 Multiscale Modeling of Material Failure at High-Strain Rates, *M. Ortiz, A. M. Cuitiño*

11:00 Closed Trans-Scale Approximation to Wave-Induced Damage, *Y. L. Bai, F. J. Ke, M. F. Xia, H. Y. Wang, Y. J. Wei*

Deformation, Fracture, and Mass Transport I
Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: M2D, Mon., June 24, 9:30-11:35 am
Room: Torg 2150
Chair: F. Spaepen

9:30 Mechanics of Propagating Buckle Delaminations, *J. W. Hutchinson*

9:55 A Mechanism for the Premature Failure of Cyclically-Loaded Polycrystalline Silicon Structural Films, *C. L. Muhlstein, E. A. Stach, R. O. Ritchie*

10:20 Compressed Elastic Islands on a Viscous Layer: Expansion, Wrinkling, and Fracture, *R. Huang, J. Liang, H. Yin, J. C. Sturm, K. D. Hobart, Z. Suo*

10:45 In-situ TEM Observations of Cracking of Interfacial Films, *J. K. Shang, X. Tan, T. Du*

11:10 Models for the Nonlinear Switching of Ferroelectrics, *R. M. McMeeking*

Microelectronics, MEMS, and Coatings I

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: M3G, Mon., June 24, 1:00-3:05 pm
Room: Torg 2150
Chair: R. Vinci

1:00 Thermo-Mechanical Challenges of Cu/Low k Interconnects, *J. He*

1:25 Material and Reliability Issues of Cu/low k Damascene Interconnects *P. S. Ho*

1:50 Chemistry at Interfaces and Adhesion, *M. Lane, J. Lloyd, E. Liniger*

2:15 Mechanics of Stress Voiding in Thin Films, *X. H. Liu*

2:40 Current-Induced Fatigue in Chip Level Interconnects, *R. Keller, C. A. Volkert, R. Mónig, O. Kraft, E. Arzt*

Nanostructures and Nanomechanics I

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: M4G, Mon., June 24, 3:30-5:35 pm
Room: Torg 2150
Chair: J. Israelichvili

3:30 Semiconductor Nanostructures: Phase Separation, Self-Assembly, and 3d Quantum Dot Crystals, *R. S. Goldman*

3:55 Stable Islands by Height-Constrained Stranski-Krastanov and Lithographically-Induced Self-Assembly, *J. Liang, Z. Suo*

4:20 Formation of Nanocrystal Islands During Heteroepitaxial Growth, *C.-H. Chiu*

4:45 A Continuum Description of the Evolution of Stepped Surfaces in Strained Nanostructures, *V. Shenoy, L. B. Freund, C. Ciobanu*

5:10 Critical Layer Thickness in Stranski-Krastanow Growth of Ge on Si(001), *K. Varga, Z. Zhang, L. G. Wang, S. T. Pantelides*

Deformation, Fracture, and Mass Transport II

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: T2D, Tues., June 25, 9:30-11:35 am
Room: Torg 2150
Chair: J. W. Hutchinson

9:30 Modeling Plasticity in Polyscrystalline Gold thin Films on Silicon Substrates, *W. D. Nix, O. S. Leung*

9:55 In-Situ Nanoindentation: A Novel Method for Exploring Thin Film Mechanical Behavior, *A. M. Minor, E. A. Stach, E. T. Lilleodden, J. W. Morris, Jr.*

10:20 Discrete Dislocation Plasticity for Small Scales, *E. Van der Giessen, A. Needleman*

10:45 Crack-Like Grain Boundary Diffusion Wedges in Thin Films on Substrates, *H. Gao*

11:10 Interfacial Failure of Thin Epoxy Films, *N. R. Moody, M. S. Kent, E. D. Reedy, J. A. Emerson, D. F. Bahr*

Microelectronics, MEMS, and Coatings II

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: T3Q, Tues., June 25, 1:00-3:05 pm
Room: Torg 2150
Chair: R. McMeeking

1:00 Pull-in Voltage of a MEMS Microphone, *L. B. Freund, P. Guduru*

1:25 The Mechanics of Thick Deposited Layers and Their Implications for Practical MEMS, *S. M. Spearing*

1:50 Design of Multilayered Polysilicon for MOEMS Applications, *R. Ballarini*

2:15 The Mechanical Behavior of LIGA Ni Structures for MEMS Applications, *K. J. Hemker, H. S. Cho*

2:40 Plasticity in LIGA Nickel MEMS Structures: Size Effects and Dislocation Substructures, *J. Lou, P. Shrotriya, S. Allameh, N. Yao, T. Buchheit, W. O. Soboyejo*

Nanostructures and Nanomechanics II

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: T4Q, Tues., June 25, 3:30-5:35 pm
Room: Torg 2150
Chair: S. Baker

3:30 Strain-Induced Morphologies and Compositional Modulations in Compound Semiconductor Thin Films, *J. M. Millunchick*

3:55 Forces that Drive Nanoscale Self-Assembly on Solid Surface, *W. Lu*

4:20 Modeling of Nanostructure Patterning, *K. J. Cho*

4:45 The In-Plane and Out-of-Plane Self-Organization of Heteroepitaxial Islands in Superlattices, *Y.-W. Zhang, A. F. Bower, P. Liu, C. Lu*

5:10 A Phase-Field Model for Coherent Microstructure Evolution in a Thin Film Constrained by a Substrate, *Y. L. Li, S. Y. Hu, Z. K. Liu, L.-Q. Chen*

Deformation, Fracture, and Mass Transport III

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: W2D, Wed., June 26, 9:30-11:35 am
Room: Torg 2150
Chair: K. Hemker

9:30 Mechanical Properties of Metallic and Ceramic Thin Films, *F. Spaepen*

9:55 Stress and Structure Evolution During Formation of Polycrystalline Thin Films, *C. V. Thompson, C. A. Friesen, S. C. Seel*

10:20 The Mechanical Properties of Electroplated Cu Thin Films, *J. J. Vlassak*

10:45 Effects of Microstructure and Solute Content in Pt Thin Films, *R. P. Vinci*

11:10 Relaxation Kinetics of a Compressed Film on a Viscous Substrate, *N. Sridhar, B. N. Cox, D. J. Srolovitz*

Microelectronics, MEMS, and Coatings III

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: W3Q, Wed., June 26, 1:00-3:05 pm
Room: Torg 2150
Chair: W. D. Nix

1:00 On the Mechanics of Thermally Grown Oxides and Thermal Barrier Coating Systems, *D. R. Mumm*

1:25 Fracture Mechanics Applied to TBC failure, Experiments and Analysis, *E. H. Jordan, K. Vaidyanathan, M. Gell*

1:50 Toughness Degredation in Thermal Barrier Coating Systems, *J. L. Beuth, Q. Ma, G. H. Meier, F. S. Pettit, M. J. Stiger*

2:15 Phase Transformation and Transformation Strain in Thermally Cycled Platinum Aluminide Bond Coats, *M.-W. Chen, M. L. Glynn, K. J. Hemker, P. K. Wright*

2:40 Coupled Diffusion and Creep in Multiphase Coatings, *Z. Suo*

Nanostructures and Nanomechanics III

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: W4Q, Wed., June 26, 3:30-5:35 pm
Room: Torg 2150
Chair: K.-S. Kim

3:30 Coalescence of Ductile Metal Surfaces: When Solids Can Behave Like Liquids at the Nano-Scale, *J. Israelichvili, C. Park, N. Alcantar, J.-M. Pan*

3:55 Deformation and the Origins of Strength in Metallic Multilayers, *H. Kung*

4:20 Deformation Behavior of High-Strength Nanoscale Al_3Sc Multilayers, *M. A. Phillips, B. M. Clemens, W. D. Nix*

4:45 Computer Simulations and Experimental Observations of Dislocation Motion in Nanoscale Multiplayer Films, *P. M. Anderson, Q. Li, Y. Shen, R. G. Hoagland, A. Misra, T. J. Foecke, D. Kramer*

5:10 Experimental Results on Freestanding Nanoscale Al Films, *T. Saif, A. Haque*

Deformation, Fracture, and Mass Transport IV

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: R2D, Thurs., June 27, 9:30-11:35 am
Room: Torg 2150
Chair: L. B. Freund

9:30 A Volume to Surface Length Scale for Thin Film Mechanics, *W. W. Gerberich, J. M. Jungk, J. W. Hoehn*

9:55 Mechanical Properties of Nano-Structured Solid Surface Layers, *H. Yu, K.-S. Kim, Y. T. Cheng*

10:20 Interfacial Force Microscopy Studies of ?-APS on Glass and SiO_2, *K. M. Liechti, K. C. Vajapeyajula, M. Wang, H. Cabibil, H. Celio, J. M. White, R. M. Winter*

10:45 Measurement of Mixed-Mode Interfacial Failure in Thin Films Using Laser Induced Stress Waves, *J. Wang, R. L. Weaver, N. R. Sottos*

11:10 On the Mechanics of Foreign Object Damage, *X. Chen, J. W. Hutchinson*

Microelectronics, MEMS, and Coatings IV

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: R3Q, Thurs., June 27, 1:00-3:05 pm
Room: Torg 2150
Chair: C. Thompson

1:00 CGS Interferometry as a Full-Field, Real-Time, and In-Situ Wafer Inspection and Reliability Tool, *A. J. Rosakis*

1:25 Cladding Layer Thickness Effect on Optical Performance in Ridged Waveguide, *X. Yan*

1:50 Optimal Design of Microclips for Mounting of Optical Fibers in Silicon V-Shaped Grooves, *T. J. Lu, D. F. Moore*

2:15 A Comparison Study of Ti/GaAs Ti/Si Fracture, *A. A. Volinsky, M. L. Kottke*

2:40 Effects of Adhesion on Deformation Behavior of Thin Metal Films on Substrates, *S. P. Baker*

Nanostructures and Nanomechanics IV

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: R4Q, Thurs., June 27, 3:30-5:35 pm
Room: Torg 2150
Chair: W. Gerberich

3:30 Depth-Dependent Hardness, *T.-Y. Zhang*

3:55 An Atomistic Modeling of the Mechanical Behavior of Carbon Nanotubes, *C. Li, T.-W. Chou*

4:20 Surface Wrinkling of Two Mutually Attracting Elastic Bodies Due to van der Waals-Like Interaction, *C. Q. Ru*

4:45 Spontaneous Correlation of Crystallographic Orientations in Crystallite Aggregation, *M. Wang, D.-W. Li, N.-B. Ming*

5:10 Characterization of Indentation Damage in Boron Carbide/DLC Nanocomposite Coatings, *S. Nekkanty, M. E. Walter*

Deformation, Fracture, and Mass Transport V

Symposium on Mechanics of Thin Films and Other Small Structures
Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: F2D, Fri., June 28, 9:30-11:35 am
Room: Torg 2150
Chair: J. Vlassak

9:30 Mechanical Properties and Stresses in Two Thin Film-Substrate Systems, *C. Xie, W. Tong*

9:55 Microtensile Testing in the Scanning Electron Microscope, *D. T. Read, J. D. McColskey, Y.-W. Cheng*

10:20 Theoretical Treatment of Void Nucleation due to Coupling of Mechanics and Vacancy Composition, *K. Garikipati*

10:45 Multiscale Simulations of Interface Separation in Pre-Stressed Thin-Film Structures, *S. Strohband, R. H. Dauskardt*

11:10 Critical Crack Lengths for Debond-Resistant Bimaterial Layers, *N. W. Klingbeil, S. Bontha*

Microelectronics, MEMS, and Coatings V

Symposium on Mechanics of Thin Films and Other Small Structures

Sponsored by ASME Electronic Materials Committee

Organizers: Z. Suo, R. Huang
Session: F3D, Fri., June 28, 1:00-3:05 pm
Room: Torg 2150
Chair: K. Liechti

1:00 In-Situ Study of the Growth Stress and Stiffness of Alumina Thin Films During Vapor Deposition, *J. Proost, F. Spaepen*

1:25 Multiscale/Multi-Physics Modeling of Void Evolution on Narrow Interconnect Lines, *R. R. Atkinson, A. M. Cuitino*

1:50 Dislocation Activities in Semiconductor Thin Film Systems, *L. Sun, E. H. Tan*

2:15 Delamination of Wear-Resistant Coatings, *D. S. Balint*

2:40 A Study of Experimental Determination of Interface Toughness with the Mixed Mode Flexure Specimen, *K. M. D. Wong, C. Li*

Symposium on Recent Advances in Experimental Mechanics: Optical Methods

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: M2E, Mon., June 24, 9:30 am-12:00 pm
Room: DB, Front Aud.
Chairs: D. Post, C. A. Sciammarella

9:30 Opening Remarks, *E. E. Gdoutos*

9:40 Moiré Interferometry - Past, Present and Future, *D. Post*

10:00 Optical Fibre Bragg Grating Sensors in Experimental Mechanics of Composite Laminated Plates, *J. Botsis, F. Bosia, M. Facchini, Th. Gmür*

10:20 Optoelectronic Displacement Measurement Method for Rotating Disks, *C. E. Bakis, B. J. Haldeman, R. P. Emerson*

10:40 Deformation Measurement of Sheet Metal Forming Using Photogrammetry, *K. Andresen*

11:00 Fracture Processes of Quasi-Brittle Materials Studied with Digital Image Correlation, *J. S. Lawler, S.P. Shah*

11:20 On the Use of Different Wavelengths to Digitally Determine the Isochromatic Fringe Order, *T. Y. Chen, Y. C. Chou, H. L. Lee, S. H. Tsao*

11:40 The Application of Speckle Meterology to Heart Mechanics, *G. R. Gaudette, E. U. Azeloglu, J. Todaro, L. Keene, I. B. Krukenkamp, F. P. Chiang*

Symposium on Recent Advances in Experimental Mechanics: Mechanical Behavior of Materials I

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: M3H, Mon., June 24, 1:00-3:05 pm
Room: DB, Front Aud.
Chairs: Z. P. Bazant, A. H. Cardon

1:00 Hopkinson Techniques for Dynamic Triaxial Compression Tests, *J. Rome, J. Isaacs, S. Nemat-Nasser*

1:25 Asymptotic Scaling of Gradient Theory of Micro-Scale Plasticity of Metals, *Z. P. Bazant*

1:50 The Role of Pressure in the Behavior of Time-Dependent Materials, *T. Prodan, I. Emri*

2:15 High Strain Rate Testing of Sandwich Core Materials, *M. Vural, G. Ravichandran*

2:40 Development of a Shear Test for Low Modulus Foam Materials, *A. K. Roy, J. D. Camping*

Symposium on Recent Advances in Experimental Mechanics: Mechanical Behavior of Materials II

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: M4H, Mon., June 24, 3:30-5:10 pm
Room: DB, Front Aud.
Chairs: S. Nemat-Nasser, S. Guralnick

3:30 Indentation of a PVC Cellular Foam, *E. E. Gdoutos, J. L. Abot*

3:55 Nanomanipulation and Characterization of Individual Carbon Nanotubes, *R. S. Ruoff, M.-F. Yu, H. Rohrs*

4:20 Quasi-Static and Dynamic Torsion Testing of Ceramic Micro and Nano-Structured Coatings Using Speckle Photography, *F. Barthelat, K. Malukhin, H. D. Espinosa*

4:45 Grain Level Analysis of Fracture Initiation and Evolution in Brittle Materials, *H. D. Espinosa, P. Zavattier, S.-S. Lee*

Symposium on Recent Advances in Experimental Mechanics: Non-Destructive Evaluation

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: T2E, Tues., June 25, 9:30 am-12:10 pm
Room: DB, Front Aud.
Chairs: J. D. Achenbach, M. Y. Y. Hung

9:30 Line Focus Acoustic Microscopy for Thin-Film Measurements, *Z. Guo, J. D. Achenbach*

9:50 Recent Advances in Acoustography-Based NDE, *J. S. Sandhu, H. Wang*

10:10 Experimental Limitations to Guided Wave Generation in Elastic Materials, *D. A. Sotiropoulos, E. Babatsouli*

10:30 Nondestructive Testing Using Shearography, *M. Y. Y. Hung*

10:50 Theoretical and Experimental Study of Laser-Ultrasonic Signal Characteristics Enhanced by Wetting the Surface, *S.-C. Wooh*

11:10 Defect Detection by the Scattering Analysis of Flexural Waves, *P. Fromme, M. B. Sayir*

11:30 Evaluation of Fiber Waviness in Thick Composites by Ultrasonic Test, *H.-J. Chun*

11:50 Development of a Dry-Contact Ultrasonic Technique and its Application to NDE of IC Packages, *H. Tohmyoh, M. Saka*

Symposium on Recent Advances in Experimental Mechanics: Composite Materials I

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: T3H, Tues., June 25, 1:00-3:05 pm
Room: DB, Front Aud.
Chairs: R. M. Jones, J. Botsis

1:00 Measured Response: State Variables for Composite Materials, *K. Reifsnider, M. Pastor*

1:25 On The Modeling of the Mechanical Properties of Composite Materials at High Strain Rates, *J. R. Vinson, S. Xiao*

1:50 Damage Quantification in Metal Matrix Composites, *G. Z. Voyiadjis, A. R. Venson, R. K. Abu-Alrub*

2:15 Study of Damage in Particulate Composites, *C. A. Sciammarella, F. M. Sciammarella*

2:40 Hygric Characterization of Composite Laminates, *S.-C. Wooh, C.-L. Tsai*

Symposium on Recent Advances in Experimental Mechanics: Composite Materials II

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: T4H, Tues., June 25, 3:30-5:35 pm
Room: DB, Front Aud.
Chairs: J. R. Vinson, L. A. Carlsson

3:30 Pneumatic Behavior of Composite Materials, *C.-L. Tsai, Y.-S. Tsai*

3:55 The Effect of Specimen Size on the Compressive Strength of Carbon Fibre-Epoxy Laminates, *C. Soutis, J. Lee*

4:20 Interfacial Strength and Toughness Characterization Using a Novel Test Specimen, *G. P. Tandon, R. Y. Kim, V. T. Bechel*

4:45 A Model for the Accurate Prediction of the Residual Strength after Damage Due to Impact and Erosion of FRPs, *G. C. Papanicolaou, G. Samoilis, S. Giannis, N.-M. Barkoula, J. Karger-Kocsis*

5:10 Experimental Characterization of Viscoelasticity and Damage In High Temperature Polymer Matrix Composites, *E. Ahci, R. Talreja*

Symposium on Recent Advances in Experimental Mechanics: Composite Structures

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: W2E, Wed., June 26, 9:30 am-11:50 am
Room: DB, Front Aud.
Chairs: C. C. Chamis, G. A. Kardomateas

9:30 Future Experimental Methods Needed to Verify Composite Life-Cycle Simulations, *C. C. Chamis, L. Minnetyan*

9:50 Experimental Observations on the Delamination Behavior in Composite Structures, *G. A. Kardomateas, V. La Saponara, G. J. Simitses*

10:10 Direct Identification of Elastic Properties of Composite Structures: A Wave-Controlled Impact Approach, *S. Abrate*

10:30 Static Behaviour of Pre-Stressed Polymer Composite Sandwich Beams, *R. A. W. Mines, Q. M. Li, R. S. Birch, R. Rigby, M. Al-Khalil, A. Tanner*

10:50 On Debond Failure of Foam Core Sandwich, *L. A. Carlsson*

11:10 Core Crush Mechanisms and Solutions in the Manufacturing of Sandwich Structures, *H. M. Hsiao, S. M. Lee, R. A. Buyny*

11:30 Displacement Fields Around a Circular Hole in Composite Laminates, *S. M. Chern, M. E. Tuttle*

Symposium on Recent Advances in Experimental Mechanics: Hybrid Methods I

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: W3H, Wed., June 26, 1:00-3:05 pm
Room: DB, Front Aud.
Chairs: A. S. Kobayashi, G. Z. Voyiadjis

1:00 Reflections on the Importance of Experimental Results to all Mechanicists, Especially Theoreticians, *R. M. Jones*

1:25 Mixed Numerical-Experimental Techniques : Past, Present and Future, *A. H. Cardon, H. Sol, W. P. De Wilde, J. De Visscher, K. Hoes, D. Dinescu*

1:50 A Moiré-FE Method for Internal CTOA Determination, *J. H. Jackson, A. S. Kobayashi*

2:15 Patterns of Modern Experimental Mechanics, *J. T. Pindera*

2:40 Inverse Methods in Experimental Mechanics, *J. F. Doyle*

Symposium on Recent Advances in Experimental Mechanics: Hybrid Methods II

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: W4H, Wed., June 26, 3:30-4:45 pm
Room: DB, Front Aud.
Chairs: R. E. Rowlands, H. Espinosa

3:30 Complex Stiffness Identification by Inverse Methods, *H. Sol, W. P. De Wilde*

3:55 Considerations of a Flutter Prediction Methodology Using a Combined Analytical-Experimental Procedure, *P. Marzocca, L. Librescu, W. A. Silva*

4:20 Displacement-Based Smoothing Hybrid Finite-Element Representation for Stress Analyzing Perforated Composites, *K. Y. He, R. E. Rowlands*

Symposium on Recent Advances in Experimental Mechanics: Structural Testing and Analysis

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: R2E, Thurs., June 27, 9:30 am-12:00 pm
Room: DB, Front Aud.
Chairs: G. J. Simitses, D. A. Sotiropoulos

9:30 Recent Advances in Long-Term Monitoring of Bridges, *J. R. Casas*

9:55 An Experimental Mechanics Approach to Structural Health Monitoring for Civil Aircraft, *E. W. O'Brien*

10:20 Smart Structures Application to Air Worthiness and Repair, *R. Jones, I. H. McKenzie, S. Galea, S. Pitt*

10:45 Experimental Investigation of Shrinkage Strains in Multilayered Stereolithography Parts, *D. E. Karalekas*

11:10 Suppression of Dimpling In Sheet Metal Parts Formed on Discrete Tooling, *R. C. Schwarz, J. Nardiello, J. M. Papazian*

11:35 Effect of Loading Rate and Geometry Variation on the Dynamic Shear Strength of Adhesive Lap Joints, *V. Srivastava, V. Parameswaran, A. Shukla, D. Morgan*

Symposium on Recent Advances in Experimental Mechanics: Fracture and Fatigue I

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: R3H, Thurs., June 27, 1:00-3:05 pm
Room: DB, Front Aud.
Chairs: C. W. Smith, A. Shukla

1:00 The Origin and Inception of Fatigue in Steel - A Probabilistic Model, *S. A. Guralnick, J. Mohammadi*

1:25 Fatigue Damage Tolerant Analysis Using the Fatigue Damage Map, *C. A. Rodopoulos, J. R. Yates*

1:50 Crack Growth Behavior and SIF's as Observed by Optical Methods, *C. W. Smith*

2:15 A Model for Failure Initiation in Ductile Materials, *J. Zuo, M. A. Sutton, X. Deng*

2:40 Crack Paths in Adhesive Bonds, *L. Banks-Sills, J. Schwartz*

Symposium on Recent Advances in Experimental Mechanics: Fracture and Fatigue II

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: R4H, Thurs., June 27, 3:30-5:35 pm
Room: DB, Front Aud.
Chairs: K. Reifsnider, A. J. Rosakis

3:30 Experimental Determination of Fracture Parameters for Predicting Crack Growth in Viscoelastic Polymers, *D. H. Allen, J. J. Williams*

3:55 Failure of Spot Weld: A Competition Between Crack Mechanics and Plastic Collapse, *Y. J. Chao*

4:20 Investigating the Effects of Specimen Thickness and Pressure on the Crack Growth Behavior of a Particulate Composite Material, *C. T. Liu*

4:45 Dynamic Fracture Experiments Using Point Impact, *D. Rittel*

5:10 Experimental and Numerical Investigation of Shear-Dominated Intersonic Crack Growth and Friction in Unidirectional Composites, *A. J. Rosakis, C. Yu, M. Ortiz, D. Coker, A. Pandolfi*

Symposium on Recent Advances in Experimental Mechanics: Neutron Diffraction and Synchrotron Radiation Methods I

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: F2E, Fri., June 28, 9:30 am-11:35 am
Room: DB, Front Aud.
Chairs: A. G. Youtsos, A. Baczmanski

9:30 High-Resolution Neutron Diffraction Techniques For Strain Scanning, *P. Mikula, M. Vrana, P. Lukas, V. Wagner*

9:55 Draft Standard for the Measurement of Residual Stresses by Neutron Diffraction, *G. A. Webster, A. G. Youtsos, C. Ohms, R. C. Wimpory*

10:20 Microstresses Determined by Neutron Diffraction and Self-Consistent Model, *A. Baczmanski, C. Braham, R. Levy-Tubiana, A. Lodini, K. Wierzbanowski*

10:45 Residual Stress Measurements at the Metal/Ceramic Interface Using Modelling of Neutron Diffraction Spectrometer, *A. Carrado, J.-M. Sprauel, L. Barrallier, A. Lodini*

11:10 Elastoplastic Deformation of Two Phase Steels Studied by Neutron Diffraction and Self-Consistent Modelling, *M. R. Daymond, H. G. Priesmeyer, A. M. Korsunsky*

Symposium on Recent Advances in Experimental Mechanics: Neutron Diffraction and Synchrotron Radiation Methods II

In Honor of I. M. Daniel

Organizer: E. E. Gdoutos
Session: F3E, Fri., June 28, 1:00-2:15 pm
Room: DB, Front Aud.
Chairs: H. J. Prask, G. A. Webster

1:00 Residual Stresses and Elastic Constants in Thermal Deposits, *T. Gnäupel-Herold, H. J. Prask, F. S. Biancaniello*

1:25 Neutron Diffraction Assisted Residual Stress Analysis in Welded Structures, *C. Ohms, A. G. Youtsos*

1:50 Synchrotron Radiation In-Situ Analyses of AA 6061 + $A\ell_2O_3$ During Tensile Deformation at Ambient and Elevated Temperature, *A. Pyzalla, B. Reetz, A. Jacques, J.-P. Feiereisen, O. Ferry, T. Buslaps*

Keynote Session
Developments in Composite Materials and Structures

Organizer: M. W. Hyer
Session: M2F, Mon., June 25, 9:30-11:45 am
Room: SQ, Brush A
Chair: M. W. Hyer

9:30 Self-Healing Composites, *S. R. White*

10:45 On the Structural Mechanics of Sandwich Structures of Composite Materials, *J. R. Vinson*

Flow of Complex Fluids I

In Memory of C. G. Speziale

Organizer: D. A. Signier
Session: M2G, Mon., June 26, 9:30-12:00 noon
Room: SQ 234
Chairs: D. A. Signier

9:30 Turbulence Modeling for Intermittent Pulsatile Flows, *B. A. Younis, S. A. Berger*

9:55 A Generalized Nonlinear Two-Equation Turbulence Model: Development and Applications, *S. Thangam, K. R. Rajagopal*

10:20 Prediction of Equilibrium States in Turbulence Models for Flows Induced by Rayleigh-Taylor and Richtmyer-Meshkov Instabilities and in Oceanic and Atmospheric Applications, *Y. Zhou, D. Eliason*

10:45 Optimal and Robust Control of Thermal Convection in Porous Media, *S. Qian, H. H. Bau*

11:10 The Generation and Structure of High Reynolds Number Homogeneous Turbulence, *J. V. Larssen, W. J. Devenport*

11:35 The Physics of the Secondary Flows of Viscoelastic Fluids in Straight Tubes, *D. A. Signier*

Flow of Complex Fluids II
In Memory of C. G. Speziale

Organizer: S. A. Signier
Session: M3F, Mon., June 26, 1:00-3:05 pm
Room: SQ 234
Chairs: D. A. Signier

1:00 Continuous Models:Variants of LES, *M. Y. Hussaini, C. G. Speziale, S. L. Woodruff*

1:25 Internal Constraint Theories for the Thermal Expansion of Viscous Fluids, *S. E. Bechtel*

1:50 Yield Stress Measurements of Suspensions, *D. De Kee*

2:15 Stokes' Mechanism of Drag Reduction, *P. R. Bandyopadhyay*

2:40 Spreading Liquid Layers onto Moving Substrates: How-does Ambient Air Affect the Contact Line? *P. Bourgin*

Metal Working and Metallurgy

Session: M2O, Mon., June 24, 9:30-10:45 am
Room: DB Rm A
Chairs: T. J. Burns

9:30 Penalty formulation of Upper Bound Elemental Technique for Shape Rolling of Super Alloy Rings, *V. Ranatunga, J. S. Gunasekera*

9:55 Measurement and Simulation of Temperature During Orthogonal Metal Cutting, *A. T. Zehnder, Y. K. Potdar*

10:20 Impact-Oscillator Model for Low Radial Immersion Milling, *T. J. Burns, M. A. Davies, B. F. Feeny, M. Liao, B. Dutterer, J. R. Pratt*

Heat Transfer and Thermodynamics

Session: M2M, Mon., June 24, 9:30-11:35 am
Room: SQ 341
Chairs: H. P. Cherukari

9:30 A New Method for the Estimation of Heat-Transfer Coefficients in Quenching Problems, *X. Ling, H. P. Cherukuri, R. G. Keaniki*

9:55 New Thermodynamic Cycle for Heat and Mass Transfer, *V. Maisotsenko, L. E. Gillan*

10:20 Unsteady Heat Transfer Problem in Functionally Grading Wood-Based Board for Higher Insulation, *Y. Obata, K. Kanayama, K. Takeuchi, H. Imanishi*

10:45 Modeling for the Hot Section Structures by Genetic Algorithm, *K. Ohtake, Y. Sutoh*

11:10 To Numerical Modeling of Some Processes in a Nonlinear Moving Media, *M. Aripov, A. Khaydarov*

Soft Actuators and Sensors

Session: F2C, Fri., June 28, 9:30-11:35 am
Room: SQ, Brush A
Chairs: M. Shahinpoor

9:30 Tailoring Actuation Response of IPMC's, *S. Nemat-Nasser, Y. Wu*

10:20 Implementation of Strain Sensitive Skin, *P. Ifju, P. Hubner, K. Schanze, D. Jenkins*

10:45 The Optimal Configuration of Piezopolymer Actuators for Active Vibration Control of Cylindrical Shell: Applicationt on Antifouling Process, *M. A. H. Alaoui, M. Rahmoune, H. Ridouane, M. Behamou*

11:10 Stiffness and Energy Density Determinations in Ionic Polymer Transducers, *M. Bennett, D. J. Leo*

Material Modeling and Optimization

Session: M2N, Mon., June 24, 9:30-12:00 noon
Room: SQ 345
Chairs: S. Skaar, R. V. Grandhi

9:30 Strain Energy Based Homogenization of Elastic Two-Dimensional Model Foams at Finite Strain, *J. Hohe, W. Becker*

9:55 A Variational Model of Precipitate Growth Under the Influence of Elastic Strain, *M. G. Cornforth, S. P. A. Gill, A. C. F. Cocks*

10:20 Optimal Shape Design of Cooling Fins with Varying Conductivity Parameters, *F. Bobaru*

10:45 Enhancing the Optimization of Composite Structures using Gradient Architecture, *H. A. Bruck, H. Surendranath, S. Gowrisankaran*

11:10 Airframe Structural Design for Reliability and Robustness, *R. C. Penmetsa, R.V. Grandhi*

11:35 An Integrated Approch of Sensitivity Analysis Applied on Elastic Structure, *Y. Gholipour*

Material Behavior I

Session: M2I, Mon., June 24, 9:30-11:35 am
Room: DB, Rm F
Chair: L. Wang, T. W. Wright

9:30 On the Mechanical Behavior of Microcrystalline Cellulose during Compression, *A. I. Abdel-Hadi, O. I. Zhupanska, N. D. Cristescu*

9:55 Effect of Grain Size on the Shear Localization of Iron, *Q. Wei, D. Jia, K. T. Ramesh, E. Ma*

10:20 An Elastic/Viscoplastic Constitutive Model for Microcrystalline Cellulose, *O. I. Zhupanska, N. D. Cristescu, A. I. Abdel-Hadi*

10:45 Thermo-mechanical Study of Dynamic Shear Band in Bulk Metallic Glassesand Composites, *Y. T. Carin, G. Ravichandran, W. L. Johnson*

11:10 Mechanisms of Inhomogeneous Cyclic Plastic Deformation of 1045 Steel, *J. Zhang, Y. Jiang*

Material Behavior II

Session: T2I, Tues., June 25, 9:30-12:25 pm
Room: DB Rm F
Chair: M. A. Khaleel, L. L. Wang

9:30 Effect of Randomness in Material Properties on Forced Response of Laminated Composite Plates, *B. N. Singh,N. G. R. Iyengar, D. Yadav*

9:55 Modeling of Fatigue Damage, *M. Feng, Y. Jiang, S. Lin*

10:20 Observation of Failure Mechanism and Development of Model for Predicting Strength of Resistance Spot Weld, *Y. J. Cho*

10:45 On the Nature of Surface Modification Produced by Non-Planar Hypervelocity Sliding in TUngsten Alloy, *S. S. Satapathy, C. Persad, R. M. Gee, S. J. Bless*

11:10 Risk Based Design Criterion of Welded Details in Marine Structures with Case Studies, *M. M. El-Gammal*

11:35 Fatigue Failures and Repairs in Industry, *Z. Domazet*

12:00 Residual Stress in Electroplated Nickel Coating, *Y. P. Jiang, Y. C. Zhou, L. Xiao, Y. Pan, Z. L. Long*

Material Behavior III

Session: W2I, Wed., June 26, 9:30-12:00 noon
Room: DB Rm F
Chairs: D. Belk, M. L. Hughes

9:30 Strain Rate Sensitivity of Epoxy in Tensile and Shear Loading, *A. Gilat, R. K. Goldberg, G. D. Roberts*

9:55 On the Characterization of Material Repeated-Impact States Using a Pattern-Recognition Approach, *Y. M. Haddad, G. J. Molina*

10:20 Failure of Aluminum Honeycombs in the W-T Plane: Phenomenological and Analysis, *M. Doyoyo, D. Mohr*

10:45 Identification of the Dynamic Properties of Candidate Materials for the Nuclear Waste Container, *K. Zabotkin, B. O'Toole, M. Trabia*

11:10 Acoustic Emission Monitoring of Contact Induced Damage in Ultra-Small Volumes, *N. I. Tymiak, A. Daugela, T. Wyrobek, W. W. Gerberich*

11:35 Inverse Analysis for Determining Embedded Delamination in Composite Laminates, *M. Urago*

Material Behavior IV

Session: R2I, Thurs., June 27, 9:30 am-12:00 noon
Room: SQ 236
Chairs: J. Wu, S. Mall

9:30 Microstructure Influence on the Surface Heat Treated Steels Characterization by the Drilling Test, *G. Mauvoisin, O. Bartier, A. Nayebi, R. E. Abdi*

9:55 Effects of Foreign Object Damage on High-Cycle Fatigue Life of Ti-6Al-4V, *S. Mall*

10:20 Thermography Detection on the Fatigue Behavior of Reactor Pressure Vessel Steels, *B. Yang, P. K. Liaw, L. Jiang, D. Fielden, H. Wang, J. Y. Huang, R. C. Kuo, J. G. Huang*

10:45 Discrete Modeling of Transformation Toughening in Heterogeneous Materials, *D. Zeng, N. Katsube, W. O. Soboyejo*

11:10 A Rate and Damage Dependent Constitutive Relation for Polymers at Strain Rates from 10^{-4} to 10^{-3} s^{-1}, *L.-L. Wang, S.-C. Shih, M.-Q. Xu*

11:35 Use of Resolved Shear Stress Criteria in Design Applications Involving Material Damping Under Combined Stresses, *T. A. Cupschalk, S. G. Cupschalk*

Material Behavior V

Session: R4G, Thurs., June 27, 3:30-5:35 pm
Room: DB, Rm C
Chairs: M. L. Hughes, D. Belk

3:30 Optimization of a Materials Microstructure Through Microstructure Sensitive Design, *M. Lyon, B. L. Adams, B. Henrie*

3:55 Effect of Geometric Distribution on Cellular Solids, *X. Wang, D. Shu, G. E. B. Tan*

4:20 Modeling the Variability in Strength in a Turbine Disk, *D. G. Harlow, T. M. Pollock*

4:45 Modeling, Recrystallization and Grain Growth in 304L Steel, *A. A. Brown, D. J. Bammann, R. A. Regueiro, M. L. Chiesa, B. R. Antoun, N. Y. C. Yang*

5:10 Kinetic Theory For Granular Flow: Effect of Unequal Granular Temperature on Pressure and Viscosity, *M. F. Rahaman, J. Naser, P. Witt*

Mathematical Analysis of Continuua I

Session: F2A, Fri., June 28, 9:30 am-11:35 am
Room: DB Rm A
Chair: B. Jiang

9:30 Semigroups and Some Nonlinear Fractional Differential Equations, *M. M. El-Borai*

9:55 Green's Functions for Steady-State Heat Transfer and Elastostatics in an Exponentially Graded Solid, *J. R. Berger, P. A. Martin*

10:20 An Efficient Reformulation of Duhamel's Integral to Reduce Execution Time, *S. H. Razavi, A. Abolmaali*

10:45 Analytical Solutions of a Degenerate Diffusion Equation, *J. B. Salomon, S. N. Prasad*

11:10 Coalescence Due to Gravitational Settling: The Universal Self-Similarity Velocity-Size Law, *D. O. Pushkin, S. Balachandar, H. Aref*

Mathematical Analysis of Continuua II

Session: F3L, Fri., June 28, 1:00 pm-3:30 pm
Room: DB, Exec.
Chair: B. Jiang

1:00 On Telegraph Reaction Diffusion and Coupled Map Lattices in Some Biological Systems, *H. L. Abdusalam*

1:25 Kinematic Analysis of Multibody System using the Tool of Multidimensional Matrices, *S. V. Tarasov*

1:50 Description of Structure of Multibody Mechanical System by the Tool of Multidimensional Matrices, *L. M. Mishchanin*

2:15 Elastic Modulus and Distribution of Local Loads over the Amorphous Sections of Macromolecules in Oriented Crystalline Polymer, *U. Gafurov*

2:40 The Distribution Functions of Atoms Escaped from the Surface of the Condensed Phase, *L. V. Pletnev, Zh. L. Kurek*

3:05 Distance, Size, Volume, Speed, Mass, Energy, University are Relative, *O. Ayodeji*

Fracture Mechanics I

Session: M2S, Mon., June 24, 9:30 am-12:00 noon
Room: DB, Rm D
Chair: L. Chen

9:30 How Fast Can Cracks Propagate?, *H. Gao*

9:55 Redistribution of the Cohesive Stress and Variations in Microstructural Properties Associated with Quasistatic Crack Extension, *M. P. Wnuk*

10:20 Analysis of Slant Fracture in Specimens under Nominal Mode I Loading Conditions, *X. Deng, E. Mahgoub, M. A. Sutton*

10:45 Mixed Mode I/III Fracture of Solids: Tensile-Shear Transition, *S. Liu, Y. J. Chao*

11:10 Crack Arrest Model for Internal and External Cracks Weakening a Plate–A Dugdale Model Approach, *R. R. Bhargava, S. Hasan*

11:35 Shear Fatigue of Cross-Linked and Linear PVC Foams, *K. Kanny, H. Mahfuz, T. Thomas, S. Jeelani*

Fracture Mechanics II

Session: M3S, Mon., June 24, 1:00-3:05 pm
Room: DB, Rm A
Chair: L. Chen

1:00 The Dynamic Growth of a Single Void in a Viscoplastic Material under Transient Hydrostatic Loading, *X. Y. Wu, K. T. Ramesh, T. W. Wright*

1:25 On Three-dimensional Singular Stress Field at the Front of a Crack/Anticrack in an Orthotropic Plate, *R. A. Chaudhuri*

1:50 Physical Significance of Fracture Criterion in GYFM and EPFM Zone, *D. M. Kulkarni*

2:15 The SIF for Deep Semi-elliptical Surface Crack in Finite Thickness Plates Determined by the Nodal-Displacement Method, *K. M. Kuok*

2:40 Failure Mechanism of Thermal Barrier Ceramic Coating, *Y. C. Zhou, T. Hashida*

Fracture Mechanics III

Session: M4S, Mon., June 24, 3:30-6:00 pm
Room: DB, Rm A
Chairs: W. J. Drugan

3:30 Dimple Fracture Simulation of Cracked Specimen Under Different Constraint Conditions, *M. Kikuchi, J. Sasaki*

3:55 Experimental Study on Ductile Crack Growth of Aluminum 7050 Alloy by Rubber Impression Method, *Y. Kim, S. K. Jang, S. Liu, Y. J. Chao, M. A. Sutton*

4:20 Mode III Crack Growth in Elastic-Plastic Strain Gradient Solid, *E. Radi, M. Gei*

4:45 Fracture Initiation at Sharp Reentrant Corners in Elastic Plates in Bending, *C.-S. Huang, P. E. Labossiere*

5:10 Crack Tip Fields in Ductile Single Crystals: Experiment and Theory, *W. C. Crone, W. J. Drugan*

5:35 Molecular Processes in Creep and Fracture of an Oriented Linear Crystalline Polymer, *U. Gafurov*

Fracture Mechanics V

Session: T3S, Tues., June 25, 1:00-3:05 pm
Room: DB, Rm A
Chairs: L. Chen

1:00 Explicit Analysis of Stochastic Fracture Processes at the Microstructural Level, *V. Tomar, M. Zhou*

1:25 A Study on the Delamination of a Ductile Film on an Elastic Substrate, *W. Li*

1:50 Nucleation and Propagation of an Edge Crack in a Uniformly Cooled Epoxy/Glass Bimaterial, *E. D. Reedy, T. R. Guess*

2:15 Peridynamic Modeling of Interfaces and Fracture, *S. A. Silling*

2:40 Application of Ring Dislocations to Penny Shaped Crack Problems Under Combined Tension and Torsion, *C. E. Truman, A. Sackfield, D. A. Hills*

Fracture Mechanics VI

Session: T4S, Tues., June 25, 3:30-5:35 pm
Room: DB, Rm A
Chairs: J. R. Klepaczko

3:30 A Study on the Use of Cohesive Model in Ductile Fracture, *C. T. Sun, B. Rangarajan*

3:55 Transient Dynamic Response and Fracture Mechanism of Brittle Spheres Under Impact Loads, *S. Z. Wu, K. T. Chau*

4:20 Fracture Model for Spalling of Titanium Alloy Based on the Mesoscale Approach, *P. Chevrier, J. R. Klepaczko, J. Lebeau*

4:45 Estimation of Dynamic T-Stress Using a Domain Version of Interaction Integral, *T. S. Ramamurthy*

5:10 Creep Crack Growth Under Nonsteady Load, *K. S. Kim*

Fracture Mechanics VII

Session: W2S, Wed., June 26, 9:30 am-12:00 pm
Room: DB, Rm C
Chairs: J. Dolbow

9:30 On the Trajectory of a Crack Near a Graded Interface in a Ductile Material, *M. M. Rashid, V. Tvergaard*

9:55 Mixed Mode Stress Intensity Factor Computation for Cracks in Functionally Graded Materials, *M. Gosz, J. Dolbow*

10:20 A Theoretical and Numerical Study of Axisymmetric Blistering Film Under Elastic Deformation and Delamination in the Presence of Residual Stress, *S. Guo, K.-T. Wan, D. A. Dillard*

10:45 A Disc-Shaped Interface Crack in a Laminated Plate Subject to Uniform Temperature Change, *K. Fukagawa, M. Oda, M. Aritomi, M. Toya, R. R. Bhargava*

11:10 The J-Integral and the Strain Energy Release Rate G for the Double Cantilever Beam Specimen, *A. J. Paris, F. W. Del Rio, R. J. Huot, J. M. Guerricabeitia, L. Dennison*

11:35 Effect of the Boundary Conditions on the Theoretical Stress Concentration Factors for Short Members, *N. Troyani, G. Sterlacci, C. Morillo, C. Gomes*

Analysis of Piezoelectric Materials

Session: W2P, Wed., June 26, 9:30 am-12:35 pm
Room: SQ 219
Chairs: A. Baz, J. Q. Tarn

9:30 Interfacial Cracks between Piezoelectric and Elastic Materials under In-plane Loading, *M. Liu, K. J. Hsia*

9:55 Observation of Inner Hysteresis Loops of BaTiO3 Single Crystals Under Electric/Mechanical Loadings, *R. Zhang, G. Ravichandran, K. Bhattacharya*

10:20 Saint-Venant End Effects in Multilayered Piezoelectric Laminates, *J. Q. Tarn, L.-J. Huang*

10:45 Two Variants of Self-Consistent Scheme Applied to Micromechanics Predictions of Piezoelectric Composites, *R. Rodriquez-Ramos, F. Sabina, V. Levin, M. Carmen-Rivalta, R. Guinovart-Diaz, J. Bravo-Castillero*

11:10 Irreversible Thermodynamic Modelling of Phase Transition in Ferroelectric Ceramics Under Large Mechanic or Electric Loadings, *S. Hanagud, X. Lu*

11:35 Assessment of Interfacial Adhesion of PZT Ferroelectrics Thin Films by Nano-Indentation Test, *X. J. Zheng, Y. C. Zhou*

12:00 Thermal Fatigue of Piezoelectric Thin Film due to a Laser Pulse, *X. J. Zheng, Y. C. Zhou, M. Z. Ning*

Friction and Wear I

Session: M2K, Mon., June 24, 9:30 am-12:50 pm
Room: SQ 232
Chair: G. G. Adams, H. A. Sherif

9:30 Friction-stir Welding Process Simulation: Material Flow and Microstructure Issues, *X. Deng, S. Xu*

9:55 Vibration and Stability of Frictional Sliding of Two Elastic Bodies With a Wavy Contact Interface, *G. G. Adams, M. Nosonovsky*

10:20 Dynamic Tribological Response of Engaged Fracture Surfaces, *H. Huang, R. Feng*

10:45 Steady Power Continuously Variable Speed Traction Devices, *O. Cretu*

11:10 Predicting Mechanism of Energy Dissipation in Mechanical System with Dry Friction, *H. A. Sherif, T.M. Abu Omar*

11:35 On the Analysis of Thermo-elastic Frictional Contact Problems, *A. M. Elhady, F. F. Mahmoud*

12:00 Research on the Damping Characteristics of Metal Rubber Material, *H. Ao, H. Jiang, Y. Xia, S. Wang, A. M. Ulanov*

12:25 Contact Interaction of Thin-walled Elements and Bodies with Coating IncludingWear and Friction, *O. Maksymuk, M. Marchuk, V. Pakosh*

Plasticity I

Session: M2H, Mon., June 24, 9:30-11:35 am
Room: DB, Rm C
Chairs: Z. Wei, A. Nayebi

9:30 Microstructure Influence on Deformation and Failure Mechanism of Composite Tungsten, *Z. Wei*

9:55 Symmetry Limit Theory and Steady-State Limit Theory: A General Theory for Critical Behavior Prediction of Elasto-Plastic Structures Under Cyclic Loading, *K. Uetani, Y. Araki*

10:20 Thermomechanical Cyclic and Creep Loading Behavior of Pressure Vessels Under Kinematic Hardening, *A. Nayebi, R. E. Abdi*

10:45 Element-Size Independent Analysis of Elasto-Plastic Damage Behaviors of Framed Structures, *Y. Toi, J.-G. Lee*

11:10 Simulation of Plastic strain Localization in Polycrystals, *G. V. Lasko, Y. Y. Deryugin, S. Schmauder*

Plasticity II

Session: T2H, Tues., June 25, 9:30 am-12:00 pm
Room: DB, Rm C
Chairs: A. S. Khan, E. P. Chen

9:30 On the Method of Calculation of Complex Loading in Plasticity, *R. A. Abirov, S. Kh. Turanov*

9:55 Cyclic Loading and Accumulation of Damages of Carrying Elements of Thin-Walled Constructions, *A. A. Abdusattarov*

10:20 Computer Simulation of Plastic Strain Propagation at Localized Shear, *G. V. Stepanov, A. V. Shirokov*

10:45 Multistage Deformation of Microcrystalline Al-Li Alloy under High Strain Rate Superplasticity, *M. M. Myshlyaev, M. M. Kamalov*

11:10 Structure - Kinetic Principle for Superplasticity of Solid States, *M. M. Myshlyaev*

Plasticity III

Session: W2K, Wed., June 26, 9:30 am-12:00 noon
Room: SQ 232
Chairs: E. P. Chen, A. S. Khan

9:30 Dislocation Patterning in Two Dimensions and Size Effects in Plasticity, *R. L. B. Selinger, B.R. Smith, W. Luo*

9:55 Investigation of the Low Plastic Strain Amplitude Cyclic Plasticity of Single Crystal Nickel, *D. Zhou, D. J. Morrison, J. C. Moosbrugger, Y. Jia*

10:20 Kink Shear Sector Boundaries in Single Crystal Crack Tip Fields, *J. W. Kysar*

10:45 Discrete Dislocation Modeling of Edge Cracks in Single Crystals, *V. S. Deshpande, A. Needleman, E. van der Giessen*

11:10 Modeling of the Plastic Deformation of Two-phase Polycrystalline Materials, *N. Alexandrova*

11:35 Effect of Grain Structure on Elastic-Plastic Response of Polycrystalline Aggregate, *M. Kovac, I. Simonovski, L. Cizelj*

Elasticity I

Session: M2L, Mon., June 24, 9:30 am-12:00 noon
Room: SQ, Brush B
Chair: V. Yerikalapudi, M. G. Hilgers

9:30 The Present State and Needed Development of the Strain Gradient Stress Analysis, *F. W. Hecker, J. T. Pindera*

9:55 Asymptotic Method in Static and Dynamic Problems of Thin Plate on Asymmetric of Elasticity, *S. H. Sargsyan*

10:20 A Novel Sinc Solution of Boundary Integral Form for Two- and Three-Dimensional Bi-material Elasticity Problems, *R. A. Chaudhuri, F. Stenger*

10:45 Boussinesq Problem in Three-Dimensional Anisotropic Elasticity, *V.-G.Lee*

11:10 Longitudinally-Transversal Curving of the Tape Bases with Allowance for Influences of Tangents of Jet Pressure, *K. Mamasoliev*

11:35 Regularization of Solutions of the Cauchy Problem for Systems of Elasticity Theory, *O. I. Makhmudov*

Elasticity II

Session: T2M, Tues., June 25, 9:30-11:35 am
Room: DB, Rm A
Chairs: V. D. Seremet, M. G. Hilgers

9:30 Local Stresses in Composite Plates with Pin-Loaded Holes, *I. Guz, P. Berbinau, C. Soutis*

9:55 Some New Results in 3D Thermoelasticity, *V. D. Seremet*

10:20 Theory of Elastic Materials with Voids in NDT of Bond quality, *V. R. Yerikalapudi*

10:45 Correctness of the Plane Elasticity Problem in a Semi-Plane, *A. V. Rychahivskyy*

11:10 Method of Direct Integration of Equations for Two- and Three-Dimensional Thermoelasticity Problems, *V. M. Vihak, A. V. Rychahivskyy, Y. V. Tokovyi*

Composite Materials I

Session: W2N, Wed., June 26, 9:30 am-11:35 am
Room: SQ 236
Chairs: B. L. Lee, B. Shafiq

9:30 Thermal-Oxidative Aging Effects on the Properties of a CFR Phenylethynyl-Terminated Poly (etherimide), *A. C. Loos, T. A. Bullions, J. E. McGrath*

9:55 A Pseudo-Viscoelastic Model for Evaluation of Residual Stresses in Thermoset Composites During Cure, *N. Zobeiry, A. Poursartip, R. Vaziri*

10:20 Synergistic Effects Of UV Radiation and Condensation on Degradation of Carbon/Epoxy Composites, *B. G. Kumar, R. P. Singh, T. Nakamura*

10:45 Composite's Quality Estimation: An Micromechanics and Image Processing Symbiosis, *A. F. Avila, D. T. S. Moraes*

11:10 Strongly Nonlinear Temperature Rise in Fibrous Composites, *I. T. Georgiou*

Composite Materials II

Session: W3N, Wed., June 26, 1:00-3:05 pm
Room: DB, Rm A
Chairs: B. L. Lee, U. Vaidya

1:00 Slip Characteristics during Dynamic Fiber Pullout, *N. Sridhar, Q. D. Yang, B. N. Cox*

1:25 A Micromechanics-Based Nonlocal Model for Isotropic Composites Containing Non-Spherical Inclusions, *I. Monetto, W. J. Drugan*

1:50 A Model for the Pull-Out of Bone-Shaped Short Fibers, *T. Tippetts, I. Beyerlein, Y. Zhu*

2:15 Stress in a Single Fiber $A\ell_2O_3$/Al Composite: Analysis of Experiments through Modeling, *S. Mahesh, I. J. Beyerlein, J. C. Hanan, E. Ustundag*

2:40 A New Tool for Analyzing Textile Composites, *Q. D. Yang, K. L. Rugg, B. N. Cox*

Composite Materials III

Session: R2N, Thurs., June 27, 9:30 am-11:35 am
Room: DB, Rm F
Chair: M. Peterson, H. Mahfuz

9:30 Strain Energy Release Rates for Crack-Induced Delaminations in Fibre-Reinforced Composite Laminates, *M. Kashtalyan, C. Soutis*

9:55 Compressible Composites with Interlaminar Microcracks: Exact Stability Solutions for Distinct Roots, *I. A. Guz, A. N. Guz*

10:20 Mode-I Fracture in Pultruded Composites, *R. F. El-Hajjar, R. M. Haj-Ali*

10:45 The Effect of a Crack on a Circularly-Layered Fiber Reinforced Composite, *E. V. Honein, H. Rai, M. I. Najjar, T. Honein*

11:10 Effective Mechanical Modeling of Composite Conductor, *W. Sun, J. T. Tzeng*

Composite Materials IV

Session: F2N, Fri., June 28, 9:30-11:35 am
Room: SQ Brush B
Chair: M. Peterson, B. L. Lee

9:30 Fracture Toughness Improvement using Optimally Shaped Short Ductile Fibers, *J. Tsai, R. Bagwell, A. Patra, R. Wetherhold*

9:55 Vibration of Rotating Turbine Blades Made of Functionally Graded Materials, *S.-Y. Oh, L. Librescu, O.Song*

10:20 A Nonlinear Solid Shell Element Formulation for Analysis of Composite Panels under Blast Wave Pressure Loading, *H. Park, S. W. Lee*

10:45 Thermal Fatigue of Particle Reinforced Metal Matrix Composites Induced by Laser Heating and Mechanical Load, *S. G. Long, Y. C. Zhou*

11:10 Energy Limit Method for Strength Design of Reinforced Concrete Beams, *S. Marjanishvili*

Composite Materials V

Session: F3N, Fri., June 28, 1:00-3:30 pm
Room: SQ 341
Chairs: S. S. Vel, H. Mahfuz

1:00 Modeling of Interface Mechanical Behavior of Bimaterial Systems by Cohesive Zone Models, *H. Li, N. Chandra*

1:25 Mesomechanics of Fabric Reinforced Composites, *T. M. Damiani*

1:50 Application of the Theory of Doubly Periodic Riemann Boundary Value Problems to Composites, *C. P. Jiang, Y. L. Xu, X. W. Liu*

2:15 Nonlinear Oscillations Pliable to Shear Transversal Deformations and Compression of Composite Plates, *M. Marchuk, V. Pakosh, O. Maksymuk*

2:40 Mixed Mode Delamination and Bridging Modeling in Laminated Plates, *D. Bruno, F. Greco, P. Lonetti*

3:05 Calculation of Anisotropically Rectangular Plates on an Elastic Foundation Dependent on Normal Reactive and Tangential Stress-Strain Effects, *T. S. Shirinkulov, K. Shirinkulov*

Seismic Analysis

Session: F3A, Fri., June 28, 1:00-3:05 pm
Room: DB, Rm A
Chairs: O. Cazacu

1:00 Strain State of the Crust of Some Regions of the Central Asia, *A. A. Abidov, I. U. Atabekov, F. G. Dolgopolov, A. I. Hodjimetov*

1:25 Dynamic Design of Ground Dams under Non Stationary Seismic Effects, *K. S. Sultanov, K. D. Salyamova*

1:50 Stress-Strain State of Ground Dam Under Seismic Loads, *K. S. Sultanov, S. I. Umarkhonov*

2:15 Research of the Ground Movement with the Help of Percussive Waves, *M. A. Akhmedov*

Structures I

Session: T2J, Tues., June 25, 9:30-11:35 am
Room: DB, Exec.
Chairs: R. H. Plaut, M. G. Hilgers

9:30 Mechanics of Folded Media, *L. Bevilacqua*

9:55 Smooth Approximations of Tension Field Deformations of Various Membranes, *M. G. Hilgers*

10:20 Large Deformations of Nearly Spherical Inflated Membranes, *E. M. Mockensturm*

10:45 Modeling Underground Pipe Lines with Initial Imperfection, *J. A. Villarraga, J.F. Rodriguez and C. E. Martinez*

11:10 Uniform Stabilization of a One-Dimensional Hybrid Thermo-Elastic Structure, *M. Grobbelaar*

11:35 Dynamic Compression of Cross-linked & Linear PVC Cores, *T. Thomas, H. Mahfuz, K. Kanny, S. Jeelani*

Structures II

Session: W2J, Wed., June 26, 9:30 am-12:00 pm
Room: DB, Exec.
Chair: W. Bottega

9:30 Structural Response of an Ancient Wooden Construction to Dynamic Loadings, *F. Lu, D. Zhang*

9:55 Comparison of the Two Formulations of w-u-v and w-F in Nonlinear Plate Analysis, *J. Lee*

10:20 Adherence of an Axisymmetric Flat Punch onto a Clamped Circular Plate and its Application to Mechanical Chacterization of Thin-Walled Bio-Capsules, *K.-T. Wan, D. A. Dillard*

10:45 On the Importance of Classical Plate Theory for Getting Accurate Results for Thick Plates, *R. P. Shimpi*

11:10 A New Approach of Differential Quadrature Element Method for Analyses of Euler Beams, *Y.-T. Chou, S.-T. Choi*

11:35 Reconstruction of Elastic Constants of Laminated Shells Using a Combined Inverse Technique, *X. Han, G. R. Liu*

Structures III

Session: R2J, Thurs., June 27, 9:30-11:35 pm
Room: SQ 219
Chairs: M. Skrinkar, R. P. Shimpi

9:30 RC T Cross Sections Bending Design According to EC2 Standard Implementing Analytical Solutions, *M. Skrinar*

9:55 A Semi-Analytical Method for Analysis of Floor Slabs in Tall Building Structures, *J.-S. Kuang, H. X. Zhang*

10:20 Validation of 3D Modelling of a Steel Portal Structure Using a Modified Genetic Algorithm, *S. Y. Mahfouz*

10:45 Reliability Analysis Applied to Pipelines Under Axial Tension, Bending, and External Pressure Loads, *T. Alves, L. A. Aguiar, S. F. Estefen*

11:10 The Analysis of the Intense Condition of Construction of a Station, *A. Khakimov*

Structures IV

Session: F3J, Fri., June 28, 1:00-3:30 pm
Room: DB, Rm C
Chairs: L. Librescu, J. Hohe

1:00 A general nonlinear theory for sandwich shells with transversely compressibile core, *J. Hohe, L. Librescu*

1:25 Importance of Geometric Nonlinearity on the Vibration of a Shell Under Pressure, *A. K. Jha, D. J. Inman, R. H. Plaut*

1:50 Modelling a bistable composite structure, *D. A. Galletly, S. D. Guest*

2:15 Virtual Load and Substructure Method in Repetitive Structural Analysis by Discrete Fourier Transform, *E. G. Karpov, N. G. Stephen, D. L. Dorofeev*

2:40 A Comparitive Study of FE Model Order Reduction Schemes for 2D Linear Transient Elastodynamics, *C.V.S. Sastry, D. R. Mahapatra, S. Gopalakrishnan, T.S. Ramamurthy*

3:05 Calculation and Analysis of Support Force for Large-scale Rotary Kiln with Multi-support, *X.-J. Li, P.-Y. Zhu, Y.-L. Liu, X.-B. Li*

Applications of Finite Element Methods I

Session: R4R, Thurs., June 27, 3:30-5:35 pm
Room: SQ 232
Chair: M. N. Raftenberg

3:30 Hygro-Mechanical Deformation of Cardboard: A Numerical Study, *A. Cloutier, G. Gendron, M.-L. Dano*

3:55 Numerical Simulations of Dynamic Fracture Process in Brittle Materials, *F. Zhou, J.-F. Molinari*

4:20 On Modeling Bonds in Fused, Porous Networks: 3D Simulations of Fibrous/Particulate Joints, *L. M. Berhan, A.M. Sastry*

4:45 Fractal Interpolation in Solid Modeling and Meshless Structural Analysis, *N. Marignetti, M. Pomini*

5:10 Two Dimensional Finite Element Analysis for Cantilever Beam, *A. A. Hussain*

5:35 More Readable, Manageable and Extensible Codes For Finite Element Analysis Using JAVA, *A. Madan*

Applications of Finite Element Methods II

Session: F2I, Fri., June 28, 9:30-11:35 am
Room: DB, Rm F
Chair: M. N. Reftenberg

9:30 Effect of Heat Sink on the Final Fatigue Life of Flip-Chip Packages, *C. Xie, D. Zhang, S. Liu*

9:55 Homogenization Techniques to Include Plasticity Effects in Materials, *C. Shet, N. Chandra*

10:20 Finite Element Limit Formulation for Dynamic Simulation of Structural Members, *K. P. Kim, H. Huh*

10:45 Incomplete Constitutive Relationship in Computer Simulation in Manufacturing Processes, *E. Gomes*

11:10 Finite Element Simulation of Impact to a Kevlar Vest Worn by a Human Thorax, *M. N. Raftenberg*

Applications of Finite Element Methods III

Session: F3I, Fri., June 28, 1:00-3:30 pm
Room: DB, Rm F
Chair: N. Chandra

1:00 A New Finite Element Method Integrating Extrinsic and Intrinsic Cohesive Zone Models, *P. K. Jha, C. Shet, N. Chandra*

1:25 Finite Element Line-of-Sight Jitter Performance under Gunfire Vibration, *H. Shainian*

1:50 Saint Venant and Almansi-Michell Problems for a Prismatic Beam with a General Cross-section, *S. B. Dong*

2:15 An Economic Efficient Stable Algorithm for Damped Coupled Thermal-Structural Problems, *A. M. Elhady*

2:40 Radial Boundary Node Method for Elastic Problem, *H. Xie, T. Nogami, J.-G. Wang*

3:05 Hybrid Scheme of Finite Element Method in the Problems of Calculation of Layered Shells and Plates with Regard for Possibility of Weakening or Breaking the Interlayer Contacts, *M. Marchuk, M. Khomyak, V. Pakosh, R. Tuchapskyj*

Structural Dynamics I

Session: R3E, Thurs., June 27, 1:00-3:05 pm
Room: SQ 236
Chairs: J. C. Duke

1:00 Detection of Transient Mechanical Displacements in Aluminum Plates with Optical Fiber Sensors, *J. C. Duke, B. A. Childers, W. H. Prosser*

1:25 Experimental and Analytical Study of Flyrod Mechanics, *M. D. Sensmeier, M. Carter, J. Demoyse, M. Krizansky*

1:50 Modal Analysis of Cantilever Plates Undergoing Accelerated In-plane Motion, *H. H. Yoo, S. K. Kim, D. J. Inman*

2:15 Experimental Investigation of the Nonlinear Normal Modes of a Parametrically Excited Buckled Beam, *W. Lacarbonara, M. Ohkuma, H. Yabuno*

2:40 Sensitivity Analysis of Transmisibility of a Piecewise Linear Isolator for Steady State Vibration, *A. Narimani, M. F. Golnaraghi, G. N. Jazar*

Structural Dynamics II

Session: R4E, Thurs., June 27, 3:30-6:35 pm
Room: SQ 236
Chairs: D. I. Caruntu

3:30 Static and Dynamic Response of Torsionally Strain Anisotropic Composite Thin-Walled Beams, *L. Librescu, Z. Qin, D. R. Ambur*

3:55 Coupling of Rigid Motion and Large Deformation in Dynamics of Elastic Bodies, *G. Szefer*

4:20 Dynamic Stability of Circular Cylindrical Shells Subjected to Axial Loads, *F. Pellicano, M. Amabili*

4:45 On Transverse Vibrations' Equation of Annular Plates of Convex Parabolic Thickness Variation, *D. I. Caruntu*

5:10 Impact of a Pressurized Thin Spherical Shell with a Flat Rigid Surface, *A. J. Paris, J. M. Guerricabeitia, R. J. Giordano*

5:35 Experimental Investigation and Computer Simulation on Elasto-Plastic Dynamic Buckling Behavior of Liquid-Filled Cylindrical Shells Under Axial Impact, *Z. Shanyuan, L. Jianping, C. Guoqiang, L. Guoyun*

6:00 Coupling of Rigid Motion and Large Deformation in Dynamics of Elastic Bodies, *S. Gwidon*

Wave Motion I

Session: W2L, Wed., June 26, 9:30-12:00 noon
Room: SQ, Brush B
Chairs: J. C. Duke

9:30 Stability of Solitary Waves in Compacting Media, *F. Dong, D. H. Riahi, A. T. Hsui*

9:55 Stress Wave Propagation in Functionally Graded Materials using Continuously Graded Finite Elements, *P. Thamburaj, M. H. Santare, G. A. Gazonas*

10:20 A Theoretical Model for the Detection of Surface-Breaking Cracks with Laser-Generated Ultrasound, *I. Arias*

10:45 Elastic Plate Waves in High Porosity Materials, *M. L. Peterson, Z. Wang*

11:10 Modeling Kissing Bonds for Ultrasonic Leaky Lamb Wave NDT, *V. R. Yerikalapudi, S. Gopinathan*

11:35 Nonlinear Normal Waves in Free Crystal Lamina of Cubical Systems, *K. I. Kurennaja, V. I. Storozhev, V. A. Shpack*

Wave Motion II

Session: R2L, Thurs., June 27, 9:30 am-12:00 noon
Room: SQ 234
Chair: T. L. Geers

9:30 Pressure and Particle Velocity Fields Generated by an Underwater Explosion, *K. S. Hunter, T. L. Geers*

9:55 The Effect of Material Heterogeneity on High Amplitude Wave Propagation in Layered Material Systems, *X. Chen, N. Chandra, A. M. Rajendran*

10:20 A Green Function for Radially Inhomogeneous Elastic Medium with an Impulsive SH-Wave Source, *K. Watanabe*

10:45 Impact Fracture in Destructive Disassembly of Joining Elements: Analysis and Experiment, *K. G. Pak, R. S. Sodhi*

11:10 Inverse Scattering and Lattice Motion Due to Generalized Nonlinear Interaction, *S. Cohn, H. Voljpen*

11:35 Mechanisms which Use Traveling Deformation Waves, *A. Dobrolyubov, G. Douchy*

Wave Motion III

Session: F2L, Fri., June 28, 9:30-11:35 am
Room: DB, Exec.
Chair: K. Watanabe

9:30 Research of the Ground Movement with the Help of Percussive Waves Created by Permeation of a Blunt Wedge, *M. A. Akhmedov*

9:55 Complex Representation in Nonlinear Dynamics and Localized Elastic Waves, *L. I. Manevitch*

10:20 Wave and Crack Propagation in Elastoplastic Solid (Mountain Bodies) by Influence of Explosion and by Accounting Rheologic Properties, *S. K. Toshev, M. B. Karimov, Z. C. Mukhamadieva*

10:45 Investigation on SHPB Technique for Soft Materials Testing, *F. Lu, Y. Lin*

11:10 Nonlinear Electroelastic Waves in Fluid-Filled Porous Media, *A. G. Bagdoev, A. V. Shekoyan*

Vibration Analysis

Session: F2J, Fri., June 28, 9:30 am-12:25 am
Room: DB, Rm C
Chair: T. Majewski

9:30 Destruction and shock-wave processes in isotropic and anisotropic materials under dynamic loads, *A. V. Radchenko*

9:55 On Interactions between Parametric and Self-excited Vibrations in the System with Ideal and Non-ideal Energy Source, *J. Warminski, J. M. Balthazar*

10:20 Vibrational Mechanics – A New Effective Approach in Nonlinear Dynamics, *I. I. Blekhman*

10:45 Bending, Vibration and Stability of Three-Layer Anistropically Right-Angled Plates, *O. G. Temirov*

11:10 Wave Propagation in Cylindric Body that Includes an Internal Holder, *B. E. Khusanov*

11:35 Interaction of Plane Waves in Elastic Medium with Extensive Cylindrical Obstacles, *E. V. Rozhkova, K. S. Sagdiev, V N. Frolov*

12:00 Dynamic Interaction of Deformable Rod Structures with an Elastic Medium by Coulomb Dry Friction Law, *T. Rashidov, S. M. Mamatkulov, M, Mamatkulova, A. Matkarimov*

Vibration and Control

Session: R2P, Thurs., June 27, 9:30 am-12:00 noon
Room: DB, Exec.
Chair: E. Austin

9:30 Elasto-Plastic Modeling of Shaking Table Tests, *M. R. Massimino, M. Maugeri, D. M. Wood*

9:55 Vibration Forces in Physical Systems, *T. Majewski*

10:20 Fundamental Vibration of Rotating Pre-twisted Conical Shells, *T. Sakiyama, X.X. Hu, H. Matsuda, C. Morita*

10:45 Synchronous Eliminator of Vibrations in 3-D, *T. Majewski*

11:10 Large Amplitude Free Vibration Study of Square Clamped Plate Through a Static Analysis, *K. N. Saha, D. Misra, G. Pohit, S. Ghosal*

11:35 On a Control Technique to a Simple Machine Foundation with Limited Power Supply by Using Internal Resonance and Saturation Phenomenon, *J. L. P. Felix, J. M. Balthazar, R. M. L. R. F. Brasil*

Dynamics I

Session: M2J, Mon., June 24, 9:30-11:35 am
Room: DB, Exec.
Chairs: S. A. Cummings, S. P. Doughty

9:30 Capture into Resonace: A Novel Method of Efficient Control, *D. L. Vainchtein, I. Mezic*

9:55 The Role of Internal Variables on the Control of Viscoelastic Structures, *L. A. Silva, D. J. Inman, E. M. Austin*

10:20 Wavelet-Galerkin Method for the Free Vibrations of an Elastic Cable Carrying an Attached Mass, *M. Al-Qassab, S. Nair*

10:45 K-L or POD Analysis of Large Amplitude Vibrations of Forced Geometrically Exact Arches, *I. T. Georgiou*

11:10 Coupled Triggers of Coupled Singularities and Transformation of Homoclinic Orbits in the Special Rheonomic Systems, *K. Hedrih*

Dynamics II

Session: T2K, Tues., June 25, 9:30 am-12:00 noon
Room: SQ, 232
Chairs: S. Skaar, S. P. Doughty

9:30 Exploiting Discontinuities for Stabilization of Recurrent Motion, *H. J. Dankowicz, P. T. Piiroinen*

9:55 On the Dynamics of a Railroad Freight Wagon Wheelset with Dry Friction Damping, *H. C. G. True*

10:20 Lumped Mass Track Model with Rubber Bushings, *C. Sandu, A. Dhaliwal*

10:45 Bifurcations of Periodic Orbits in a Class of Autonomous Non-Conservative Perfect Systems, *D. S. Sophianopoulos, P. G Asteris*

11:10 Hamiltonian Mechanics for Functionals Involving Second Order Derivatives, *B. Tabarrok, C. M. Leech*

11:35 Control of Hopping Apparatus, *V. B. Larin, V. M. Matiyasevich*

Dynamics III

Session: W2M, Wed., June 26, 9:30-12:00 noon
Room: DB, Rm A
Chairs: H. J. Dankowicz

9:30 Low-Cost Health Monitoring using the Impedance Method, *D. Peairs, G. Park, D. J. Inman*

9:55 Semi-active Fluid Mount Design, *N. Vahdati*

10:20 On a Receptance Coupling Method for Tool-Point Frequency Response Prediction in High-Speed Machining, *T. L. Schmitz, T. J. Burns*

10:45 Deformation Mechanism and Defect Sensitivity of Notched Free-free Beam and Cantilever Beam under Impact, *H. H. Ruan, T. X. Yu*

11:10 Kinematical Investigations of the Five-Link Lever Mechanism, *R. A. Abdullaevich, B. G. Atahanovich, M. R. Harisovich*

11:35 Solid Rotor Dynamics, *J. S. Rao, R. Sreenivas, C. V. Veeresh*

Fluid Mechanics

Session: W3J, Wed., June 26, 1:00-3:30 pm
Room: SQ 234
Chair: N. D. Cristescu, D. J. Ivanovic

1:00 The Characteristics and Dynamics of Vortex Dislocations in Wake-Type Flow with Local Spanwise Non-uniformity, *G. Ling, H. Zhao*

1:25 Selective Model Domain Reduction in Fluid Systems with Complex Geometry, *M. S. Stay, V. H. Barocas*

1:50 Closed Form Solution for a Falling Cylinder Viscometer, *N. D. Cristescu, B. P. Conrad, R. Tran-Son-Tay*

2:15 Modeling Flow-induced Suspension Head Vibrations in Disk Drives, *M. Kazemi, H. Haj-Hariri, J. A. C. Humphrey*

2:40 Injection/Ejection Influence on Velocity Field and Laminar-turbulent Transition of Unsteady Boundary Layer on Porous Contour for a Great Decelerating Fluid Flow, *D. J. Ivanovic*

3:05 Real Time, Three-dimensional Imaging of Gas-Liquid-Solid Flows using Electrical Capacitance Tomography with Neural Network Based Multi-criterion Optimization Image Reconstruction Technique, *W. Warsito, L.-S. Fan*

Turbulence

Session: M2P, Mon. June 24, 9:30-11:35 am
Room: SQ 236
Chair: Y. Zhou

9:30 Construction of a Subgrid Model for Fluid and MHD Turbulence, *Y. Zhou, O. Schilling, S. Ghosh*

9:55 Turbulence Intensity Distribution for Flow Along a Streamwise External Corner, *K. A. M. Moinuddin, S. Hafez, P. N. Joubert, M. S. Chong*

10:20 Self-Sustaining Mechanism of Organized Structures in Near-Wall Quasi-2D Turbulence, *M. F. Baig, S. I. Chernyshenko*

10:45 Numerical Study of Stratified Oil-Water Two-Phase Turbulent Flow in a Horizontal Tube, *H. Gu, H. Gao, L. Guo*

Flow Control

Session: M2R, Mon. June 24, 9:30-11:35 am
Room: SQ 219
Chair: J. B. Freund

9:30 Effect of the Cavity on Reduction of Skin-Friction Drag, *S. Hahn, H. Choi*

9:55 Optimal Shape Design of a Plane Diffuser in Turbulent Flow, *S. Lim, H. Choi*

10:20 On Control of a Pair of Vortex Patches, *D. L. Vainchtein, I. Mezic*

10:45 Adjoint-Based Control and Analysis of Free-Shear Flow Noise, *M. Wei, J. B. Freund*

11:20 Capturing of the Horseshoe Vortices by Vortex Fusion, *T.-C. Su, C. Wu*

Flow and Modeling

Session: T2P, Tues. June 25, 9:30 am-12:00 pm
Room: SQ 219
Chair: R. H. Plaut

9:30 Development of Patched Grid Model for a Flow Solver, *S. J. Zhang, J. Liu, Y.-S. Chen*

9:55 An Adaptive Wavelet Method for Fluid Flows, *Y. A. Rastigejev, S. Paolucci*

10:20 Experiments and Analyses of Water-Filled Geomembrane Tubes as Temporary Flood-Fighting Devices, *R. H. Plaut, G. M. Filz*

10:45 On Blade Coating Flow of Viscoelastic Fluids, *N. Ashrafi*

11:10 Simulation of Long-Time Evolution of Water Waves in Deep Water, *H. Liu, P. A. Madsen*

11:35 Theoretical Modeling of the Effect of Drag Reducing Polymer Solution on TBL Induced Flow Noise, *V. B. Rao*

Computation Fluid Dynamics

Session: T3D, Tues. June 25, 1:00-3:05 pm
Room: SQ, Brush B
Chair: J. B. Freund, B. Grossman

1:00 Atomistic Simulation of a Liquid Drop Sliding on a Solid Surface, *J. B. Freund*

1:25 Unsteady Fluid Flow in a Lid-Driven Cavity Due to a Moving Thin Partition, *X. Shi*

1:50 Computation of Vortex-Dominated Flows Using Compressible Vorticity Confinement Methods, *B. Grossman, G. Hu*

2:15 Reactive Flows and Slow Manifolds, *S. Singh, J. M. Powers, S. Paolucci*

2:40 Reynolds Stress Turbulence Model for Prediction of Shear Stress Terms in Film Cooling Cross Flow - Numerical Simulation, *K. Javadi, M. Taeibi-Rahni, A. Javadi*

Turbulent Flows & Instabilities

Session: T4D, Tues. June 25, 3:30-6:00 pm
Room: SQ, Brush B
Chair: W. J. Devenport

3:30 Turbulent Transport Downstream From a Step Change in the Heat Flux From the Wall of a Channel, *P. Le, B. M. Mitrovic, D. V. Papavassiliou*

3:55 Interaction Between a Trailing Vortex and External Turbulence, *N. Takahashi, M. Ito, T. Miyazaki, K. Yamamoto*

4:20 Continuous Three-Component Velocity Measurements in a Near-Wall Cross-Stream Plane in Channel Flow, *J. C. Wells, K. Kishida, N. Ukai, Y. Himeno*

4:45 Investigation of the Instantaneous Dynamics of the Large-Scale Structures In The Impinging Jet, *J. Hall, D. Ewing, Z. Xu, H. Hangan*

5:10 Thermal Effect on Crossflow Instability in Supersonic Boundary Layers, *C.-L. Chang*

5:35 Nonlinear Instability of a Liquid Compound Jet, *S. P. Radev, M. Kaschiev, L. Tadrist, F. Onofri*

Flow Instablities

Session: T3E, Tues. June 25, 1:00-3:05 pm
Room: DB, Rm C
Chair: Y. Fukumoto, J. J. Healey

1:00 Intermittent Instability Induced by Long Wavelength Klebanoff Modes, *X. Wu, M. Choudhari*

1:25 Characteristics of the Shear Layer Separating from a Circular Cylinder, *J. Kim, H. Choi*

1:50 Perturbation Analysis of a Meandering Rivulet, *H. Y. Kim, J. H. Kim, B. H. Kang*

2:15 Linear Stability of an Elliptically Strained Vortex Tube Revisited, *Y. Fukumoto*

2:40 On the Effect of Nonparallel Terms on the Absolute and Convective Instabilities of the Rotating Disk Boundary Layer, *J. J. Healey*

Flow in Porous Media

Session: T4F, Tues. June 25, 3:30-5:35 pm
Room: SQ 234
Chair: K. M. Hill

3:30 Prediction of Non-Darcy Flow Coefficients Using Pore Network Modeling, *H. W. Lao, D. V. Papavassiliou, H. J. Neeman*

3:55 Controller Granular Segregation in Unsteady Dense Sheared Flows, *K. M. Hill, J. Keegan*

4:20 Diffusion of Fluids in Swelling Solids, *A. R. Srinivasa, S. Baek*

4:45 Characterization of Porous Membrane Elements in Microfluidic Devices, *K. Sarkar, S. Kassegne, D. Hodko, M. Madou, K. Greiner, S. Maity*

5:10 An Application of Flow Through Parallel Porous Plates, *M. Sankaranarayanan*

Fluid Flows

Session: T2R, Wed. June 26, 9:30-11:35 am
Room: SQ 234
Chair: E. C. Eckstein, A. Prokunin

9:30 Numerical Simulation of the Deformation and Breakup Process of Agglomerates in Polymer Melts, *T. Moribe, J. L. White*

9:55 On Cavitation in Spherical Particle Slow Motion in Liquid Along a Wall, *A. Prokunin, O. V. Voinov*

10:20 SPH Applied to Hydrodynamic Ram, *M. Gourma, R. Vignjevic, T. de Vuyst*

10:45 Depicting Random Velocities in Suspension Flows with the Helmholtz Theorem on Vector Fields, *E. C. Eckstein, J. A. Goldstein*

11:10 Motive Thermodynamics of Multiphase Flows, *A. Sukhodolsky*

Arterial Flows In Health and Disease

Session: W3G, Wed. June 26, 1:00-3:30 pm
Room: SQ 345
Chair: S. Berger

1:00 Predicting Outcomes of Cardiovascular Surgery: Mathematical Models and Experimental Validation, *C. A. Taylor*

1:50 A Blood Particle Residence Time Model for the Evaluation and Design of Femoral Bypass Grafts, *P. W. Longest, C. Kleinstreuer*

2:15 Weighted Temporal and Spatial Smoothing for the Inverse Problem of Electrocardiography, *L. G. Olson, R. D. Throne, J. R. Windle*

2:40 Viscous Drag of Deformed Vesicles in an Optical Trap: Numerical Simulation and Experiments, *K. K. Liu, J.-J. Foo, V. Chang*

3:05 Chaotic Onset of Sickle Cell Blood Flow Crisis, *A. Apori, R. J. Coral Pinto, W. Harris*

Theory and Modeling in Fluids

Session: W2O, Wed. June 26, 9:30am-12:00 noon
Room: SQ 234
Chairs: H. Aref

9:30 Towards a Split Lagrangian-Eulerian Model for Autorotation Phenomena, *F. L. Ponta, H. Aref*

9:55 Enhancement of Heat Transfer in Oscillating Flows, *E. Lundgren, U. Marksten, A. Holst*

10:20 Exact Solutions for the Unsteady Plane Couette Flow of a Dipolar Fluid, *P. M. Jordan, P. Puri*

10:45 Wake/Vortex Breakdown in Supersonic Flows, *A. I. Ruban, N. Battam, G. L. Korolev*

11:10 Spectral Filtering Formalism and its Application for Multi-Resonant Multi-Phase Water Waves, *I. L. Kliakhandler*

11:35 The Model of Accelerately Deforming Fluid, *I. N. Khusanov*

Multiphase and Suspension Flows

Session: R3D, Thurs. June 27, 1:00-2:40 pm
Room: SQ, Brush B
Chairs: T. Kumagai

1:00 Revaluation of the Validity of Oseen's Approximation in Microhydrodynamics, *T. Kumagai, T. Baba*

1:25 Blood Flow in Small Curved Vessels, *C. Y. Wang, J. B. Bassingthwaighte*

1:50 Rising Bubbles Testing Water Contamination, *J. F. Harper*

2:15 Models for Stratification of a Sedimenting Suspension, *J. H. C. Luke*

Bifurcations and Nonlinear Dynamics in Fluids

Session: R4D, Thurs. June 27, 3:30-5:35 pm
Room: SQ, Brush B
Chairs: M. Brons

3:30 Three-Dimensional Simulation on Flow Bifurcation in a Plane-Symmetric Channel with Sudden Expansion, *R. R. Hwang, T. P. Chiang, T. W. H. Sheu*

3:55 Mixing Enhancement by Dual Speed Rotating Stirrer, *A. Goullet, N. Aubry, R. Lima, M. Vittot*

4:20 Topological Fluid Dynamics Applied to the Steady Axisymmetric Cylinder with Rotating End-Covers, *A. Bisgaard, M. Brons, J. N. Sorensen*

4:45 Streamline Patterns in the Flow Around a Circular Cylinder, *M. Brons, R. Petersen*

5:10 On the Dynamics of Transitional Boundary Layer, *C. B. Lee*

Keynote Session
Nonlinear Dynamics and Control I

Organizers: J. L. Junkins
Session: M2Q, Mon., June 24, 9:30-11:45 am
Room: DB, Rear Aud.
Chair: J. L. Junkins

9:30 Predicting the Dynamics and Control of Geometrically Nonlinear Systems Operating Under Micro Gravity Conditions, *C. Blaurock, D. W. Miller*

10:15 Dynamic Programming Method for DAEs, *J. E. Hurtado*

11:00 A Momentum-Based Symbolic Lagrange's Formulation, *J. D. Turner*

Keynote Session
Nonlinear Dynamics and Control II

Organizer: J. L. Junkins
Session: T2Q, Tue., June 25, 9:30-11:45 am
Room: DB, Rear Aud.
Chair: J. L. Junkins

9:30 Configuration Control of a Rolling Sphere: Application to a Spherical Mobile Robot, *R. Mukherjee, T. Das*

10:15 Rigid-Body Attitude Control Without Rate-Gyros Using Only Inclinometer Measurements, *M. R. Akella, G. R. Kotamraju*

11:00 Recent Advances in the Biorobotics Laboratory at Case Western Reserve University, *R. Quinn*

Keynote Session
Nonlinear Dynamics and Control III

Organizer: J. L. Junkins
Session: W2Q, Wed., June 26, 9:30-11:45 am
Room: DB, Rear Aud.
Chair: J. L. Junkins

9:30 Robust Feedback/Feedforward Control of Flexible Structures, *M. Muenchhof, T. Singh*

10:15 Spacecraft Relative Orbit Description Through Orbit Element Differences, *H. Schaub*

11:00 Vision-Based Control of Robots on Unconstrained Platforms in Space, *J. A Cardens, S. B. Skaar, J. W. Goodwine*

Contemporary Issues in Mechanics I
In Honor of
Millard F. Beatty

Organizers: Q. Jiang, M. S. Wu, E. Baesu
Session: M3B, Mon., June 24, 1:00-3:05 pm
Room: SQ, Haymarket
Chair: D. E. Carlson

1:00 On Pure Torsion of a Compressible Elastic Circular Cylinder, *E. Kirkinis, R. W. Ogden*

1:25 Constitutive Modeling of Hyperelastic Materials with Limiting Chain Extensibility, *G. Saccomandi, C. O. Horgan*

1:50 Boundary-Value Problems for Hyperelastic Materials with Limiting Chain Extensibility, *C. O. Horgan, G. Saccomandi*

2:15 A Variational Problem Modelling Behavior of Unorthodox Silicon Crystals, *J. B. Hannon, M. Marcus, V. J. Mizel*

2:40 Non-Isochoric Bending and Shearing, *M. M. Carroll*

Contemporary Issues in Mechanics II
In Honor of
Millard F. Beatty

Organizers: Q. Jiang, M. S. Wu, E. Baesu
Session: M4B, Mon., June 24, 3:30-6:25 pm
Room: SQ, Haymarket
Chair: D. Warne

3:30 Hysteresis in the Stress-Cycling of Bars Undergoing Solid-Solid Phase Transitions, *J. K. Knowles*

3:55 Why Do Cracks in Rubber Turn Sideways?, *A. N. Gent, M. Razzaghi-Kashani, G. R. Hamed*

4:20 Modeling and Analysis of Nonlinearly Elastic Rods with Chirality, *T. J. Healey*

4:45 Invariants of the Stretch Tensors and their Application to Finite Elasticity Theory, *D. J. Steigmann*

5:10 A Constrained Mixture Model for Cell Mechanics, *J. D. Humphrey*

5:35 Continuum Modeling of Cell Membranes, *E. Baesu*

6:00 Universal Relations for Transversely Isotropic Elastic Materials, *R. C. Batra*

Contemporary Issues in Mechanics III
In Honor of
Millard F. Beatty

Organizers: Q. Jiang, M. S. Wu, E. Baesu
Session: T3B, Tues., June 25, 1:00-3:05 pm
Room: SQ, Haymarket
Chair: D. Barnett

1:00 Inflating a Rubber Balloon, *I. Müller, H. Struchtrup*

1:25 A WKB Analysis of the Buckling of an Everted Neo-Hookean Cylindrical Tube, *Y. B. Fu, Y. P. Lin*

1:50 Asymptotic Analysis of an Isotropic Compressible Hyperelastic Half-Space Under a Tensile Point Load, *D. A. Warne, P. G. Warne*

2:15 Numerical Computation for Singular Nonlinear Solid Mechanics Problems: The Modified Picard Method, *P. G. Warne, D. A. Warne, K. I. Dickson*

2:40 Eversion Problems for Nonlinearly Elastic Shells, *S. S. Antman*

Contemporary Issues in Mechanics IV

In Honor of
Millard F. Beatty

Organizers: Q. Jiang, M. S. Wu, E. Baesu
Session: T4B, Tues., June 15, 3:30-6:00 pm
Room: SQ, Haymarket
Chair: Q. Jiang

3:30 An Experimental Study of the Thermo-Mechanical Response of Elastomers Undergoing Scission and Cross-Linking at High Temperatures, *A. Jones, A. Wineman, J. Shaw*

3:55 A Pressurized Spherical Elastomeric Membrane Undergoing Temperature Induced Scission and Cross-Linking, *K. Myers, A. Wineman*

4:20 On Agmon's Condition for Incompressible Finite Elasticity, *G. P. MacSithigh*

4:45 Rapid Mode III Interface Flaw Extension: Dissimilar Anisotropic Solids With Largely Arbitrary Orientations of Their Principal Material Axes, *L. M. Brock*

5:10 Some Exact Solutions for Coharmonic Elastic Materials, *F. Rooney, B. O'Dowd, M. M. Carroll*

5:35 Mechanoelectrical Phenomena In Ionic Polymers, *M. Shahinpoor*

Contemporary Issues in Mechanics V

In Honor of
Millard F. Beatty

Organizers: Q. Jiang, M. S. Wu, E. Baesu
Session: W2B, Wed., June 26, 9:30 am-12:00 pm
Room: SQ, Haymarket
Chair: E. Baesu

9:30 On Modeling the Anisotropic Plastic Response of Aluminum Alloys, *O. Cazacu, F. Barlat*

9:55 Microstructural Analysis of Polycrystalline Ceramics Using Voronoi Tessellations, *S. Xue, D. Zhang, R. Feng, M. S. Wu*

10:20 On the Elliptic Balance Method, *A. Elas-Zuñiga*

10:45 Small Oscillations and Stability of a Thick, Highly Elastic Slab, *S. A. Usmani*

11:10 Existence of Point Defects in Nematic Gels, *J. Dolbow, E. Fried, A. Q. Shen*

11:35 Referential Doyle-Ericksen Formulae for the Energy-Momentum Tensor in Finite Plasticity, *J. Lu*

Contemporary Issues in Mechanics VI

In Honor of
Millard F. Beatty

Organizers: Q. Jiang, M. S. Wu, E. Baesu
Session: W3B, Wed., June 26, 1:00-3:05 pm
Room: SQ, Haymarket
Chair: D. Steigmann

1:00 Response of Viscoelastic Polymer Melts at High Shear Rates: New Experiment and Modeling, *Y. Hu, R. Feng*

1:25 Nonlinear Vibrations of Atomic Force Microscope Beams with a Hertzian Contact Boundary Condition, *J. A. Turner, K. Shen*

1:50 An Experimental Study of Thermal Buckling in Plates, *K. D. Murphy, D. M. Ferreira*

2:15 Analysis of Interfacial Wedge Disclination Dipoles by the Image Dislocation Method, *M. S. Wu*

2:40 The Excess Energy of a Multiwalled Carbon Nanotube Due to a Core Extrusion, *Q. S. Zheng, J. Z. Liu, Q. Jiang*

Contemporary Issues in Mechanics VII

In Honor of
Millard F. Beatty

Organizers: Q. Jiang, M. S. Wu, E. Baesu
Session: W4B, Wed., June 26, 3:30-6:00 pm
Room: SQ, Haymarket
Chair: M. S. Wu

3:30 Stability and Bifurcation of Inflation of Elastic Cylinders, *Y.-C. Chen, D. M. Haughton*

3:55 The Anatomy of Plasticity: A Case Study, *M. Negahban*

4:20 Two Versions of Fourier's Law for Heat Conducting, Perfectly Elastic, Isotropic Solids, *J. Dunwoody*

4:45 Analytical Solutions for Bending and Flexure of Helically-Reinforced Cylinders, *A. H. England, J. A. Crossley, A. J. M. Spencer*

5:10 Representation Theorems for Isotropic Functions, with Application to Basis-Free Representation of Kinematic Quantities, *G. Dui*

5:35 Effect of Inhomogeneous Inclusions on Anisotropic Elastic Fields of Dislocations, *L. Sun, H. T. Liu*

Fluid Mechanics and Multiphase Flow I
In Honor of Dan Joseph

Organizers: Y. Renardy, P. Wapperom, E.B. Pittman, D. S. Khismatullin
Session: M3C, Mon., June 24, 1:00-3:05 pm
Room: SQ 219
Chairs: F. Feng, S. Balachandar

1:00 Dynamics of Particle Sedimentation in a Confined Channel, *E.-J. Ding, C. K. Aidun*

1:25 A Simplified Two-Fluid Model Based on Equilibrium Approximation, *S. Balachandar, J. Ferry, S. Rani*

1:50 On Thermal Instabilities in a Viscoelastic Fluid, *H. Ramkissoon, G. Ramdath, D. Comissiong, K. Rahman*

2:15 Electrospinning of a Viscoelastic Jet, *J. J. Feng*

Fluid Mechanics and Multiphase Flow II
In Honor of Dan Joseph

Organizers: Y. Renardy, P. Wapperom, E. B. Pittman, D. S. Khismatullin
Session: M4C, Mon., June 24, 3:30-5:35 pm
Room: SQ 219
Chairs: A. Kamp, H. Hu

3:30 The Direct Numerical Simulation of the Motion of Settling Ellipsoids in Fluid, *R. Glowinski, T.-W. Pan*

3:55 Migration of Spheres in Poiseuille Flow in a Circular Pipe, *H. H. Hu, M. Zhu*

4:20 Onset of Air Entrainment in Cusp and High-Speed Wetting Flows, *D. Jacqmin*

4:45 Modelling of the Depletion of Sand Packs Filled With Live Heavy Oil, *C. M. Rodriguez, A. M. Kamp, J. A. Torres, A. A. Rodriguez, P. C. Hammond*

5:10 Analogies in the Transient Momentum and Energy Equations for Particles, Bubbles and Drops, *E. E. Michaelides, Z.-G. Feng*

Fluid Mechanics and Multiphase Flow III
In Honor of Dan Joseph

Organizers: Y. Renardy, P. Wapperom, E. B. Pittman, D. S. Khismatullin
Session: T3C, Tues., June 25, 1:00-3:05 pm
Room: SQ 219
Chairs: B. Pitman, N. Patankar

1:00 Front Propagation in Dilute Sedimentation: Particle Simulations and Model Continuum Equations, *P. J. Mucha, M. P. Brenner*

1:25 Steady and Unsteady Computational Simulations for Internal Condensing Flows, *Q. Liang, A. S. Barve, X. Wang, A. Narain*

1:50 A Projection Scheme for DNS of Rigid Particulate Flows, *N. A. Patankar*

2:15 Simulation-Based Risk Management of Data for Rapid Mass Flows, *A. K. Patra, A. C. Bauer, E. B. Pitman, M. F. Sheridan, M. I. Bursik*

2:40 Averaged Equations for Particle Flow by Numerical Simulation, *A. Prosperetti*

Fluid Mechanics and Multiphase Flow IV
In Honor Of Dan Joseph

Organizers: Y. Renardy, P. Wapperom, E. B. Pittman, D. S. Khismatullin
Session: T4C, Tues., June 25, 3:30-5:10 pm
Room: SQ 219
Chairs: P. Singh, G. Schleiniger

3:30 Breakup of Viscoelastic Filaments, *M. Renardy*

3:55 PROST: a Proper Representation Of Surface Tension for the Volume-of-Fluid Method, *Y. Renardy*

4:20 Mechanical Response of TSM Resonators to Contact With Stratified Viscoelastic Overlayers, *R. Platte, G. Schleiniger, E. Nwanko*

4:45 Deformation of Bubbles in Three-Dimensional Viscoelastic Flows, *S. Pillapakkam, P. Singh, D. Blackmore*

Fluid Mechanics and Multiphase Flow V
In Honor of Dan Joseph

Organizers: Y. Renardy, P. Wapperom, E. B. Pittman, D. S. Khismatullin
Session: W3C, Wed., June 26, 1:00-3:05 pm
Room: SQ 219
Chairs: V. Verdier, Y. Zhou

1:00 Electrohydrodynamic Fibration of Droplet Suspensions-Direct Numerical Simulations, *G. Tryggvason*

1:25 Polymer Droplet Interactions: The Case of Coalescence, *C. Verdier*

1:50 Direct Numerical Simulation of an Electro-Rheological Channel Flow, *S. H. Cho, J. Y. Yoo, H. G. Choi*

2:15 St-Re Relationship of the Laminar Flow Around a Freely Falling cylinder, *K. Namkoong, J. Y. Yoo, H. G. Choi*

2:40 DNS study of Transient and Turbulent Mixing Induced by the Rayleigh-Taylor and Richtmyer-Meshkov Instabilities, *Y. Zhou, W. Cabot*

Fluid Mechanics and Multiphase Flow VI
In Honor of Dan Joseph

Organizers: Y. Renardy, P. Wapperom, E. B. Pittman, D. S. Khismatullin
Session: W4C, Wed., June 26, 3:30-5:35 pm
Room: SQ 219
Chairs: D. O. Olagunju, G. Forest

3:30 Single-Phase Fingering in Porous Media Revisited, *J. R. A. Pearson*

3:55 Effect of Viscous Heating on Linear Stability of Viscoelastic Cone-and-Plate Flow: Axisymmetric Case, *D. O. Olagunju, L. P. Cook, G. H. McKinley*

4:20 Viscous and Viscoelastic Potential Flow Analysis of Kelvin-Helmholtz Instability on a Liquid Column, *T. Funada, D. D. Joseph*

4:45 Real Time, 3-Dimensional Imaging of Gas-Liquid-Solid Flows using Electrical Capacitance Tomography with Neural Network Based Multi-criterion Optimization Image Reconstruction Technique, *W. Warsito, L. S. Fan*

5:20 Free Energy Characterizations of Mechanical Incompressibility in Thermal Viscous Flows, *M. G. Forest, S. E. Bechtel, F. J. Rooney, Q. Wang*

Numerical Simulation of Turbulent Flows I

Organizer: K. Mahesh
Session: M3D, Mon., June 24, 1:00-3:05 pm
Room: SQ, Brush B
Chairs: K. Mahesh

1:00 Simulation of Complex Flows on Cartesian Grids, *R. Mittal, H. S. Udaykumar*

1:25 Towards DNS and LES of Turbulent Flows in Engineering Geometries, *K. Mahesh*

1:50 A High-Reynolds Number Update to the Comte-Bellot & Corrsin Experiment and Applications in Large-Eddy Simulation, *C. Meneveau, H.-S. Kang*

2:15 Application of a Vortex-based Subgrid-scale Model to Large-eddy Simulation of Compressible Turbulence, *D. I. Pullin, D. Hill, R. Samtaney*

2:40 The Effect of Topology and Scale Decomposition when using Variational Multiscale LES, *K. E. Jansen, A. E. Tejada-Martinez*

Numerical Simulation of Turbulent Flows II

Organizer: K. Mahesh
Session: M4D, Mon., June 24, 3:30-5:10 pm
Room: SQ, Brush B
Chairs: K. Mahesh

3:30 RANS-LES Approaches to High Reynolds Number Prediction, *K. D. Squires*

3:55 Wall Modeling for LES of Complex Turbulent Flows, *M. Wang, J. Templeton, P. Moin*

4:20 Large-Eddy Simulation of Single and Two-Phase Turbulent Flames, *S. Menon*

4:45 Large-Eddy-Simulation of Turbulent Combustion, *H. Pitsch*

Advances in Three-Dimensional Flow Modeling I

Organizers: E. E. Khalil
Session: M3E, Mon., June 24, 1:00-4:15 pm
Room: SQ 236
Chair: S. N. Tiwari

1:00 The Art of Mathematical Modeling of Fluid Flow Regimes Interactions in Complex Geometries, *E. E. Khalil*

1:25 Three-Dimensional Analysis of a Scramjet Combustor, *T. M. Abdel-Salam, S. N.Tiwari*

1:50 Experimental & Numerical Investigations of Air Flow Regimes in Operating Theatres, *R. Kameel, E. E. Khalil*

2:15 Three Dimensional Numerical Study and Analysis of Cylindrical Assemblies Trees, *A. M. Al-Mogbel*

3:50 Simulation of Free-Surface Flow in Curved Channels with Velocity-Pressure-Free Surface Correction, *W. Z. Lu, W. S. Zhang, C. Z. Cui, A. Y. T. Leung, S.M. Lo*

Advances in Three Dimensional Flow Modeling II

Organizer: E. E. Khalil
Session: M4E, Mon., June 24; 3:30-5:35 pm
Room: SQ 236
Chair: M. Prek

3:30 Three-Dimensional Numerical Simulation of the Human Body Heat Loss in Surgical Operating Theatre, *R. Kameel, E. E. Khalil*

3:55 Computations of Air Flow Regimes in Air Conditioned Operating Theatres, *R. Kameel, E. E. Khalil*

4:20 Effect of Pilot Energy on the Combustion of Hydrocarbon Fuels in Scramjet Engines, *A. A. Taha, S. N. Tiwari, T. O. Mohieldin*

4:45 Modeling Self-Similarity in Turbulent Velocity Fluctuations, *M. Prek*

5:10 Numerical Computations of Relative Humidity in Operating Theatres and Its Experimental Verifications, *R. Kameel, E. E. Khalil*

Viscoelasticity in Composites I
In honor of R. A. Schapery

Organizer: D. H. Allen
Session: M3I, Mon., June 24, 1:00-3:05 pm
Room: DB, Rear Aud.
Chair: J. Weitsman

1:00 Size Effects in Sea Ice Fracture and Triggering of Avalanches, *Z. P. Bazant*

1:25 The Viscoelastic Fracture and Indentation of Sea Ice, *J. P. Dempsey*

1:50 Dynamic Fracture in a Linear Viscoelastic Body, *J. R. Walton*

2:15 Elastothermodynamic Analysis of a Griffith Crack, *V. Kinra, J. E. Bishop*

2:40 Analysis of Viscoelastic Microcracking in a Rubber-Toughened Composite, *R. T. Bocchieri*

Viscoelasticity in Composites II
In honor of R. A. Schapery

Organizer: D. H. Allen
Session: M4I, Mon., June 24, 3:30-6:25 pm
Room: DB, Rear Aud.
Chair: R. Kim

3:30 Stress Relaxation in Prestressed Composite Laminates, *A. P. Suvorov, G. J. Dvorak*

3:55 Time-Temperature Superposition of Strain Components in Asphalt Concrete, *C. W. Schwartz, J. Uzan, N. H. Gibson, M. W. Witczak*

4:20 Multiscale Representations of Lattice Materials, *P.-G. Martinsson, I. Babuska, G. J. Rodin*

4:45 The Time-Dependent Torque and Normal Force Responses of Polymer Glasses, *G. B. McKenna*

5:10 The Non-Linear and Time-Dependent Behavior of Graphite Fiber Strand/Urethane Resin Composite, *Y. J. Weitsman*

5:35 Static and Dynamic Measurements of the Bulk Material Properties of Elastomers and Gels, *J.-H. Yu, D. A. Dillard*

6:00 Micromechanical Models for the Nonlinear Viscoelastic Behavior of Pultruded Composites, *R. M. Haj-Ali, A. H. Muliana*

Viscoelasticity in Composites III
In honor of R. A. Schapery

Organizer: D. H. Allen
Session: T3I, Tues., June 25, 1:00-3:05 pm
Room: DB, Rear Aud.
Chair: J. Walton

1:00 Strain Rate Effect on Compressive and Shear Strengths of Polymeric Composites, *C. T. Sun, J. L. Tsai*

1:25 High-Temperature Mechanics of Thermal Oxidation, Degradation and Damage in Polymer-Matrix Composites, *S. S. Wang, X. H. Chen*

1:50 Characterization of Asphalt-Aggregate Mixtures in Tension Using Visco-Elasto-Plastic Continuum Damage Model, *Y. R. Kim, G. Chehab, R. A. Schapery, M. W. Witczak, R. Bonaquist*

2:15 Modeling of Debond Growth Along a Viscoelastic Adhesive Interface Exposed to Aggressive Environments, *S. Roy, F.-W. Shiue, S. J. Park, K. M. Liechti*

2:40 A Multiscale Continuum Mechanics Model for Predicting Damage Evolution in Laminated Composites, *D. H. Allen*

Advances in Composite Materials I
In Honor of G. J. Dvorak

Organizers: Z. Bazant, S. Torquato, R. M. Christensen
Session: M3J, Mon., June 24, 1:00-3:05 pm
Room: DB, Rm D
Chair: S. Torquato

1:00 Failure Plane Orientations For Fiber Composites, *R. M. Christensen, S. J. Deteresa*

1:25 On The Spallation of Graded Coatings, *F. Erdogan*

1:50 Computational and Analytical Approaches to Scaling in Solid Mechanics, *Z. P. Bazant*

2:15 Constitutive Modelling of Composites and Laminates Based on Homogenization and Parameter Identification, *G. Maier, G. Bolzon, A. Corigliano*

2:40 The Saint-Venant Torsion of a Circular Rod Consisting of a Composite Cylinder Assemblage, *Y. Benveniste, T. Chen*

Advances in Composite Materials II
In Honor of G. J. Dvorak

Organizers: Z. Bazant, S. Torquato, R. M. Christensen
Session: M4J, Mon., June 24, 3:30-5:35 pm
Room: DB, Rm D
Chair: Z. P. Bazant

3:30 Actuated Composite Truss Plates, *N. Wicks, J. W. Hutchinson*

3:55 Maximally Random Jammed State of Particle Packings, *S. Torquato*

4:20 Elastically Optimal Microstructures in the High-Porosity Regime, *B. Bourdin, R. V. Kohn*

4:45 Field Fluctuations and Macroscopic Properties in Nonlinear Composites, *P. P. Castaneda*

5:10 Inelastic Response of Random Fibrous Composites, *M. Sejnoha, J. Sejnoha, M. Zeman*

Advances in Composite Materials III
In Honor of G. J. Dvorak

Organizers: Z. Bazant, S. Torquato, R. M. Christensen
Session: T3J, Tues., June 25, 1:00-3:05 pm
Room: DB, Rm D
Chair: F. Erdogan

1:00 Scale-dependence in Nickel Alloys, *N. A. Fleck, J. R. Willis*

1:25 A Comparison of Nonlocal Continuum and Discrete Dislocation Predictions for a Composite Material, *E. Bittencourt, A. Needleman, M.E. Gurtin, E. Van der Giessen*

1:50 Debonding of Short Fibres Among Particulates in a Metal Matrix Composite, *V. Tvergaard*

2:15 Thermodynamics of Damage and Damage Evolution, *D. Krajcinovic*

2:40 Nonlinear Multiscale Material Modeling: From Periodic Homogenization to Eshelby Based Mean Field Methods, *J. L. Chaboche, N. Carrere, P. Kanoute*

Advances in Composite Materials IV
In Honor of G. J. Dvorak

Organizers: Z. Bazant, S. Torquato, R. M. Christensen
Session: T4J, Tues., June 25, 3:30-5:35 pm
Room: DB, Rm D
Chair: R. M. Christensen

3:30 Dynamic Response of Bulk Amorphous Metal Rods Reinforced with Refractory Metal Wires, *R. J. Clifton, D. Steingart*

3:55 The Incompressible Limit in Linear Anisotropic Elasticity, with Applications to Surface Waves and Elastostatics, *M. Destrade, P. A. Martin, T. C. T. Ting*

4:20 Nonlocal Dispersive Model For Wave Propagation In Heterogeneous Media, *J. Fish, W. Chen, G. Nagai*

4:45 Generalized Hashin-Shtrikman Variational Principles, *P. Prochazka*

5:10 Scale and Boundary Conditions Effects on Elastic Moduli of Composites with Imperfect Interfaces, *J. D. Struble, I. Jasiuk*

Low Velocity Impacts I
Symposium on Impact on Composites

Organizer: S. Abrate
Session: M3K, Mon., June 25, 1:00-2:40 pm
Room: SQ 341
Chairs: M. H. Fatt, S. Abrate

1:00 Low-Speed Impact Damage Tolerance of Anisotropic Composite Plates, *D. R. Ambur, J. H. Starnes, Jr.*

1:25 Influence of the Laminate Thickness in Low Velocity Impact Behavior of Composite Material Plate, *G. Belingardi, R. Vadori*

1:50 Single and Repeated Low Velocity Impact Studies on Stitched Woven s2-glass/sc15 Epoxy Composites, *M. V. Hosur, M. R. Karim*

2:15 Simulation of Structure Submitted to Drop-Test, *V. Tita, J. de Carvalho*

Low Velocity Impacts II
Symposium on Impact on Composites

Organizer: S. Abrate
Session: M4K, Mon., June 25, 3:30-6:00 pm
Room: SQ 341
Chairs: R. Mines, M. Hosur

3:30 Modelling Soft Body Impact on Composite Structures, *A. F. Johnson, M. Holzapfel*

3:55 Carbon, Polyethylene and PBO Hybrid Fibre Composites for Structural Lightweight Armour, *F. Larsson, L. Svensson*

4:20 Initiation and Propagation of Delamination in Thick-Section Composites Under Dynamic Loading, *B. Chottopadhyay, B. A. Gama, J. W. Gillespie Jr.*

4:45 Impact Design of the Front Structure of a High Speed Train Made by Composite Material, *G. Belingardi, M. P. Cavatorta, R. Duella*

5:10 Delamination and Dynamic Response of Through-Thickness Reinforced Delaminated Composites, *R. Massabo, L. Brandinelli*

5:35 Contact Between a Cylindrical Indenter and a Sandwich Beam with Functionally Graded Core, *N. A. Apetre, B. V. Sankar*

Impacts on Sandwich Structures and Fiber-Metal Laminates
Symposium on Impact on Composites

Organizer: S. Abrate
Session: T3K, Tues., June 26, 1:00-3:05 pm
Room: SQ 341
Chairs: R. Massabo, A. Johnson

1:00 Impact Behaviour of Pre-Stressed Polymer Composite Sandwich Beams, *R. A. W. Mines, Q. M. Li, R. Birch, T. Muenz, K. Schweizerhopf*

1:25 Numerical Modeling of Impact Damaged Sandwich Composites Subjected to Compression After Impact Loading, *Y. Hwang, T. Lacy*

1:50 A Study of Sandwich Plates Under Explosive Loading, *Z. Xue, J. W. Hutchinson*

2:15 Ballistic Impact of Fiber-Metal Laminates, *M. S. H. Fatt, C. Lin*

2:40 Modeling the Interfacial Fracture of a Sandwiched Structure due to Cavitation in a Ductile, Adhesive Layer, *S. Zhang, K. J. Hsia, A. J. Pearlstein*

Dynamic Properties of Composite Materials and Ceramics
Symposium on Impact on Composites

Organizer: S. Abrate
Session: T4K, Tues., June 26, 3:30-6:00 pm
Room: SQ 341
Chairs: C. Navarro, C. Conley

3:30 Shock Response of a Glass-Fiber-Reinforced Polymer Composite, *D. P. Dandekar, C. A. Hall, L. C. Chhabildas, W.D. Reinhart*

3:55 The Limits of Classic Split Hopkinson Pressure Bar Data Reductions, *S. Lopatnikov, B. Gama, J. Gillespie*

4:20 Non-equilibrium Dynamic Deformation and Energy Absorption of Metal Foams, *S. Lopatnikov, B. Gama, C. Krauthauser, J. Haque, J. Gillespie, I. Hall, M. Guden*

4:45 The Ballistic Damage Mechanisms and Their Sequence in Confined Alumina Tiles, *D. Sherman*

5:10 Experimental Studies Using Hopkinson Tensile Bars of Damage Mechanisms in Reinforced Carbon Fiber Used on Multihull Race Sailboats, *L. Gornet, A. Neme, G. Ollier*

5:35 Low Temperature Effects on G30-500/EH-80 Graphite/Epoxy Composite Material Properties at High Strain Rates, *S. Song, J. R. Vinson*

Impact Damage
Symposium on Impact on Composites

Organizer: S. Abrate
Session: W3K, Wed., June 26, 1:00-3:05 pm
Room: SQ 341
Chairs: K. Lyle, G. Belingardi

1:00 Fracture Prediction of 3D C/C Material Under Impact, *O. Allix, J. Sen-Gupta*

1:25 Time Dependent Fracture Processes in Composites: Modelling and Identification of interface Behaviour, *A. Corigliano, A. Pandolfi*

1:50 Nonlinear Dynamic Behavior of Parachute Static Lines, *S. Abrate, R. Dooley, R. Kaste, G. Thibault, W. Millette*

2:15 The Lyapunov Exponents as a Quantitative Criterion for the Dynamic Buckling of Composite Plates, *R. Gilat, J. Aboudi*

2:40 Ballistic Impact on Brittle Composites: Shear-Plugging Phenomenon, *B. Chaitanya, K. Reddy, P. Shrirao, N. K. Naik*

Ballistic Impacts
Symposium on Impact on Composites

Organizer: S. Abrate
Session: W4K, Wed., June 26, 3:30-5:35 pm
Room: SQ 341/45
Chairs: C. T. Sun, A. G. Caliskan

3:30 Numerical Modelling of the Impact Behaviour of New Particulate Loaded Composite Materials, *A. Arias, R. Zaera, J. López-Puente, C. Navarro*

3:55 Ballistic Impact into Fabric and Compliant Laminates, *B. A. Cheeseman, T. A. Bogetti, C. P. R. Hoppel*

4:20 Ballistic Impact of VARTM processed Carbon Epoxy Composites, *U. K. Vaidya, C. Ulven, M. Hosur*

4:45 Ballistic Behaviour of Hemp Fabric Reinforced Polypropylene Composites, *P. Wambua, I. Verpoest*

5:10 Projectile Impact on FRP Laminates, *H. M. Wen*

Crash Impact and Blast Loading
Symposium on Impact on Composites

Organizer: S. Abrate
Session: R3K, Thurs., June 27, 1:00-3:05 pm
Room: SQ 341
Chairs: S. Schonfelt, A. Corigliano

1:00 Correlation of Full-Scale Crash Simulations with Test Results, *K. H. Lyle, L. E. Jones, A. E. Stockwell*

1:25 Finite Element Analysis of Crush in Carbon Fiber Composites for Vehicle Structures, *A. G. Caliskan*

1:50 An Embedded-Tow Shell Model for Crush Simulation of a Textile Composite Tube, *C.-K. Kok, R. C. Averill*

2:15 Modeling and Analysis of Transient Delamination in a Layered Composite Laminate Panel Subjected to Explosive Blast, *A. D. Gupta*

2:40 Characterization of Air Blast-Loaded FRP Composites, *C. H. Conley, F. H. Gregory*

Impact on Composites and Graded Materials
Symposium on Impact on Composites

Organizer: S. Abrate
Session: R4K, Thurs., June 27, 3:30-5:35 pm
Room: SQ 341
Chairs: R. C. Averill, B. A. Cheeseman

3:30 Damage Mechanisms and Energy Absorption of Plain Weave S-2 Glass/SC-15 Composites Under Quasi-Static Punch-Shear and Low Velocity Impact Loading, *B. A. Gamal, B. Chottopadhyay, J. W. Gillespie Jr.*

3:55 Smart Fins - Actuation of Laminated Composite Plates by Anisotropic Piezoelectric Layers, *O. Rabinovitch, J. R. Vinson*

4:20 Wave Propagation in Functionally Graded Materials, *S. Abrate*

4:45 Optimal Design of a Functionally Graded Elastic Strip Subjected to Transient Loading, *A. P. Velo, G. A. Gazonas, M. J. Scheidler*

5:10 Ground Impact of a Sandwich Plate, *V. Perel, A. Palazotto*

Mechanical Properties of the Thin-Films and MEMS Materials

Organizers: H. D. Espinosa, R. Ballarini, W. G. Knauss
Session: M3L, Mon., June 24, 1:00-3:05 pm
Room: Torg 3100
Chairs: R. Ballarini, W. O. Soboyejo

1:00 CGS Interferometry Applied to the Study of Large Deformations and Curvature Instability Regimes of Si Substrates with Thin Films, *T. S. Park, S. Suresh, A. J. Rosakis, L. B. Freund*

1:25 Nanoindentation Strain Effect on Photoemission of Self-Assembled Quantum Dot Arrays, *H. T. Johnson, A. F. Bower, B. Goldberg*

1:50 Spatial Stiffness Variations in Polysilicon by Atomic Force Acoustic Microscopy, *J. A. Turner, R. Nilchiani*

2:15 Fracture, Fatigue and Strength of Silicon and Silicon Carbide MEMS, *R. Ballarini*

2:40 Multi-Range Nanoprobe for Mechanical Properties Testing, *A. Daugela, O. L. Warren, E. Cyrankowski, T.J. Wyrobek*

Computational Modeling of MEMS

Organizers: H. D. Espinosa, R. Ballarini, W. G. Knauss
Session: M4L, Mon., June 24, 3:30-6:00 pm
Room: Torg 3100
Chairs: N. A. Patankar, R. A. Radovitzky

3:30 Computational Techniques for Sub-Micron/Nanoscale Fluid Dynamics, *N. A. Patankar*

3:55 Computational Methods for Electrostatic MEMS, *N. R. Aluru, G. Li*

4:20 Compliant Micro-Mechanisms with Distributed Compliance, *L. Yin, N. Mankame, G. K. Ananthasuresh*

4:45 Multi-Scale Analysis of Au/Si MEMS Structures, *K. Gall, M. L. Dunn, J. Diao, B. Corff*

5:10 Mechanical Characterization of Microfabricated Elastomeric Membranes, *K.-K. Liu, F.-G. Tseng*

5:35 Application of Asymptotic Expansion Homogenization to Atomic Scale, *S. Namilae, N. Chandra*

Design of MEMS

Organizers: H. D. Espinosa, R. Ballarini, W. G. Knauss
Session: T3L, Tues., June 25, 1:00-3:05 pm
Room: Torg 3100
Chairs: T. Saif, H. D. Espinosa

1:00 Modeling and Experiments of a Bi-Stable MEMS Actuated by Radiation Pressure, *T. Saif, M. Sulfridge, N. Miller, K. Ohara*

1:25 Indentation of Mechanical Properties of Ultra-Nano-Crystalline-Diamond, *H. D. Espinosa, B. Prorok, O. Auciello*

1:50 Experimental Investigations of MEMS Configurations, *W. G. Knauss*

2:15 On the Use of Self-Assembled Monolayers for the Suppression of Fatigue Damage Accumulation in Polycrystalline Silicon Thin Films, *C. L. Muhlstein, W. R. Ashurst, E. A. Stach, R. Maboudian, R. O. Ritchie*

2:40 Coupled ab initio and Finite Element Modeling of Nanoindentation, *C. R. Krenn, D. C. Chrzan, J. W. Morris, Jr.*

Computational Approaches for the Modeling of Nanodevices

Organizers: H. D. Espinosa, R. Ballarini, W. G. Knauss
Session: T4L, Tues., June 25, 3:30-6:00 pm
Room: Torg 3100
Chair: H. D. Espinosa, B. I. Yakobson

3:30 Nanoscale Mechanics of Fullerene Tubes and Structures, *B. I. Yakobson, Y. Zhao, L. S. Couchman*

4:20 Atomistic-Based Finite Deformation Continuum Analysis of Carbon Nanotubes, *M. Arroyo, T. Belytschko*

4:45 Equivalent Continuum for Dynamically Deforming Atomistic Particle Systems, *M. Zhou, D. L. McDowell*

5:10 Self Excitation and Frequency Locking of NEMS Oscillators, *M. Zalalutdinov, L. Sekaric, A. T. Zehnder, H. G. Craighead, J. M. Parpia*

5:35 Stress at the Atomic Level, *J. M. Rickman, T. J. Delph*

Mechanics of Nanomaterials and Nanocomposites

Organizers: H. D. Espinosa, R. Ballarini, W. G. Knauss
Session: W3L, Wed., June 26, 1:00-2:40 pm
Room: Torg 3100
Chairs: M. Walter, K. Gall

1:00 Molecular Dynamics Investigation of the Fracture Behavior of Nanocrystalline Fe, *A. Latapie, D. Farkas*

1:25 Shape Memory Polymer Based Nano-Reinforced Composites, *K. Gall, M. L. Dunn, Y. Liu*

1:50 Fracture of Polystyrene/Clay and Polystyrene/Nanoporous Silica Nanocomposites, *P. Sholapurmath, M. E. Walter*

2:15 Interfacial Characteristic of Carbon Nanotube-Polystyrene Composite System, *K. Liao, S. Li, H. C. Yeo*

Scale Effects in Plasticity and Fracture

Organizers: H. D. Espinosa, R. Ballarini, W. G. Knauss
Session: W4L, Wed., June 26, 3:30-5:35 pm
Room: Torg 3100
Chairs: S. Krishnaswamy, K. Garikipati

3:30 Size Effects on the Plasticity and Fracture of Freestanding Gold Thin Films, *H. D. Espinosa, B. C. Prorok, M. Fischer*

3:55 Photo-Acoustic Characterization of Mechanical Properties and Residual Stresses in Thin-Film MEMS Structures, *C. Hernandez, F. Zhang, S. Krishnaswamy*

4:20 Plastic Slip Gradient-Induced Lattice Rotation at Submicron and Nanometer Scales, *K. Garikipati*

4:45 Atomistic Studies of Crack Propogation in Nanocrystalline Ni, *D. Farkas, H. V. Swygenhoven, P. M. Derlet*

5:10 Molecular Dynamics Studies of Phase-Transitions and Plasticity in Nano-Scale Materials, *P. Lomdahl*

5:35 Glass-Modified Waves for Measuring Adhesion of Ultrathin Layers and Multilayers, *V. Gupta, V. Kireev*

Nanotribology/Nanomachining

Organizers: H. D. Espinosa, R. Ballarini, W. G. Knauss
Session: R3L, Thurs., June 27, 1:00-3:05 pm
Room: Torg 3100
Chairs: A. F. Bastawros, G. J. Molina

1:00 Molecular Dynamic Simulation for 3-D Nanometric Cutting Processes, *Y. Kim, Y. Lee, C. Kim*

1:25 Triboemission of Charged Particles and Nanotribology, *G. J. Molina, M. J. Furey, C. Kajdas*

1:50 Material Removal Mechanisms in Micro and Nano-Machining, *A. F. Bastawros, W. Che, A. Chandra*

2:15 A Coordinated Theoretical and Experimental Approach for Large-Scale Simulation of Nanoindentation, *H.-K. Lee, C. J. Kim, A. Mal*

2:40 Acoustic Measurements for Nanomechanical Test Instruments, *A. Daugela*

Mechanics of Nanostructures

Organizers: H. D. Espinosa, R. Ballarini, W. G. Knauss
Session: R4L Thurs., June 27, 3:30-6:00 pm
Room: Torg 3100
Chairs: A. A. Spector, R. A. Radovitzky

3:30 A Numerical Approach for the Design of Nanomechanical Biodetectors, *R. A. Radovitzky, M. Paul*

3:55 Cochlear Outer Hair Cell: A Biological Piezoelectric Actuator, *A. A. Spector, R. P. Jean*

4:20 Inorganic Nanotubes and Inorganic Fullerene-Like Materials; From Concept to Applications, *R. Tenne*

4:45 Stuffed Carbon Nanotube Materials: Production and Properties, *H. Shinohara*

5:10 Mechanical Modeling of Finite Deformation of Fullerene Balls, Graphene Plate, and Carbon Nanotubes, *T. Xiao, X. J. Xu, K. Liao*

5:35 Continuum Models and Fracture of Nanotubes, *T. Belytschko, M. Arroyo, S. P. Xiao*

Optical Methods I

In Honor of
James Dally

Organizers: W. L. Fourney
Session: M3M, Mon. June 24, 1:00-3:05 pm
Room: SQ 232
Chair: R. J. Sanford

Opening Remarks: W.L. Fourney

1:00 Real-time Full-field Optical Measurement Methods for Experimental Mechanics, *Y. Morimoto, M. Fujigaki, S. Yoneyama*

1:25 Observations on Crack Growth from Frozen Stress Models of Complex Shapes, *C. W. Smith*

1:50 Measurement on the Acoustoelastic Effect of Lamb Waves Using Laser Ultrasound Technique, *C. H. Yang, Y. F. Tseng, Y-M. Chen*

2:15 Thermoelastically-measured Isopachics and BEM for Inverse Stress Analysis on and Adjacent to Loaded and Traction-free Boundaries, *Y. Y. Ni, R. E. Rowlands*

2:40 Experimental Verification of Moiré Hole Drilling to Obtain Material Elastic Constants and Residual Stresses, *J. F. Cardenas-Garcia, B. Han*

Optical Methods II

In Honor of
James Dally

Organizer: W. L. Fourney
Session: M4M, Mon., June 24, 3:30-6:00 pm
Room: SQ 232
Chair: R. Bonenberger

3:30 A Mathematical Model for Random Bundle Illumination in Electronic Holography, *C. A. Sciammarella, F. M. Scammarella*

3:55 Photoelastic Analysis of Reinforcements of Plates with Superficial Defects, *J. L. F. Freire, R. D. Vieira, A. C. Souza, J. C. Diniz*

4:20 Obtaining Full Field Subsurface Rayleigh Wave Displacements From Surface Measurements, *J. F. Cardenas-Garcia, W. H. Wilson*

4:45 Recent Advances in Computer Vision for Surface Deformation, *M. A. Sutton, H. S. Schreier, P. Cheng, N. Li*

5:10 Electron-Beam Moiré: The Technique and Its Application to Advanced Packaging, *E. S. Drexler*

5:35 Inverse Problems in Experimental Mechanics: Whole-field Data, *J. F. Doyle*

Dynamic Fracture I

In Honor of
James Dally

Organizer: W. L. Fourney
Session: T3M, Tues., June 25, 1:00-3:05 pm
Room: SQ 232
Chair: A. Shukla

1:00 Dynamic Failure of Brittle-Ductile Laminates, *R. P. Singh, V. Parameswaran, T. Nakamura*

1:25 Dynamic Behavior of Composite Materials, *I. M. Daniel*

1:50 Failure of Unidirectional Composites Under Dynamic Transverse Loading, *M. Vural, G. Ravichandran*

2:15 Mechanisms of Deformation and Fracture of NACRE, *F. Barthelat, H. D. Espinosa*

2:40 Dynamic Crack Growth in Functionally Graded Syntactic Epoxy Foams, *H. V. Tippur, M. A. El-Hadek*

Dynamic Fracture II

In Honor of
James Dally

Organizer: W. L. Fourney
Session: T4M, Tues., June 25, 3:30-5:35 pm
Room: SQ 232
Chair: W. L. Fourney

3:30 High Speed, Two-dimensional Infrared Observations of Transient Temperature Vortical Microstructures in Solids during Adiabatic Shear Banding, *A. J. Rosakis, G. Ravichandran, P. R. Guduru*

3:55 Direct Observation of High-Velocity Impact and Penetration in Ceramic Targets, *S. Nemat-Nasser, S. Sarva, J. Isaacs*

4:20 CTOA as a Dynamic Fracture Criterion, *M. T. Kokaly, A. S. Kobayashi*

4:45 Multiple Impact Penetration and the Effect of Induced Damage on the Constitutive Behavior of Concrete and Granite, *J. T. Gomez, A. Shukla*

5:10 The Use of Fracture Mechanics and Wave Propagation in Precise Initiation Blasting, *H. P. Rossmanith*

Micromechanics

In Honor of
James Dally

Organizer: W. L. Fourney
Session: W3M, Wed., June 26, 1:00-3:30 pm
Room: SQ 232
Chair: B. Han

1:00 The Read-Dally Thin-Film Tensile Specimen, *W. N. Sharpe, Jr.*

1:25 Progress in Microtensile Testing, *D. T. Read*

1:50 Silicon Piezoresistive Stress Sensors and their Application in Electronic Packaging, *J. C. Suhling, R. C. Jaeger*

2:15 Applications of Nano/Micro Experimental Mechanics Technique Using Random Speckles, *F. P. Chiang*

2:40 Extension of Moiré Interferometry into Micromechanics, *B. Han*

3:05 A Novel Wafer-Level Test for Investigating Plasticity and Fracture of Freestanding Thin Films and MEMS Materials, *H. D. Espinosa, B. C. Prorok, M. Fischer*

Education in Experimental Mechanics

In Honor of
James Dally

Organizer: W. L. Fourney
Session: W4M, Wed., June 26, 3:30-5:35 pm
Room: SQ 232
Chair: H. Bruck

3:30 Using LEGO Bricks and ROBOLAB to Teaching Engineering Students, *E. L. Wang*

3:55 Learning by Doing: Hands-on Learning Pervades the Integrated Teaching and Learning Program, *J. F. Sullivan, L. E. Carlson*

4:20 Engineering Design and Build Experience, *D. N. Rocheleau*

4:45 Integration of Statics and Strength of Materials Curriculum with an Emphasis on Design, *H. A. Bruck, D. K. Anand, W. L. Fourney, P. C. Chang, J. W. Dally*

5:10 The History of Experimental Mechanics Education - B.D. and A.D. (Before Dally and After Dally), *C. E. Taylor*

Instability in Solids and Structures I

Sponsored by
ASME/AMD Technical Committee
Instability in Solids and Structures

Organizers: S. Kyriakides, E. Corona
Session: M3N, Mon., June 24, 1:00-3:05 pm
Room: SQ 345
Chairs: E. Corona, A. F. Bastawros

1:00 Macroscopic Shear Response of Porous Materials *A. F. Bastawros, Y. Guo, A. Chandra*

1:25 A Study of the Evolution of the Biaxial Deformation Patterns on Circular Honeycomb Based on an Energy Approach, *A. M. Cuitiño, S. F. Zheng*

1:50 Dynamic Properties of Aluminum Foam: Measurements and Modeling, *J. J. Harrigan, P. J. Tan, S. R. Reid*

2:15 On the Axisymmetric Progressive Crushing of Circular Tubes Under Axial Compression, *F. C. Bardi, H. D. Yun, S. Kyriakides*

2:40 The Influence of Material Response on the Stability Behaviour of Finitely Deformed Solids, *F. Greco, A. Grimaldi, R. Luciano*

Instability in Solids and Structures II

Sponsored by
ASME/AMD Technical Committee
Instability in Solids and Structures

Organizers: S. Kyriakides, E. Corona
Session: M4N, Mon., June 24, 3:30-5:35 pm
Room: SQ 345
Chairs: J. H. Starnes, Jr., G. Kardomateas

3:30 In-Plane and Lateral Buckling, Postbuckling and Imperfection Sensitivity of Arches, *E. Byskov, J. Kloster, M. Ostergaard, L. P. Mikkelsen*

3:55 Effects of Imperfections on the Buckling Response and Failure of Composite Shells, *J. H. Starnes, Jr., M. W. Hilburger*

4:20 Buckling Behavior of Long Anisotropic Plates Restrained Against Thermal Expansion and Contraction, *M. P. Nemeth*

4:45 Buckling of Long Sandwich Cylindrical Shells Under Pressure, *G. A. Kardomateas, G. J. Simitses*

5:10 Nonlinear Response of Fuselage Panels with Cracks and Subjected to Combined Loads, *R. D. Young, C. A. Rose, J. H. Starnes, Jr.*

Instability in Solids and Structures III

Sponsored by
ASME/AMD Technical Committee
Instability in Solids and Structures

Organizers: S. Kyriakides, E. Corona
Session: T3N, Tues., June 25, 1:00-3:05 pm
Room: SQ 345
Chairs: K. Neale, E. Fried

1:00 Onset-of-Failure Surfaces in Periodic Solids-Theory, *N. Triantafyllidis*

1:25 Onset-of-Failure Surfaces in Periodic Solids-Applications, *N. Triantafyllidis*

1:50 Effects of Texture Gradients on Shear Band Localization in FCC Polycrystals Under Plane Strain Tension, *K. Inal, K. W. Neale*

2:15 Shear Band Instabilities in Metal Powder Compaction, *P. Redanz, V. Tvergaard*

2:40 Shear Band Development in a Bulk Metallic Glass Under Dynamic Loading, *T. Jiao, K. T. Ramesh, T. Hufnagel, C. Fan*

Instability in Solids and Structures IV

Sponsored by
ASME/AMD Technical Committee
Instability in Solids and Structures

Organizers: S. Kyriakides, E. Corona
Session: T4N, Tues., June 25, 3:30-5:35 pm
Room: SQ 345
Chairs: E. Byskov, N. Triantafyllidis

3:30 Necking Instabilities in Electromagnetically Formed Rings *J. Waldenmyer, N. Triantafyllidis*

3:55 Buckling of a Column on an Elastic-Plastic Foundation Under Cyclic Loading, *E. Corona, S. Yin*

4:20 Thermally Induced Displacive Transformations in Bi-Atomic Crystals, *R. S. Elliot, J. A. Shaw, N. Triantafyllidis*

4:45 Investigations of a Sharp-Interface Theory for Hydrogels Using the Extended Finite Element Method, *J. E. Dolbow, E. Fried, H. Ji*

5:10 Solitary Wave Interaction in a Beam on a Nonlinear Elastic Foundation, *C. D. Coman, K. M. Wadee, A. P. Bassom*

Plasticity and Cyclic Plasticity

In Honor of Z. Mroz

Organizers: G. Z. Voyiadjis
Session: M3O, Mon., June 24, 1:00-3:00 pm
Room: DB, Rm F
Chairs: G. Z. Voyiadjis, P. Perzyna

1:00 Numerical Investigation of Macrocrack Propagation along a Bimaterial Interface in Adiabatic Processes, *W. Dornowski, P. Perzyna*

1:25 Energy Balance and Identification of Hardening Moduli in Plastic Deformation Processes, *Z. Mroz, W. Oliferuk*

1:50 Modeling of Temperature Dependency of Ratchetting Deformation Behavior in Ferritic Steel, *M. Yaguchi, Y. Takahashi*

2:15 Inverse Approach to Identification of Material Parameters of Cyclic Elasto-Plasticity for Component Layers of a Bimetallic Sheet, *F. Yoshida, M. Urabe, R. Hino, V. V. Toropov*

2:40 Some Critical Experimental Results in Finite Plasticity, *A. S. Khan*

Crystal Plasticity

In Honor of Z. Mroz

Organizers: G. Voyiadjis
Session: M4O, Mon., June 24, 3:30-5:35 pm
Room: DB, Rm F
Chairs: T. Lodygowski, G. Beda

3:30 Crystallographic Texture and Strain Localization in Metals, *K. Kowalczyk*

3:55 Analysis of Serration Characteristics during Serrated Flow of 5000 Series Aluminum, *J. M. Reed, M. E. Walter*

4:20 A Mechanistic Description of Combined Hardening and Size Effects in Crystalline Materials, *J. G. Swadener*

4:45 A Macroscopic Slip Model of Anisotropic Plasticity of Textured Sheet Metals, *W. Tong, N. Zhang*

5:10 Simulation of Welding with Enhanced Models of Thermal Plasmas and Thermo-Mechano-Metallurgical Processes in the Heat Affected Zone, *J. Ronda, H. Murakawa, M. Ushio, G. J. Oliver*

5:35 Elasto-Plasticity of Paper, *J. Castro, M. Ostoja-Starzewski*

Viscoplasticity

In Honor of Z. Mroz

Organizer: G. Z. Voyiadjis
Session: T3O, Tues., June 25, 1:00-3:05 pm
Room: DB, Rm F
Chairs: F. Yoshida, H. W. Haslach

1:00 On Some Applications of Unified Viscoplastic Constitutive Equations, *J.-L. Chaboche, P. Kanouté, P. Paulmier*

1:25 Viscoplastic Model Accounting for the Strength-Differential in Inconel 718, *S. K. Iyer, C. J. Lissenden*

1:50 An Hypoelastic Framework for Integration of Visco-Plasticity and Mixed Hardening Constitutive Laws, *J. P. Ponthot*

2:15 A Time/Space Multiscale Computational Method for (Visco) Plastic Structures with Contacts *P. Ladevze, A. Nouy, H. Bavestrelo*

2:40 Goal-Oriented Control in Space-Time for (Visco)Plasticity with Damage, *K. Runneson*

Gradient Plasticity

In Honor of Z. Mroz

Organizer: G. Z. Voyiadjis
Session: T4O, Tues., June 25, 3:30-6:00 pm
Room: DB, Rm F
Chairs: P. Ladevze, I. Vardoulakis

3:30 Multiple-Scale Damage Mechanisms with Inelastic Behaviour in Composite Materials, *G. Z. Voyiadjis, R. J. Dorgan*

3:55 Numerical Treatment of Plastic Strain Localization Phenomena, *T. Lodygowski, A. Glema, P. Perzyna*

4:20 High Gradient Deformations of Polycrystals-Experimental Investigation, *L. V. Berka*

4:45 The Characteristics of the Solution of Cosserat Plasticity Theory, *G. Chen, G. Baker*

5:10 Achievements in Applied Mesomechanics of Shear Instability and Shear Fracture, *E. S. Dzidowski*

Damage Mechanics I

In Honor of Z. Mroz

Organizer: G. Z. Voyiadjis
Session: W3O, Wed., June 26, 1:00-3:05 pm
Room: DB, Rm F
Chairs: J.-L. Chaboche, T. Belytschko

1:00 A Linked FEM-Damage Percolation Model of Aluminum Alloy Sheet Forming, *Z. T. Chen, N. Cinnotti, M.J. Worswick, A. K. Pilkey, D. Lloyd*

1:25 Anisotropic Damage Model for Brittle Materials with Different Tensile-Compressive Response, *L. Gambarotta, I. Monetto*

1:50 A Physically Motivated Anisotropic Representation of Damage for Ductile Materials, *Y. Hammi, M. F. Horstemeyer, D. J. Bammann*

2:20 Damage Mechanics, *D. Krajcinovic*

2:45 Analytical Solutions for the Cam Clay Model: Drained Loading and Comparisons, *P. Dunja*

Damage Mechanics II

In Honor of Z. Mroz

Organizer: G. Z. Voyiadjis
Session: W4O, Wed., June 26, 3:30-5:35 pm
Room: DB, Rm F
Chairs: D. Krajcinovic, E. T. Camponeschi, Jr.

3:30 Extended Finite Elements for Multiple Crack Growth, *T. Belytschko, E. Budyn*

3:55 Modeling Impact Damage in Laminated Composites with High-Order Cohesive Zone Models, *T. Tippetts, I. Beyerlein, T. Williams*

4:20 A Continuus Damage Mechanics Model for the Pre- and Post - Failure Behaviour of a Compactive Shell-Stone Used for the Restoration of the Zeus Temple in Olympia, *I. Vardoulakis, S. K. Kourkoulis*

4:45 Effect of Particle Density on Fracture of Cementbased Composites: Lattice Analysis and Experiments, *J. G. M. van Mier, A. Meda, G. Lilliu*

5:10 Load-Induced Oriented Damage and Anisotropy of Rock-Like Materials, *A. Litewka, J. Debinski*

Fracture Mechanics

In Honor of Z. Mroz

Organizer: G. Z. Voyiadjis
Session: R3O, Thurs., June 27, 1:00-3:05 pm
Room: DB, Rm F
Chairs: M. Ostoja-Starzewski, J. P. Ponthot

1:00 On Thermoplastic Waves in Solids, *G. Beda*

1:25 A Non-equilibrium Thermodynamics Model for the Crack Propagation Rate, *H. W. Haslach, Jr.*

1:50 Notch Plasticity Influence on Small Fatigue Crack Growth, *L. Wenfong*

2:15 On Solder Mechanics, *Z. Qian*

2:40 Advances in Plasticity for Complex Loading Processes, *R. A. Abirov*

Composite Material Behavior

In Honor of Z. Mroz

Organizer: G. Z. Voyiadjis
Session: R4O, Thurs., 3:30-6:00 pm
Room: DB, Rm F
Chairs: C. J. Lissenden, J. Runneson

3:30 The Plastic Anisotropy Ratio for Rolled Particulate Metal Matrix Composites, *S. K. Kourkoulis*

3:55 On the Moisture Sorption of Composites, *A. Szekeres, A. Pramila*

4:20 Strengthening Mechanism in Ti-6Al-4V/TiC Composites, *A. J. Wagoner Johnson, C. L. Briant, K. S. Kumar, C. W. Bull*

4:45 Micromechanical Modeling of Particle-Debonding Process and its Influence on the Effective Elastoplastic Behavior of Composites, *L. Sun, H. T. Liu, J. M. Ju*

5:10 Short-Term Mechanical Behavior of Biaxially Stressed Wood: Experimental Observations and Constitutive Modeling as an Orthotropic Multi-Surface Elasto-Plastic Material, *P. Helnwein, J. Eberhardsteiner, H. A. Mang*

Magnetoelasticity I

Organizers: Y. Shindo
Session: M3P, Mon. June 24, 1:00-3:05 pm
Room: DB, Exec
Chairs: Y. Shindo, D. J. Hasanyan

1:00 Mechanics and Electrodynamics of New Materials: Magneto-Poro-Elastics (Penetrable Poroelastic Bodies Filled with Ferro-Fluids), *S. Lopatnikov, A. H.-D. Cheng, C. Krauthauser, J. Gillespie*

1:25 Nonlinear Magnetoelasticity of Flat Structures Carrying an Electric Current: Foundation of the Theory and Behavior, *D. J. Hasanyan, L. Librescu, D. R. Ambur*

1:50 Three Dimensional Numerical Simulation of Magnetic Microstructure, *M. Bernadou, S. Depeyre, S. He, P. Meilland*

2:15 A Non-Dilute Microstructural Model for Magnetorhelogical Elastomers, *K. Dutta, J. C. Nadeau*

2:40 Ultrasonic Imaging of Structural Damage using Integrated Sensor Signals, *X. D. Wang, G. L. Huang*

Coupled Problems

Organizer: Y. Shindo
Session: M4P, Mon., June 24, 3:30-6:00 pm
Room: DB, Exec
Chairs: L. Librescu, G.A. Altay

3:30 Finite Element Modelling and Simulation of Magnetostrictive Materials, *J. L. Perez-Aparicio, H. Sosa*

3:55 Mechanics of Cracked Ferromagnetic Plates in a Magnetic Field, *Y. Shindo, K. Horiguchi*

4:20 Constitutive Modeling of Soft Ferromagnetic Materials, *D.-N. Fang, X. Feng, K.-C. Hwang*

4:45 Coupled Structural-Acoustic-Piezoelectric Dynamic Modeling of High-Frequency Undersea Transducers, *R. M. Koch*

5:10 Propagation of Spin Waves in a Periodic Layered Space, *D. J. Hasanyan, S. L. Sahakyan, G. S. Grigoryan*

5:35 Magnetoelastic Vibrations and Stability of Ferromagnetic Plates and Shells, *G. Y. Bagdasaryan, M. A. Mikilyan*

Piezoelectric Fracture and Damage Mechanics

Organizer: Y. Shindo
Session: T3P, Tue, June 25, 1:00-3:05 pm
Room: DB, Exec
Chairs: D. J. Inman, M. Denda

1:00 Electroelastic Fracture Mechanics of Piezoelectric Ceramics, *F. Narita, Y. Shindo*

1:25 Experimental Study of Fatigue and Fracture of Piezoceramics, *D.-N. Fang, C. T. Sun*

1:50 Coupled Electromechanical Fracture of Electroceramics Subjected to Transient Thermal Loads, *B. L. Wang, Y. W. Mai*

2:15 An Exact Solution for Doubly Periodic Cracks in Piezoelectric Materials Under Antiplane Shear, *C. P. Jiang, Z. H. Tong, X. W. Liu*

2:40 The M-Integral Description for Microcrack Damage in Piezoelectric Materials Under Combined Mechanical-Electric Loading, *Y. H. Chen*

Modeling and Simulations for Piezoelectric Material Systems

Organizer: Y. Shindo
Session: T4P, Tues., June 25, 3:30-6:00 pm
Room: DB, Exec
Co-Chairs: C. T. Sun, Y. H.Chen

3:30 Damage Evolution Equation of Piezoelectric Ceramics and its Application to Simplified Analysis of Crack Growth, *M. Mizuno*

3:55 On the Nonlinear Behaviour of Dielectric Cracks in Piezoelectric Media, *X. D. Wang, L. Y. Jiang*

4:20 Two-Dimensional Electromechanical Analysis of Piezoelectric Ceramics, *F. Yang*

4:45 A Mesoscopic Electromechanical Theory of Ferroelectric Films and Ceramics, *J. Li, K. Bhattacharya*

5:10 Eigenvalue Analysis for 2-D Piezoelectric Problems by the Time-Barmonic BEM, *M. Denda, Y. Araki*

5:35 Computation of Electrostatic Fields Around Overlapping Spheres and Cylinders, *D. Palaniappan*

Piezoelectric Buckling, Stability and Vibration

Organizer: Y. Shindo
Session: R3P, Thurs. June 27, 1:00-3:05 pm
Room: DB, Exec
Chairs: T. R. Tauchert, D.-N. Fang

1:00 Enhancement Flutter and Buckling Capacity of Column by Piezoelectric Layers, *Q. Wang*

1:25 Dynamics of a Coated Piezoelectric Composite Bar, *G. A. Altay, M. C. Dökmeci*

1:50 Equations of High-Frequency Vibrations of Porous Piezoelectric Plates, *M. C. Dökmeci, G. A. Altay*

2:15 Computer Simulations and Design Optimizations of Piezoelectric Resonator, *Y. Chen, M. Riegelman, J. Li, M. E. Zaghloul*

2:40 Frequency Stability of Piezoelectric Resonators, *J. S. Yang*

Smart Sensors and Actuators

Organizer: Y. Shindo
Session: R4P, Thurs. 3:30-6:00 pm
Room: DB, Exec
Chairs: M. E. Zaghloul, J. C. Nadeau

3:30 Control of Transient Deformation in a Heated Intelligent Composite Disk, *F. Ashida, T. R. Tauchert, S. Sakata, Y. Yamashita*

3:55 Active Vibration Suppression of a Gossamer Spacecraft, *E. Ruggiero, G. Park, D. J. Inman*

4:20 Micro-Actuators for Structural Control, *B. J. Pokines, R. W. Rietz*

4:45 Formulation of Inertial Sensors Based on the Classical Linear Plate Theory, *B. Sun*

5:10 Effects of Static Electric Field on the Fracture Behavior of Piezoelectric Ceramics, *T.-Y. Zhang*

5:35 Piezoelectric Passive Distributed Controllers for Beam Flexural Vibrations, *U. Andreaus, F. dell'Isola, M. Porfiri*

Solid and Fluid Mechanics Education I

In Honor of R. P. McNitt

Organizer: N.J. Salamon
Session: M3Q, Mon., June 24, 1:00-3:05 pm
Room: DB, Rm C
Chairs: N.J. Salamon, G. Dasgupta

1:00 Teaching Mechanics Then and Learning it Now, *R. P. McNitt*

1:25 The Role of Demonstrations in Mechanics Education: Phenomena Driven by Surface Tension, *J. N. Libii*

1:50 An Active Engagement Pedagogy for Introductory Solid Mechanics, *M. C. Boyce, E. Bamberg, J. S. Sandhu*

2:15 Computer Literacy and Mechanics Education, *S. Abrate*

2:40 A Pilot Module for Web-Based Mechanics Education: Integrating Models and Experiments, *J. E. Dolbow, H. P. Gavin*

Solid and Fluid Mechanics Education II

In Honor of R. P. McNitt

Organizer: N. J. Salamon
Session: M4Q, Mon., June 24, 3:30-6:25 pm
Room: DB, Rm C
Chairs: G. Dasgupta, N. J. Salamon

3:30 Computer Techniques in the Curriculum of Mechanics: Still Time for Changes!, *R. R. Gajewski*

3:55 The Impact of Technology and New Pedagogical Techniques in Mechanical Engineering Program at ITESM - Monterrey, Mexico, *A. Elias-Zuniga*

4:20 Active-Learning Initiatives in Introductory Mechanics Courses, *K. M. Hill*

4:45 Integration of Computer-Aided Engineering into Undergraduate and Graduate Mechanics Curricula, *J. L. Beuth*

5:10 Learning by Undergraduates through Participation in a Research Assistantship, *M. B. Wiley, D. L. Freyberg*

5:35 Design in Mechanics Courses: Trials, Triumphs and Tribulations, *N. J. Salamon, C. J. Lissenden*

6:00 Importance of Automatic Postprocessing of Output Data Using Text Processors in Mechanics Education, *M. Skrinar*

Advances in Computational Mechanics I

In Honor of J. Tinsley Oden

Organizer: L. Demkowicz
Session: M3R, Mon., June 24, 1:00-3:05 pm
Room: SQ, Brush A
Chair: L. Demkowicz

1:00 A Posteriori Finite Element Error Estimation for Hyperbolic Partial Differential Equations, *S, Adjerid, T. C. Massey*

1:25 Shape Function Selection in the Meshless Method, *I. Babuska, U. Banerjee*

1:50 Accuracy vs. Stability in CFD: Artificial vs. Numerical Diffusion, *A. J. Baker, A. Kolesnikov, M. B. Taylor, S. Ericson*

2:15 Nonlinear Micromechanical Analyses of Composites by BEM, *P. K. Banerjee*

2:40 Multiscale Methods in Turbulence: A Variational Approach to Large Eddy Simulation, *T. J. R. Hughes*

Advances in Computational Mechanics II

In Honor of J. Tinsley Oden

Organizer: L. Demkowicz
Session: M4R, Mon., June 24, 3:30-5:35 pm
Room: SQ, Brush A
Chair: S. Wu

3:30 Eulerian Finite Element Methods for Mechanochemical Simulations, *D. J. Benson, I. Do*

3:55 Some Results on the Numerical Analysis of Piezoelectric Thin Shells, *M. Bernadou*

4:20 Symmetric Variational Boundary Element Methods for Interface Problems in Acoustics, *T. Juneja, L. F. Kallivokas, J. Bielak*

4:45 Eigenvalue Evaluation of Symmetric Tridiagonal Matrices - A Unified Approach, *T. R. Chandrupatla*

5:10 Discontinuous and Coupled Continuous/Discontinuous Galerkin Methods for the Shallow Water Equations, *C. Dawson, J. Proft*

Advances in Computational Mechanics III

In Honor of J. Tinsley Oden

Organizer: L. Demkowicz
Session: T3R, Tues., June 24, 1:00-3:05 pm
Room: SQ, Brush A
Chair: M. Bernadou

1:00 Incompressible Media Analysis Using the Method of Finite Spheres and Some Improvements in Efficiency, *S. De, K. J. Bathe*

1:25 Integration of hp-Adaptivity with a Multigrid Solver, *L. Demkowicz, D. Pardo*

1:50 Towards Adaptive Multiscalep Multiphysics Compuatational Framework, *J. Fish*

2:15 A Flexible Parallel Adaptive Discontinuous Galerkin Procedure, *J. E. Flaherty, J.-F. Remacle, M. S. Shephard*

2:40 Some Properties of Kriging Based Meshfree Method, *L. Gu*

Advances in Computational Mechanics IV

In Honor of J. Tinsley Oden

Organizer: L. Demkowicz
Session: T4R, Tues., June 25, 3:30-5:35 pm
Room: SQ, Brush A
Chair: T. R. Chandrupatla

3:30 Hyperelastodynamics, Hamilton's Principle, and Spacetime Discontinuous Galerkin Methods, *R. B. Haber, L. Yin*

3:55 Recent Advances in the Finite Element Method for Incompressible Flow, *J. T. Holdeman*

4:20 High Frequency Dispersive Modeling of Periodic Media, *M. I. Hussein, G. M. Hulbert*

4:45 The Mesoscale Simulation Grain Growth and its Consequences, *D. Kinderlehrer, F. Manolache, I. Livshits, A. Rollett, S. Táasan*

5:10 Integral Representations of Contact Conditions in Computations of Interfacial Phenomena, *T. A. Laursen, M. A. Puso, M. W. Heinstein*

Advances in Computational Mechanics V

In Honor of J. Tinsley Oden

Organizer: L. Demkowicz
Session: W3R, Wed., June 26, 1:00-3:05 pm
Room: SQ, Brush A
Chair: K. Vemaganti

1:00 Effects of Microscale Material Randomness on the Attainment of Optimal Structural Shapes, *T. J. Liszka, M. Ostoja-Starzewski*

1:25 Modeling of a Press-Fit Problem in Computational Biomechanics Using the Fictitious Domain Method, *S.-W. Na, L. Kallivokas, B. Jaramaz*

1:50 A Perfectly Matched Layer Approach to the Nonlinear Shallow Water Equations Models, *I. M. Navon*

2:15 Parallel Adaptive Lagrangian Discontinuous Galerkin Methods, *A. K. Patra*

2:40 Direct Numerical Simulation of Polycrystals, *R. Radovitzky, A. Cuitino*

Advances in Computational Mechanics VI

In Honor of J. Tinsley Oden

Organizer: L. Demkowicz
Session: W4R, Wed., June 26, 3:30-5:35 pm
Room: SQ, Brush A
Chair: T. Liszka

3:30 Multi-Level Models for Multiple Scale Damage Analysis in Composite Materials, *P. Raghavan, P. Eder, S. Ghosh*

3:55 An Unstructured Inverse Design Method for Blade Design, *M. Rahmati*

4:20 Large-Scale Simulations of Stokesian Emulsions, *G. Rodin, J. R. Overfelt*

4:45 Discontinuous Galerkin Methods for PDEs with Higher Order Spatial Derivatives, *C.-W. Shu, J. Yan*

5:10 The Time Dimension: A Unified Theory and Design of Computational Algorithms for Transient Problems, *K. K. Tamma, X. Zhou, R. Kanapady*

Advances in Computational Mechanics VII

In Honor of J. Tinsley Oden

Organizer: L. Demkowicz
Session: R3R, Thurs., June 27, 1:00-3:05 pm
Room: SQ, Brush A
Chair: A. Patra

1:00 Some Basic Problems in Virtual Fabrication, *B. Szabo*

1:25 An Inverse FEM for Application to Structural Health Monitoring, *A. Tessler, J. L. Spangler*

1:50 Goal-Oriented Adaptive Modeling in Computational Mechanics, *K. Vemaganti*

2:15 On Accuracy of Explicit Finite Element Analysis for Structural Dynamics, *S. R. Wu*

2:40 Study of Adaptive Explicit Finite Elements for Crashworthiness Simulations, *S. R. Wu, V. Bostan*

Perturbation Theory and Computations:
A Combined Approach to Mechanics I

In Memory of
J. D. Cole

Organizer: A. K. Kapila
Session: M4F, Mon., June, 24, 3:30-5:35 pm
Room: SQ 234
Chair: A. K. Kapila

3:30 Modeling the Discharge of Alkaline Batteries, *C. P. Please*

3:55 Desorption of Saturated Polymers: Asymptotic and Numerical Results, *D. A. Edwards, R. A. Cairncross*

4:20 Global Analysis - Beyond Asymptotic Methods and Numerical Simulation, *Z. Rusak*

4:45 A Perturbation Based Numerical Method for Solving a Three Dimensional Axisymmetric Indentation Problem, *M. H. Holmes, G. A. Pavliotis*

5:10 Singular Perturbation Problems Arising in Mathematical Finance, *P. W. Duck*

Perturbation Theory and Computations:
A Combined Approach to Mechanics II

In Memory of
J. D. Cole

Organizer: A. K. Kapila
Session: T3F, Tues., June 25, 1:00-3:05 pm
Room: SQ 234
Chair: M. H. Holmes

1:00 Microwave Joining of Two Long Hollow Tubes: An Asymptotic Theory and Numerical Simulation, *G. A. Kriegsmann, J. Luke*

1:25 On the Formation of Curvature Singularities in Free-Surface Flows, *G. Baker*

1:50 A Hybrid Method for Low Reynolds Number Flow Past an Asymmetric Cylindrical Body, *M. C. Kropinski, M. Ward, M. Titcombe*

2:15 Effect of Thermal Nonhomogeneity on the Evolution of Detonation in an Annulus, *D. W. Schwendeman, A. K. Kapila*

2:40 Intermediate Asymptotics for Richards' Equation in a Finite Layer, *T. P. Witelski*

Keynote Session
Compressible Flow with Chemical Reaction I

Organizers: H. Hornung
Session: T2F, Tues., June 25, 9:30-11:45 am
Room: SQ, Brush A
Chair: H. Hornung

9:30 Computational Methods for Hypersonic Flows: Application to Double-Cone Flows, *G.V. Candler, I. Nompelis*

10:15 Effects of Boundary Layers and Wakes on Shocks and Flames, *E. S. Oran*

11:00 Miniaturization of Explosive Technology, *D. S. Stewart*

Keynote Session
Compressible Flow with Chemical Reaction II

Organizer: H. Hornung
Session: W2F, Wed., June 25, 9:30-11:45 am
Room: SQ, Brush A
Chair: H. Hornung

9:30 The Role of Transverse Waves in Gaseous Detonation, *J. E. Shepherd*

10:05 Mechanisms of Detonation Formation, *A. K. Kapila*

11:00 Isolating a Global Mechanism for Self-Initiation of Detonation, *A. Higgins*

Keynote Session
Arterial Flows: In Health and Disease I

Organizers: S. A. Berger
Session: T2G, Tues., June 25, 9:30-11:45 am
Room: SQ 341/45
Chair: S. A. Berger

9:30 The Role of Fluid Mechanics in Healthy and Diseased Arteries, *S. A. Berger, V. Rayz*

10:15 Realistic Modeling of Arterial Hemodynamics from Anatomic and Physiologic Image Data *J. R. Cebral, R. Löhner, O. Soto, P. L. Choyke, P. J. Yim*

11:00 Computational Biomechanics to Guide and Interpret Vascular Biology Experiments, *D. A. Vorp*

Keynote Session
Arterial Flows: In Health and Disease II

Organizer: S. A. Berger
Session: T3G, Tues., June 25, 1:00-3:15 pm
Room: SQ 236
Chair: S. A. Berger

1:00 Correlations Between Fluid Shear Stress or Tissue Tensile Stress and Histological Markers in Advanced Carotid Artery Disease, *A. G. Isasi, H. F. Younis, M. R. Kaazempur-Mofrad, R. C. Chan, R. D. Kamm*

1:45 Hemodynamics Changes by Endoluminal Stents in Treatment of Cerebral Aneurysms, *B. B. Lieber*

2:30 Simulation of Flow in Stented Saccular Aneurysms, *L.-D. Jou*

Keynote Session
Arterial Flows: In Health and Disease III

Organizer: S. A. Berger
Session: W2G, Wed., June 26, 9:30-11:45 am
Room: SQ 341/45
Chair: S. A. Berger

9:30 Flow Disturbance Induced by Endovascular Stents - Whole Vessel and Cellular Considerations, *A. I. Barakat, L. G. Schachter, D. K. Lieu*

10:15 Transitional Flow at the Venous Anastomosis of an Arteriovenous Graft, *F. Loth, T. J. Royston, P. F. Fischer, H. S. Bassiouny*

11:00 Stent Restenosis and Arterial Mechanics, *J. E. Moore Jr., J. L. Berry*

Keynote Session
Arterial Flows: In Health and Disease IV

Organizer: S. A. Berger
Session: W3G, Wed., June 26, 1:00-3:05 pm
Room: SQ 345
Chair: S. A. Berger

1:00 Predicting Outcomes of Cardiovascular Surgery: Mathematical Models and Experimental Validation, *C. A. Taylor*
Contd. on page 37

Mechanics of Liquid-Gas and Liquid-Solid Interfaces I

In Honor of S. H. Davis

Organizers: G. P. Neitzel
Session: T4E, Tues., June 25, 3:30-5:35 pm
Room: SQ 236
Chair: P. H. Steen

3:30 Modeling of Solidification Microstructures, *J.-H. Jeong, N. D. Goldenfeld, J. A. Dantzig*

3:55 Modeling Mushy Layers During Ternary Alloy Solidification, *D. M. Anderson, T. P. Schulze*

4:20 Reactive Wetting and Spreading in Solder Systems, *B. T. Murray, Q. Yang, T. J. Singler, L. Yin, S. J. Meschter*

4:45 Long-Scale Evolution of Thin Films of Molten Metal on a Substrate, *V. S. Ajaev, D. A. Willis*

5:10 A Dimpling Instability in Thin, Axisymmetric Liquid Droplets Heated from Below, *M. K. Smith*

Mechanics of Liquid-Gas and Liquid-Solid Interfaces II

In Honor of S. H. Davis

Organizer: G. P. Neitzel
Session: W3E, Wed., June 26, 1:00-2:40 pm
Room: SQ 236
Chair: J. A. Dantzig

1:00 Contact-Line Dynamics: Recent Developments, *S. H. Davis*

1:25 Contact Line Flow in a Rotating Horizontal Tube, *W. W. Schultz*

1:50 Interface Instability and Capillary Switches, *P. H. Steen, I. D. Gospodinov, C. G. Matalanis*

2:15 Recent Results on Permanent Non-Coalescence and Non-Wetting, *G. P. Neitzel, P. Nagy, P. Dell'Aversana, M. R. Vetrano, J.-C. Chen, C. W. Kuo*

Analysis and Durability of Adhesive Bonds

In Honor of H. Brinson, A. Cardon

Organizers: D. A. Dillard, C. Hiel, L. C. Brinson
Sessopm: T4G, Tues., June 25, 3:30-5:35 pm
Room: DB, Rm C
Chairs: D. A. Dillard, L.C. Brinson

3:30 Durability of Adhesively Bonded Composite Joints: A Review, *G. Verchery, J. Rousseau, X.-J. Gong*

3:55 Thermal Fracture in Functionally Graded Thermal Barrier Coatings due to Time-Dependent Behavior, *S. Rangaraj, K. Kokini*

4:20 Deformation of a Double Bonded Beam Under Three-Point Bending, *Y.-C. Chen*

4:45 Combined Load Testing of PSAs for Joint Design, *J. Hennage, J. W. Grohs, L. D. Mitchell, D. A. Dillard, D. C. Ohanehi*

5:10 A Study of Durability of Pressure Sensitive Adhesive Tapes, *K. Nangkala, J. W. Grohs, D. A. Dillard, D. C. Ohanehi, J. G. Dillard*

Time Dependence in Polymers

In Honor of H. Brinson, A. Cardon

Organizers: D. A. Dillard, C. Hiel, L. C. Brinson
Session: W3F, Wed., June 26, 1:00-3:05 pm
Room: DB, Rm C
Chairs: M. E. Tuttle, L. Nicolais

1:00 Time-Dependent Failure of Polymers - Energy Dependent Methods, *O. S. Brueller*

1:25 High Temperature Time Dependent Modeling of PMCs - Forget About It! IM7/PETI-5 is here!, *W.S. Johnson, W. A. Counts*

1:50 Perspectives on the Durability of Polymeric Materials, *G. B. McKenna*

2:15 Measurement of the Creep/Creep Recovery Response in a Thin Polymeric Film at Finite Strain Levels, *T. Miyazono, M. E. Tuttle*

2:40 Sorption of Water in High Tg Polymers: Analysis of Transport and Interactional Issues, *L. Nicolais, G. Mensitieri, S. Cotugno, P. Musto*

Analysis and Durability of Composites

In Honor of H. Brinson, A. Cardon

Organizers: D. A. Dillard, C. Hiel, L. C. Brinson
Session: W4F, Wed., June 26, 3:30-5:35 pm
Room: DB, Rm C
Chairs: S. S. Wang, H. Brinson

3:30 Long-Term Reliability Analysis of Fiber Composite Structures with Applications to Deep Water Offshore Engineering, *S. S. Wang*

3:55 Prediction of the Strength Evolution of Polymer Based Composite Material Systems, *A. H. Cardon, P. Bouquet*

4:20 The Effects of Loading History on the Fracture Behavior of Rubber-Toughened Epoxy, *D. L. Hunston*

4:45 Time-Dependent Deformation of Stitched T3000 Mat/Urethane IMR Cross-ply Composite Laminates, *Y. Weitsman*

5:10 Viscoelastic and Nanogeometry Effects in Carbon Nanotube-Reinforced Polymers, *L. C. Brinson, F. Fisher*

Session 4: Design and Structural Issues

In Honor of H. Brinson, A. Cardon

Organizers: D. A. Dillard, C. Hiel, L. C. Brinson
Session: R3G, Thurs., June 27, 1:00-2:40 pm
Room: DB, Rm C
Chairs: C. Hiel, H. Brinson

1:00 Design for Durability: Three Examples of Practical Design Approaches for Commercial Composite Structures, *C. Hiel*

1:25 Fatigue Performance of Glass-Reinforced Composite Springs for Automotive Applications, *G. Jeronimidis*

1:50 "Rubber-Band" Behavior of PA Materials, *I. Emri, B. V. Bernstorff*

2:15 Rate Dependent Behavior of Plastic Materials in Crash Simulation, *X. Xiao*

Mechanics of Plasticity I
In honor of Y. Tomita

Organizers: H. M. Zbib, T. Hasebe, Y. Shibutani
Session: T4I, Tues.,June 25, 3:30-5:35 pm
Room: DB, Rear Aud.
Chairs: H. M. Zbib, T. Adachi

3:30 Material Instability in Multi-Mode Inelastic Solids, *H. Petryk*

3:55 Shear Band Initiation Criterion for Materials with Incrementally Nonlinear Constitutive Response, *I. Dobovsek*

4:20 Computational Prediction of Change in Mechanical Function of Bone-Porous Scaffold Structure in Tissue Regeneration Process, *T. Adachi, Y. Tomita*

4:45 An Engineering Model for Damage due to Adiabatic Shear Bands, *S. E. Schoenfeld, T. W. Wright, D. Casem*

5:10 Computational Simulation of Impact Deformation Behavior of TRIP Steel by Dynamic Explicit, *T. Iwamoto, T. Tsuta, S. Kubo*

Mechanics of Plasticity II
In honor of Y. Tomita

Organizers: H. M. Zbib, T. Hasebe, Y. Shibutani
Session: W3I, Wed., June 26, 1:00-3:05 pm
Room: DB, Exec
Chair: H. Petryk

1:00 Material Instability at Non-Local Continua, *P. B. Beda*

1:25 Computational Simulation of Characteristic Length Dependent Deformation Behavior of Nickel-Based Superalloy using Homogenization Method, *Y. Higa, H. Kitagawa, Y. Tomita*

1:50 A Model for Nonlocal Crystal Plasticity, *E. B. Marin, D. J.Bammann*

2:15 Finite Element Simulation of Forming Limit Diagrams of Sheet Steels by Gradient Dependent Plasticity, *Y. Kim, Y. Kwon, S. Hwang*

2:40 Polycrystal Modeling of Unstable Plastic Flow Patterns in Aluminum Alloys, *S.-Y. Yang, X. Li, W. Tong*

Mechanics of Plasticity III
In honor of Y. Tomita

Organizers: H. M. Zbib, T. Hasabe, Y. Shibutani
Session: W4I, Wed., June 26, 3:30-5:35 pm
Room: DB, Exec
Chair: Y. Shibutani, T. Hasebe

3:30 Modeling of Dislocation Patterning based on Field Theory of Plasticity, *T. Hasebe*

3:55 Formation of Prismatic Dislocation Loops by Dilatation of Precipitates, *T. Ohashi*

4:20 Modeling the Behavior of FCC Single Crystals under Shock Loading: Dislocation Dynamics Analysis, *M. A. Shehadeh, H. M. Zbib, T. D. de la Rubia*

4:45 Molecular Dynamics Simulation on Dislocation Motion in γ/γ' Microstructure of Ni-based Superalloy, *K. Yashiro, M. Naito, Y. Tomita*

5:10 Microscopic Bifurcation Condition of Periodic Materials Based on a Homogenization Theory, *N. Ohno, D. Okumura, H. Noguchi*

Mechanics of Plasticity IV
In honor of Y. Tomita

Organizers: H. M. Zbib, T. Hasebe, Y. Shibutani
Session: R3I, Thurs., June 27, 1:00-3:05 pm
Room: DB, Rear Aud.
Chair: T. Ohashi

1:00 Modeling of Polymer Failure by Crazing, *S. Basu, E. van der Giessen*

1:25 An Engineering Approach to Identify Stress-Strain Relationship for High Energy Absorbing Engineering Plastics, *H. Okada, S. Kobayashi, Y. Fukui, N. Kumazawa*

1:40 Mechanical Properties of Single Trabeculae Measured by Micro-Three-Point Bending Test, *K. Tsubota, S. Nishiumi, T. Adachi, Y. Tomita*

2:15 Hyperelasticity of Magnetostricitve Particle-Filled Elastomers, *L. Sun, H. M. Yin, J. S. Chen*

2:40 On the Speed of an Unconstrained Shear Band in a Perfectly Plastic Material, *T.W. Wright*

Mechanics of Plasticity V
In honor of Y. Tomita

Organizers: H. M. Zbib, T. Hasebe, Y. Shibutani
Session: R4I, Thurs., June 27, 3:30-5:35
Room: DB, Rear Aud.
Chair: T. Hasebe

3:30 Multiscale Modeling of Plastic Deformation in Void Growth and Fracture, *R. E. Rudd, J. Belak*

3:55 Modeling of Void Growth and Coalescence in Ductile Solids, *X. Gao, J. Kim, T. S. Srivatsan*

4:20 FIB-TEM Observations of Cross Sections of Indent-Induced Plastic Zone, *Y. Shibutani, A. Koyama*

4:45 Localization Conditions for High Porosity Sandstone Using a Two Yield Surface Constitutive Model, *V. Challa, K. A. Issen*

5:10 Initiation and Propagation of Adiabatic Shear Bands in Different Materials Deformed in Plane Strain Tension, *M. Lear, R. C. Batra*

Keynote Session
Soft Actuators and Sensors I

Organizers: S. Nemat-Nasser
Session: W2C, Wed., June 26, 9:30-11:45 am
Room: Torg 3100
Chair: S. Nemat-Nasser

9:30 Modeling of Swelling/Deswelling Kinetics of Hydrogels: A Chemo-Electro-Mechanical Approach, *S. K. De, A. N. Chatterjee, N. R. Aluru*

10:15 Fundamentals of Ionic Polymer Conductor Composites as Biomimetic Sensors, Soft Actuators and Artificial Muscles, *M. Shahinpoor*

11:00 Electromechanical Modeling and Control of Ionic Polymer Material Systems *D. J. Leo, K. M. Newbury, M. Bennett, K. Farinholt*

Keynote Session
Soft Actuators and Sensors II

Organizer: S. Nemat-Nasser
Session: R2C, Thurs., June 27, 9:30-11:45 am
Room: Torg 3100
Chair: S. Nemat-Nasser

9:30 Theoretical and Experimental Investigation of Polymer Gels as Adaptive Materials, *T. Wallmersperger, B. Kroplin, R. W. Gulch*

9:55 Design and Optimization of Electrostrictive Polymer Based Composites, *J. Li, N. Rao*

10:20 Nafion Based Smart Membrane as an Actuator Array, *M. Taya, M. Le Guilly*

Keynote Session
Soft Actuators and Sensors III

Organizer: S. Nemat-Nasser
Session: F2C, Fri., June 28, 9:30-9:55 am
Room: SQ, Brush A
Chair: M. Shahinpoor

9:30 Tailoring Actuation Response of IPMC's, *S. Nemat-Nasser, Y. Wu*

Contd. in session F2C, p. 23.

Structural Mechanics I

In Honor of Arthur W. Leissa

Organizers: S. Ghosh, S. E. Bechtel, A. K. Noor
Session: W2H, Wed., June 26, 9:30 am-12:00 noon
Room: DB, Rm D
Chair: S. Ghosh

9:30 Structural Mechanics Then and Now, *A. W. Leissa*

10:20 Buckling Of Rectangular Plates Subjected To Nonlinearly Distributed In-Plane Loading, *C. W. Bert, K. K. Devarakonda*

10:45 Nonlinear Dynamics of Aeroelastic Systems, *E. H. Dowell*

11:10 Shear Deformation Factors and Shear Locking, *W. D. Pilkey*

11:35 Time Dependent Boundaries for Vibrating Threads, *F. Pfeiffer, F. Wegmann*

Structural Mechanics II

In Honor of Arthur W. Leissa

Organizers: S. Ghosh, S. E. Bechtel, A. K. Noor
Session: W3P, Wed., June 26, 1:00-3:05 pm
Room: DB, Rm D
Chair: S. E. Bechtel

1:00 Fracture Mechanical Assessment of Interface Cracks with Contact Zones in Piezoeletric Bimaterials Under Thermo-electromechanical Loadings, *K. P. Herrmann, V. V. Loboda*

1:25 Isospectral Vibrating Systems, *G. M. L. Gladwell*

1:50 Mechanics of Lightning Destruction, *J. F. Wilson*

2:15 Characterization of Helicoidal Structural Properties via an Energy Approach, *C. W. Lim, J.-J. Shu*

2:40 Free Vibration Analysis of Corner Supported Rectangular Plates with Symmetrically Distributed Edge-Beams, *D. J. Gorman*

Structural Mechanics III

In Honor of Arthur W. Leissa

Organizers: S. Ghosh, S. E. Bechtel, A. K. Noor
Session: W4P, Wed., June 26, 3:30-5:35 pm
Room: DB, Rm D
Chairs: A. K. Noor, R. Kapania

3:30 Vibration of a Cluster of Beams in Viscous Fluid, *R.-J. Zhang*

3:55 Damping in Brittle Matrix Composite Laminates with Matrix Cracks, *V. Birman, L. W. Byrd*

4:20 The Use of Asymptotic Modeling in Vibration and Stability Analysis of Structures, *S. Ilanko*

4:45 Vibrations of Oblique Shear-Deformable Plates, *R. Heuer, F. Ziegler*

5:10 Nonlinear Flexural Waves in Thin Layers, *O. M. Mukdadi, S. K. Datta*

Structural Mechanics IV

In Honor of Arthur W. Leissa

Organizers: S. Ghosh, S. E. Bechtel, A. K. Noor
Session: R2H, Thurs., June 27, 9:30-11:35 am
Room: DB, Rm D
Chair: F. Pfeiffer

9:30 Buckling of Simply Supported Rectangular Plates under Uniform Thermal and Mechanical Loading, *R. M. Jones*

9:55 Ray Method To Investigate Transient Waves Propagating In Thin Bodies Under Impact Excitations, *Y. A. Rossikhin, M. V. Shitikova*

10:20 Nonlinear Interactions in Asymmetric Vibrations of a Circular Plate, *W. K. Lee, M. H. Yeo*

10:45 Vibration Analysis with a Higher Order Shear and Normal Deformable Plate Theory, *S. Vidoli, F. Vestroni, R. C. Batra*

11:10 Buckling of Suddenly Loaded Structures, *G. J. Simitses*

Structural Mechanics V

In Honor of Arthur W. Leissa

Organizers: S. Ghosh, S. E. Bechtel, A. K. Noor
Session: R3N, Thurs., June 27, 1:00-3:05 pm
Room: DB, Rm D
Chair: S. Datta

1:00 Perspectives on Multiscale Modeling, Simulation and Visualization, *A. K. Noor*

1:25 Stress Boundary Conditions for Plate Bending, *F. Y. M. Wan*

1:50 The Effect of Crack Plane Cohesive Zones on the Vibration of Cracked Beams, *D. A. Mendelsohn*

2:15 Layerwise Optimization for the Maximum Frequency Of Laminated Composite Plates, *Y. Narita*

2:40 Three-Dimensional Contact Analysis of Layered Elastic / Plastic Solids with Rough Surfaces in Dry and Wet Conditions and its Applications, *B. Bhushan*

Structural Mechanics VI

In Honor of Arthur W. Leissa

Organizers: S. Ghosh, S. E. Bechtel, A. K. Noor
Session: R4N, Thurs., June 27, 3:30-5:35 pm
Room: DB, Rm D
Chair: R. M. Jones

3:30 Multiwave Nonlinear Resonance Couplings - Part 2: Two-Dimensional Example, *G. A. Maugin, D. A. Kovriguine, A. I. Potapov*

3:55 Rope Torque and Wire Rope Dynamics, *G. J. Butson*

4:20 Moderately Large Flexural Vibrations of Composite Plates With Thick Layers, *C. Adam*

4:45 Fundamental Frequencies of Circular Plates With Internal Elastic Ring Support, *C. Y. Wang, C. M. Wang*

5:10 On the Finite Displacement Analysis of Plates, *A. V. Singh*

Structural Mechanics VII

In Honor of Arthur W. Leissa

Organizers: S. Ghosh, S. E. Bechtel, A. K. Noor
Session: F2H, Fri., June 28, 9:30-11:35 am
Room: DB, Rm D
Chair: C. Bert

9:30 An Experimental Method for Evaluating SIF Distributions During Crack Turning in Non-Brittle Materials, *C. W. Smith*

9:55 On the Dynamics of Piezoelectric Cylindrical Shells, *P. Hagedorn, M. Berg*

10:20 Three-Dimensional Exact Solution for the Vibration of Functionally Graded Rectangular Plates, *S. S. Vel, R. C. Batra*

10:45 Experimental Study of Sound Transmission Loss in Electrorheological Liquid Under Normal and Shear Stress, *M. L. Szary*

11:10 Anisotropic Elasticity Solution of Single Layered Composite Plate Under Self-equilibrating Cubically Distributed Shear Loading, *A. G. Rezaei*

Structural Mechanics VIII

In Honor of Arthur W. Leissa

Organizers: S. Ghosh, S. E. Bechtel, A. K. Noor
Session: F3H, Fri., June 28, 1:00-3:30 pm
Room: DB, Rm D
Chair: V. Birman

1:00 Design Issues Concerning Hybrid Piezoelectric-Magnetostrictive Transducers, *M. J. Dapino*

1:25 Dynamic Stability of Pre-Twisted Beams with Nonconstant Spin Rates Under Axial Random Forces, *T. H. Young, C. Y. Gau*

1:50 Circular Cylindrical Shells Buckle Under Pure Bending, *H. Otsuka, T. Koga*

2:15 Vibrations of Advanced Turbomachinery Rotating Blades Modeled as Thin-Walled Composite Beams, *L. Librescu, S. Na*

2:40 Accurate Measurement of Stress Distributions in Anisotropic Laminated Structures. A New Method, *K. Soldatos*

3:05 Analysis of Wings Using Equivalent Continuum Models, *R. K. Kapania*

Turbulence in Chemical Processing I
In Honor of Robert S. Brodkey

Organizers: G. K. Patterson, S. Kresta, C. Meinhart
Session: W3D, Wed., June 26, 1:00-3:05 pm
Room: SQ, Brush B
Chairs: G. K. Patterson, C. Meinhart

1:00 Some Important New Experimental Observations on Surfactant Drag Reduction, *J. L. Zakin, Y. Qi*

1:25 The Turbulent Velocity Field in a High Speed, In-Line Rotor-Stator Mixer, *R. V. Calabrese, K. R. Kevala, V. P. Mishra*

1:50 3-D Laser Anemometer Measurements in a Labyrinth Seal, *G. L. Morrison, M. C. Johnson, G. B. Tatterson*

2:15 Motion of Bubbles in Turbulent Flows: Size, Shape and Directional Distribution, *A. A. Kulkarni, J. B. Joshi, D. Ramkrishna*

2:40 LES/PIV of Flow in a Stirred Tank with Rushton Turbine, *H. S. Yoon, M. Y. Ha, S. Balachandar, R. Raju, R.J. Adrian, D. Hill*

Turbulence in Chemical Processing II
In Honor of Robert S. Brodkey

Organizers: G. K. Patterson, S. Kresta, C. Meinhart
Session: W4D, Wed., June 26, 3:30-5:35 pm
Room: SQ, Brush B
Chairs: S. Kresta, G. K. Patterson

3:30 An Investigation of Hydrodynamic Interactions within Glove Line Leaching Tank, *H. Bai, P. Gillis, N. Felsted*

3:55 Turbulent Micromixing in Systems with Complex Chemistry, *M. Chakrabarti, K. Tsai, R. O. Fox, J. C. Hill*

4:20 The Application of the Spalart-Allmaras Turbulence Closure Model and GLS Finite Element Method for Predicting Stirred Tank Flows, *K. Bittorf, K. Johnson*

4:45 Numerical Simulation of a Turbulent Mixing Tank Using an Embedded Boundary Approach Within a Structured Cartesian Grid, *S. Kumar, J. Thornock, P. Smith*

5:10 Being Well Over Seventy, This is What I Still Would Like to Do, *R. S. Brodkey*

Stess Analysis of Composites
In honor of Carl T. Herakovich

Organizers: C. Lissenden, J. Beuth
Session: W3S, Wed., June 26, 1:00-3:05 pm
Room: DB, Rear Aud.
Chairs: J. Beuth, M. W. Hyer

1:00 The Nonlinear Response of a Damaged Composite Shell Subjected to Internal Pressure, *J. H. Starnes, Jr., C. A. Rose*

1:25 Vortex-Induced Vibrations of Deepwater Composite Risers, *S. S. Wang, T. P. Yu*

1:50 Durability and Damage Tolerance Design and Analysis Methods for Composite Structures, *C. E. Harris*

2:15 A Simple, Comprehensive, Nonlinear Thermodynamic Theory of Shells, *J. G. Simmonds*

2:40 A Robust Design Approach to Thermal Twist in Composite Tubes, *R. W. Gehle, R. U. Johnson*

Experimental Mechanics of Composites
In honor of Carl T. Herakovich

Organizers: C. Lissenden, J. Beuth
Session: W4S, Wed., June 26, 3:30-5:35 pm
Room: DB, Rear Aud.
Chairs: C. Lissenden, M.-J. Pindera

3:30 Oxidation and Time Dependent Effects in Modeling Life in TMCs, *W. S. Johnson, O. Jin*

3:55 Delamination Associated with Ply Cracking in Multidirectional Continuous Fiber Composites Laminates, *K. P. Herrmann, J. Zhang*

4:20 Progressive Failure Analysis of Internally-Pressurized Elliptical Composite Cylinders, *M. W. Hyer, G. F. Wolford*

4:45 Impact of a Composite Sandwich Panel upon an Elastic Foundation, *V. Perel, A. N. Palazotto*

5:10 Response of Particle Reinforced Aluminum MMC to Axial- Torsional Loading, *C. J. Lissenden, X. Lei*

Micromechanics of Composites
In honor of Carl T. Herakovich

Organizers: C. Lissenden, J. Beuth
Session: R3S, Thurs., June 27, 1:00-3:05 pm
Room: SQ 345
Chairs: J. Beuth, J. Simmonds

1:00 The Effect of Platelet Distribution on the Modulus of Nanoclay Composites, *C. T. Sun, J. L. Tsai*

1:25 High-Fidelity Micromechanics of Periodic Multiphase Materials, *J. Aboudi, M.-J. Pindera, S. M. Arnold*

1:50 Moving-Window Analysis of Composites with Random Microstructure, *L. L. Graham, S. C. Baxter*

2:15 A Fully Thermo-Mechanically Coupled Theory for General Microstructures, *T. O. Williams*

2:40 Transient Moisture Diffusion Analysis of Fiber-Reinforced Composites, *P. Vaddadi, T. Nakamura, R. P. Singh*

Damage in Composites
In honor of Carl T. Herakovich

Organizers: C. Lissenden, J. Beuth
Session: R4S, Thurs., June 27, 3:30-5:35 pm
Room: SQ 345
Chairs: C. Lissenden, T Williams

3:30 On a Damage Mesomodel for Laminates: Physical Basis, Micro-Meso Relations and Limitations, *P. Ladeveze, G. Lubineau*

3:55 Residual Stresses in Functionally Graded Composites, *S. C. Baxter, S. Fan*

4:20 A Consistent Thermodynamic and Coupled Impact Damage-Viscoplastic Model for MMCs, *G. Z. Voyiadjis, R. K. A. Al-Rub, A. N. Palazotto*

4:45 Interface Crack and Dynamic Delamination, *S. Nemat-Nasser, J. McGee*

5:10 Damage Mechanics and Delamination: Application to Low-Eenergy Impact, *O. Allix*

Dynamic Fracture

Organizer: T. Nishioka
Session: W4G, Wed., June 26, 3:30-6:00 pm
Room: SQ 236
Chair: T. Nishioka

3:30 Some Remarks on Dynamic Failure Mechanics, *J. R. Klepaczko*

3:55 Recent Advances in Dynamic Fracture Studies, *T. Nishioka*

4:20 The Intensity of a Singular Near-Tip Field around Three Dimensional Vertex, *S. Im, Y. W. Lee*

4:45 Numerical Simulations of Unsymmetrical Dynamic Branching Phenomena, *T. Nishioka, S. Tchouikov, T. Fujimoto*

5:10 Diffraction of Shear Elastic Waves on the Thin Semi-Infinite Inclusion in an Anisotropic Space, *V. S. Sarkisyan, D. J. Hasanyan, M. I. Karakhanyan*

5:35 Numerical Simulation for Dynamic Elasto Visco-plastic Fracture under Shear Load, *T. Fujimoto, T. Nishioka*

Continuum Mechanics & Thermodynamics

In honor of I. Müller

Organizers: S. Seelecke, T. Ruggeri, H. Struchtrup
Session: W4N, Wed., 3:30-5:15 pm
Room: DB, Rm A
Chair: T. Ruggeri

3:30 Welcome (5 min), *T. Ruggeri, S. Seelecke, H. Struchtrup*

3:35 Thermodynamics of Granular Gases, *G. Capriz, G.Mullenger*

4:00 Transformation and Disintegration of Strongly Nonlinear Internal Waves by Topography in Stratified Lakes, *V. I. Vlasenko, K. Hutter*

4:25 A New Continuum Model of Crystals Incorporating Microscopic Thermal Vibration, *M. Sugiyama*

4:50 A New Phenomenological Model for Stress-Softening in Elastomers, *A. E. Zuniga, M. F. Beatty*

Extended Thermodynamics / Kinetic Theory I

In honor of I. Müller

Organizer: S. Seelecke, T. Ruggeri, H. Struchtrup
Session: R2B, Thurs., June 27, 9:30-11:35 am
Room: SQ, Haymarket
Chair: G. Kremer

9:30 Grad's Moment Equations for Microscale Flows, *H. Struchtrup*

9:55 On the Determination of Unconventional Physical Boundary Conditions for Systems of Moment Equations, *I.-S. Liu*

10:20 Elliptic Type Second Order Quasilinear Partial Differential Equations for Stationary State Irreversible Heat Conduction Process and their Divergency, *E. Kiss*

10:45 Light Scattering from Extended Thermodynamic Model Equations: Binary Mon-atomic Gas Mixtures and Dense Gases, *W. Marques Jr., G. M. Kremer*

11:10 Dynamics of Small Bodies in a Nonhomogeneous Gas, *L. H. Söderholm*

Shape Memory Alloys I - Theory

In honor of I. Müller

Organizer: S. Seelecke, T. Ruggeri, H. Struchtrup
Session: R3B, Thurs., June 27, 1:00-3:05 pm
Room: SQ, Haymarket
Chair: S. Seelecke

1:00 Fatigue of NiTi Shape Memory Alloys, *K. Gall, H. Maier*

1:25 Molecular-Dynamics of a 2D Model of the Austenite-Martensite Phase Transition, *O. Kastner*

1:50 Dynamic Loading of Polycrystalline Shape Memory Alloy Rods, *D. C. Lagoudas, P. Popov, K. Ravi-Chandar*

2:15 The Evolution of Phase Transformation Fronts During Uniaxial Cyclic Deformation in Pseudoelastic NiTi, *M. A. Iadicola, J. A. Shaw*

2:40 Fracture of Shape Memory CuAlNi Single Crystals, *T. W. Shield, G. M. Vasko, P. H. Leo*

Application of Thermodynamics

In honor of I. Müller

Organizer: S. Seelecke, T. Ruggeri, H. Struchtrup
Session: R4B, Thurs., June 27, 3:30-5:35 pm
Room: SQ, Haymarket
Chair: R. C. Smith

3:30 Econophysics: Calculations of Income Distributions: Cobb Douglas and (log) Normal vs. Boltzmann, *J. Mimkes, Th. Fründ, G. Willis*

3:55 Systems of Balance Laws with a Convex Extension, *T. Ruggeri*

4:20 Effect of Density Gradients of a Binary Solution on its Phase Diagram, *Y. Huo, I. Müller*

4:45 Distance to Blow-Up of Acceleration Waves in Random Media, *M. Ostoja-Starzewski, J. Trebicki*

5:10 Modeling of Temperature Effects in Macro Fiber Composite Actuators, *R. B. Williams, D. J. Inman, W. K. Wilkie*

Shape Memory Alloys II - Applications

In honor of I. Müller

Organizer: S. Seelecke, T. Ruggeri, H. Struchtrup
Session: F2B, Fri., June 28, 9:30-11:35 am
Room: Torg 3100
Chair: J. A. Shaw

9:30 Optimal Control of Microscale SMA Actuators, *O. Heintze*

9:55 Development of an Artificial Finger Powered by Shape Memory Alloys, *M. Schleich, F. Pfeifer*

10:20 New Applications for Shape Memory Alloys in the Conservation of Cultural Heritage, *I. Müller, A. Musolff, N. Santopuoli, L. Seccia*

10:45 Instabilities of a Two-bar System with Shape Memory Alloys, *J. P. Frautschi*

11:10 On the use of the Equilibrium Configuration in the Modeling and Simulation of Phase Transformations in Shape Memory Alloys, *S. Govindjee, G. J. Hall*

Solids I

In honor of I. Müller

Organizer: S. Seelecke, T. Ruggeri, H. Struchtrup
Session: F3B, Fri., June 28, 1:00-3:05 pm
Room: Torg 3100
Chair: T. Ruggeri

1:00 Non-homogeneous Bars with Cohesive Energy, *G. Del Piero*

1:25 A Free-Energy Based Model for Hysteresis and Nonlinearities in Piezoceramic Materials, *R. C. Smith*

1:50 A Unified Model for Shape Memory Alloys and Piezoceramics, *S. Seelecke*

2:15 A Mechanism of Transformational Plasticity, *G. Puglisi, L. Truskinovsky*

2:40 Discretization and Energy Landscapes, *R. Rogers*

Solids/Extended Thermodynamics/Kinetic Theory

In honor of I. Müller

Organizer: S. Seelecke, T. Ruggeri, H. Struchtrup
Session: F4B, Fri., June 28, 3:30-5:35 pm
Room: Torg 3100
Chair: O. Kastner

3:30 On the Precipitates Induced Hardening in Crystal Plasticity, *C.-S. Han, R. H. Wagoner*

3:55 Asymptotic Behavior of the Solutions in Nesting Theories of Symmetric Hyperbolic Systems with a Convex Extension, *F. Brini*

4:20 Thermodynamics and Kinetic Theory in 2-D Cosmological Models, *G.M .Kremer, F.P. Devecchi*

4:45 Physical Analogy Between Continuum Thermodynamics and Classical Mechanics, *A. Umantsev*

5:10 Effective Properties of a Piezocomposite Containing Shape Memory Alloy and Inert Inclusions, *B. Jiang, R. C. Batra*

Coherent Structures
In Honor of A. Roshko

Organizer: D. Papamoschou
Session: R1F, Thurs., June 27, 8:00-10:05 am
Room: SQ 341/45
Chair: W. C. Reynolds

8:00 Is Viscous Dissipation Always Needed?, *A. Roshko*

8:25 Core Dynamics of a Coherent Structure in Shear: A Prototypical Physical Space Cascade Mechanism, *F. Hussain*

8:50 The Largest Scales of Turbulent Wall Flows, *J. Jimenez, J. C. del'Alamo*

9:15 Coherent Structures and Turbulent Drag Reduction in Boundary Layers, *P. Moin*

9:40 Large Reynolds Number Asymptotics of Mean Velocity Profiles in Turbulent Wall-Bounded Flows, *P. A. Monkewitz, H. M. Nagib*

Bluff Body and Cavity Flows
In Honor of A. Roshko

Organizer: D. Papamoschou
Session: R2F, Thurs., June 27, 10:20 am-12:00 pm
Room: SQ 341/45
Chair: L. W. Sigurdson

10:20 Performance and Near Wake Flow Structure of Base Drag Reducing Devices, *L. P. Bernal, S. R. Balkanyi*

10:45 The Limits of Drag Behavior for Two Bluff-Bodies in Tandem, *F. Browand, M. Hammache*

11:10 Recent Advances in Hybrid Propulsion, *A. Karabeyoglu, B. Cantwell*

11:35 The Role of the Hemodynamics Stresses in the Etiology of Arterial Aneurysms, *J. C. Lasheras*

Vortex Aerodynamics
In Honor of A. Roshko

Organizer: D. Papamoschou
Session: R3F, Thurs., June 27, 1:00-3:05 pm
Room: SQ 219
Chair: D. Pullin

1:00 Point Vortex Models of Shear Layers and Wakes, *H. Aref*

1:25 Vortex Persistence: When a Turbulent Flow Yields a Laminar Flux, *R. E. Breidenthal*

1:50 The Dilemma of an Optimal Vortex: A Study of Vortex Ring Formation in Starting Flows, *M. Gharib*

2:15 Flow Induced Vibration: Ongoing Modeling Efforts, *A. Leonard*

2:40 Resonance Forever!, *C. H. K. Williamson, R. Govardhan*

Mixing and Combustion
In Honor of A. Roshko

Organizer: D. Papamoschou
Session: R4F, Thurs., June 27, 3:30-5:35 pm
Room: SQ 219
Chair: J. W. Jacobs

3:30 Mixing Layers: What Happens at Large Density Ratio?, *W. T. Ashurst, A. R. Kerstein*

3:55 Progress in Turbulent Mixing and Combustion, *P. E. Dimotakis*

4:20 Compressible Binary Gas Mixing Layers, *S. Lele*

4:45 Flame Liftoff and Blowout, *G. Mungal*

5:10 Discussion

Flow Control
In Honor of A. Roshko

Organizer: D. Papamoschou
Session: F1F, Fri., June 28, 8:00-10:15 am
Room: SQ 341/45
Chair: C. H. K. Williamson

8:00 Experiments on Boundary Layer Receptivity, Stability and Transition at Mach 3, *G. L. Brown*

8:25 Fluidic-Based Aerodynamic Flow Control, *A. Glezer*

8:50 A Systems Control Theoretic Approach to Turbulence Control, *J. Kim*

9:20 Active Control of Separation, *H. M. Nagib, J. Kiedaisch, D. Greenblatt*

9:45 On the Dynamics of Controlled Separation and Reattachment of Turbulent Boundary Layer, *I. Wygnanski*

Jet Noise
In Honor of A. Roshko

Organizer: D. Papamoschou
Session: F2F, Fri., June 28, 10:35 am-12:50 pm
Room: SQ 341/45
Chair: D. Papamoschou

10:35 High Speed Jet Noise Reduction Using Microjets, *A. Krothapalli, V. Arakeri, B. Greska, T. Joseph*

11:00 Noise Generating Mechanisms Involving Large Scale Structures in High Speed Jets, *D. K. McLaughlin*

11:35 The Role of Large-Scale Turbulent Structures in Jet Noise, *P. J. Morris*

12:00 Turbulence and Jet Noise, *C. K. W. Tam*

12:25 Is Viscous Dissipation Always Needed? *A. Roshko*

General Mechanics
In Honor of Bruno Boley

Organizer: G. Dasgupta
Session: R2G, Thur., June 27, 9:30-11:35 am
Room: SQ Brush A
Chair: G. Dasgupta

9:30 Boley's Method for Solving Two-Dimensional Thermoelastic Problems Applied to Piezoelastic Structures, *M. Krommer, H. Irschik*

9:55 Granular Flow; Dynamics from New Experiments, *J. Bridgwater*

10:20 Elastodynamic Solutions by Application of the Reciprocity Theorem, *J. D. Achenbach*

10:45 Elastic-Plastic Contact Analysis of a Sphere and a Rigid Flat, *L. Kogut, I. Etsion*

11:10 Stationary Damage: An Analytical-Computational Approach for Examining Poroelastic Media Suceptible to Damage, *A. P. S. Selvadurai*

Granular Mechanics
In Honor of Bruno Boley

Organizer: G. Dasgupta
Session: R3J, Thurs., June 27, 1:00-3:05 pm
Room: DB, Rm A
Chair: A. Szekeres

1:00 Dynamic Behavior of an Intruder in Boundary-Driven Granular Flows, *A. D. Rosato, J. Liu, D. L. Blackmore*

1:25 Direction Simulation of Pressure Driven Flows of Dense Powders, *P. Singh, A. Wang, A. D. Rosato*

1:50 Micromechanics of High-Rate Compression Failure of Ceramics, *S. Nemat-Nasser, S. Sarva*

2:15 A Constitutive Theory of Electromagnetic Microcontinuum, *J. D. Lee, Y. Chen*

2:40 Applicability Analysis of Continuum Theories from the Viewpoint of Phonon Dispersion Relations, *Y. Chen, J. D. Lee, A. Eskandarian*

Finite and Boundary Element Methods
In Honor of Bruno Boley

Organizers: G. Dasgupta
Session: R4J, Thurs., June 27, 3:30-5:10 pm
Room: DB, Rm A
Chair: A. P. S. Selvadurai

3:30 An Extended Finite Element Method for Solidification, *T. Belytschko, J. Chessa*

3:55 Non-Singular Hybrid Boundary Element Method for Elastomechanics, *L. Gaul, F. Moser, M. Fischer*

4:20 Interpolation Constraints and Thermal Distributions, *E. A. Malsch*

4:45 FEM Prediction of steam Generator Tube Failures in Nuclear Power Plants, *T. McGreevy, J. Abou-Hanna*

Analytical Methods
In Honor of Bruno Boley

Organizer: G. Dasgupta
Session: F2G, Fri., June 28, 9:30 am -12:00 noon
Room: SQ 219
Chair: D. Barnett

9:30 Dynamics of Two van der Pol Operators Coupled via a Bath, *E. Wirkus, R. Rand, H. Howland*

9:55 Green's Functions for Anisotropic Media, *G. Dasgupta*

10:20 Snap-through of Layered Shallow Shells under Thermal Load, *R. Heuer, F. Ziegler*

10:45 A Unified Formalism for Elastostatics or Steady State Motion of Compressible or Incompressible Anisotropic Elastic Materials, *T. C. T. Ting*

11:10 Effect of Thermal Residual Stresses on Elastoplastic Behavior of Metal Matrix Composites, *L. Sun, H. Liu*

11:35 Generalized Plane Strain Thermopiezoelectric Analysis of Multilayered Plates, *S. S. Vel, R. C. Batra*

Mechanics of Materials
In Honor of Bruno Boley

Organizer: G. Dasgupta
Session: F3G, Fri., June 28, 1:00-3:05 pm
Room: SQ 219
Chair: T. C. T. Ting

1:00 Probability-Based Analysis of Size Effect in Porous Materials, *S. Thangjitham, R. A. Heller*

1:25 Solar Energy by Fiber Reinforced Composite Material, *A. Szekeres*

1:50 Bifurcation Phenomena in the Rigid Inclusion Power Law Matrix Composite Sphere, *A. J. Levy*

2:15 Line Forces in Uniform Supersonic Motion in Anisotropic Linear Elastic Solids: Radiating and Non-Radiating Solutions, *D. M. Barnett*

2:40 Short Crack Fracture Mechanics and the Fatigue Limit, *T. McGreevy, J. Abou-Hanna*

Constitutive Modeling of Shape Memory Alloys I

Organizers: D. C. Lagoudas, V. Levitas
Session: R2K, Thurs., June 27, 9:30am-12:00 noon
Room: DB, Rm A
Chair: D. C. Lagoudas

9:30 Stress-Wave-Induced Martensitic Phase Transformations in Ni-Ti Polycrystals, *S.-Y. Yang, J. C. Escobar, R. J. Clifton*

9:55 Dynamic Mesoscale Evaluation of Phase Transformation in Hybrid Porous Shape Memory Composite, *M. A. Qidwai, V. G. DeGiorgi*

10:20 FE Simulation Using Cellular Automata Approach of Martensitic Transformation Process in Single Crystal of TRIP Steel Based on Continuum Crystal Plasticity, *T. Iwamoto, T. Tsuta, S. Kubo*

10:45 The Role of Detwinning in Shape Memory Alloys, *H. Sehitoglu, R. Hamilton, D. Canadinc, K. Gall, Y. Churnlyakov, H.J. Maier*

11:10 Evaluation of Adaptability and Structural Stability of Fused NiTi Alloy by Means of Multifractal Parameterization Method, *J. M. Blednova, D. G. Budrevich*

11:35 Finite Element Analysis and Experimental Study on Superelastic Nitinol Stent, *X.-Y. Gong, A. R. Pelton, T.W. Duerig, N. Rebelo, K. E. Perry*

Constitutive Modeling of Shape Memory Alloys II

Organizers: D. C. Lagoudas, V. Levitas
Session: F2K, Fri., June 28, 9:30 am-12:00 noon
Room: SQ 234
Chair: H. Sehitoglu

9:30 A 3-D Two-tier Multivariant Model Based on Hierarchical Structural Characteristic of SMA Martensites, *L. C. Brinson, X. Gao*

9:55 Repeatable Bending Actuation in Polyurethanes Using One-Way Shape Memory Alloy Wires, *H. A. Bruck, C. L. Moore, III, T. Valentine*

10:20 Clapeyron - Clausius Equations for the Phase Transitions in Thermoelastic Meterials, *V. I. Kondaurov*

10:45 Two-phase Deformations and Phase Transition Zones, *A. B. Freidin*

11:10 Constitutive Equations for Two-Step Thermoelastic Phase Transition, *A. A. Movchan, S. A. Kazarina, P. A. Shelimagin*

11:35 Phenomenon of Stability Loss Due to Thermoelastic Phase Transition Under a Compressive Loading, *A. A. Movchan, S. A. Kazarina, L. G. Silchenko, A. N. Danilin*

Constitutive Modeling of Shape Memory Alloys III

Organizers: D. C. Lagoudas, V. Levitas
Session: F3K, Fri., June 28, 1:00-3:05 pm
Room: SQ 345
Chair: I. Movchan

1:00 Thin Film Shape Memory Actuators for Hydraulic Pumps, *G. Carman*

1:25 Porous NiTi Fabricated Using Powder Metallurgy Techniques: Characterization and Modeling, *D. C. Lagoudas, P. B. Entchev, E. L. Vandygriff*

1:50 Pseudoelastic Behavior of Nickel-Titanium Melt Spun Ribbon, *W. C. Crone, D. Wu, J. H. Perepezko*

2:15 Influence of Casting Technology on the Phase Transformation in NiTi-Based Alloys, *V. N. Slipchenko, Y. N. Koval, V. M. Slipchenko*

2:40 Effect of Transformation-Induced Plastic Strains on the Mechanical Behavior of Porous NiTi SMA, *P. B. Entchev, D. C. Lagoudas*

Topics in Mechanics of Materials I
In Honor of Wolfgang Knauss

Organizers: K. Ravi-Chandar, C. T. Liu
Session: R2M, Thur., June 27, 9:30-11:35am
Room: SQ, Brush B
Chair: K. Ravi-Chandar

9:30 Finite Step Rate Corrections in Stress Relaxation Experiments, *A. Flory, G. B. McKenna*

9:55 Rate-Dependent Rubbery Behavior of a Structural Adhesive, *S. Park, K. M. Liechti*

10:20 The VBO Model for a Semi Crystalline and an Amorphous Polymeric Solid, *E. Krempl, F. Khan*

10:45 On the Thermodynamics of Fracture in Viscoelastic Media, *D. H. Allen, C. R. Searcy*

11:10 Multiaxial Viscoelastic Behavior of Polymers, *R. Wang, K. Ravi-Chandar*

Topics in Mechanics of Materials II
In Honor of Wolfgang Knauss

Organizer: K. Ravi-Chandar, C. T. Liu
Session: R3M, Thur., June 27, 1:00-3:05 pm
Room: SQ 232
Chairs: A. J. Rosakis

1:00 Fracture Behavior of a Self-Healing Polymer Composite, *E. N. Brown, N. R. Sottos, P. H. Geubelle, S. R. White*

1:25 Scale Effects on the Fracture of Ice, *J. P. Dempsey*

1:50 Thermoviscoplastic Modeling and Numerical Analysis of Size Effects In Dynamic Tension Tests, *A. Rusinek, J. R. Klepaczko*

2:15 Some Thermodynamic Considerations in Memory Materials, *B. Bernstein*

2:40 Using the Formal Structure of Plasticity at Finite Strains to Model the Thermomechanical Behavior of Amorphous Polymers Around Their Glass Transition, *M. Negahban*

Topics in Mechanics of Materials III
In Honor of Wolfgang Knauss

Organizers: K. Ravi-Chandar, C. T. Liu
Session: R4M, Thur., June 27, 3:30-6:00 pm
Room: SQ, Brush A
Chair: C. T. Liu

3:30 Dynamic Fracture in Multi-Layered Materials Subjected to Low Speed Impact, *A. J. Rosakis, Y. Huang, L. R. Xu*

3:55 The role of PMMA in Ballistic Impact Response of Layered PMMA/PC Composites, *A. J. Hsieh, P. Moy, J. W. Song*

4:20 Dynamic Crack Propagation in Functionally Graded Materials, *Z. Wang, T. Nakamura*

4:45 Mode III Steady Dynamic Propagation of a Crack with a Rate and Temperature Dependent Cohesive Zone, *F. Costanzo, J. R. White*

5:10 Shear Wave Loading of Steel Plates with Mid-Plane Crack, *Z. Zhang, R. J. Clifton*

5:35 Measuring the Decohesion Law of a High Explosive Material, *C. Liu*

Topics in Mechanics of Materials IV
In Honor of Wolfgang Knauss

Organizers: K. Ravi-Chandar, C. T. Liu
Session: F2M, Fri., June 28, 9:30-11:35 pm
Room: SQ 232
Chair: D. L. McDowell

9:30 Crack Propagation in Functionally Graded Material, *J. R. Walton, D. A. Zeigler*

9:55 Investigating the Deformation and Failure Mechanisms in Bi-Material Systems under Tension, *C. T. Liu, F.-P. Chiang*

10:20 Some Recent Developments and Applications of Image Correlation in Experimental Micromechanics, *W. Tong, X. Li, N. Zhang*

10:45 Micromechanics of Microstructurally Small Surface Cracks in Polycrystals, *V. P. Bennett, D. L. McDowell*

11:10 Numerical Simulation of Hydrogen-Induced Interfacial Decohesion in Nickle-Base Alloys, *Y. Liang, P. Sofronis*

11:35 Pressure and Strain-Rate Dependency of Glassy Polymers, *N. Mehta, V. Prakash*

Topics in Mechanics of Materials V
In Honor of Wolfgang Knauss

Organizers: K. Ravi-Chandar, C. T. Liu
Session: F3M, Fri., June 28, 1:00-3:05 pm
Room: SQ, Brush A
Chair: V. Prakash

1:00 Measurement of Creep Compliance by Nanoindentation, *H. Lu, B. Wang, J. Ma*

1:25 Dynamic Compressive Stress-Strain Behavior of a Soft Rubber, *B. Song, W. Chen*

1:50 Some Surprising Phenomena in Fracture of a Viscoelastic Triangular Lattice, *L. I. Slepyan, M. V. Ayzenberg-Stepanenko*

2:15 A Finite Integral Approach for the Thermoelastic Properties of Multiphase Composites, *H. Gan*

2:40 The Effect of Temperature History on Behavior of PA6 and PA66, *I. Emri, B. V. Bernstorff*

Electrohydrodynamics I

Organizer: B. Khusid
Session: R3C, Thurs., June 27, 1:00-3:30 pm
Room: SQ 234
Chairs: B. Khusid, H. H. Bau

1:00 Assembly of Colloids in 2-D Electrohydrodynamic Flows Near Electrodes, *J. L. Anderson*

1:25 Shear-Flow Structure of Electrorheological Fluids, *R. Tao*

1:50 Fluid Flows in Alternating and Rotating Electromagnetic Fields, *M. Zahn, C. Rinaldi*

2:15 Dielectrophoresis and Aggregation in Suspensions Subjected to High-Gradient Electric Fields, *B. Khusid, A. Acrivos*

2:40 Electrohydrodynamic Enhanced Capillary Pumped Loop Bubbly Flow, *S. J. Shelestynsky, C. Y. Ching, J.-S. Chang*

3:05 Plane Parallel Isothermal Laminar Flow of Conducting Incompressible Fluid in MHD-Unpressured Device with Inclined Bottom and its Stability in Transversal Homogeneous Magnetic Field, *G. S. Bezirgenyan*

Electrohydrodynamics II

Organizer: B. Khusid
Session: R4C, Thurs., June 27, 3:30-6:00 pm
Room: SQ 234
Chairs: J. L. Anderson, C. D. Meinhart

3:30 The Use of Magneto-Hydrodynamics to Pump, Control, and Stir Liquids in Micro Fluidic Systems, *H. H. Bau, J. Zhu, S. Qian, Y. Xiang*

3:55 Negative Viscosity in Magnetic Fluids: Mechanisms, Manifestations, and Connected Effects, *M. I. Shliomis*

4:20 Ferrofluid Flow and Torque Measurements in Rotating Magnetic Fields, *A. D. Rosenthal, J.-H. Lee, L. J. Lalla, X. He, M. Zahn, C. M. Rinaldi*

4:45 Alternating and Traveling-Wave Magnetic-Field Induced Flow of Ferrofluid, *T. Franklin, M. Zahn*

5:10 Spin-Magnetization Coupling in Spin-up Flow of Ferrofluids, *C. M. Rinaldi, M. Zahn*

5:35 Simulating Buoyancy-Induced Thermo-Magneto-Viscoelastic Flow in a Darcy Brinkman Porous Medium using the "Caltech-Keller" Implicit Scheme, *O. A. Beg, G. Nath, H. S. Takhar, M. Kumari, M. Hussain*

Electrohydrodynamics III

Organizer: B. Khusid
Session: F3C, Fri., June 28, 1:00-3:30 pm
Room: SQ 234
Chairs: M. Zahn, D. Jacqmin

1:00 Micro PIV Measurement of the Electrothermal Effect, *C. D. Meinhart, D. Wang*

1:25 Manipulation of Particles in Mirofluidic Channels by Means of Traveling-Wave Dielectrophoresis - Design and Analysis, *D. J. Bennett, B. Khusid, P. Galambos, M. Okandan*

1:50 Studies of the Particle Motions in a Suspension Subject to High-Gradient ac Electric Field, *N. Markarian, Z. Qiu*

2:15 Numerical Simulation of the Dielectrophoretic Forcing of Particle-Laden Flows, *D. Jacqmin, B. Khusid, A. Acrivos*

2:40 Direct Simulation of Electrorheological Suspensions, *P. Singh, N. Aubry*

3:05 Couple-Stress in Peristaltic Transport of a Magneto-Fluid Through a Porous Medium, *E. S. F. El-Shehawey, W. A. F. El-Sebaei*

Electrohydrodynamics IV

Organizer: B. Khusid
Session: F4C, Fri., June 28, 3:30-5:35 pm
Room: SQ 234
Chairs: R. Tao, M. I. Shliomis

3:30 An Electroosmotic Chaotic Stirrer, *S. Qian, H. H. Bau*

3:55 Particle Migration Velocity in an Electrostatic Precipitator, *Y. S. Khodorkovsky*

4:20 Magnetohydrodynamic Bearings Under Oscillating Electric Fields, *B. Schweizer, J. Wauer*

4:45 Control of Vortex Shedding from Cylinder by Electromagnetic Field, *X. Sun, N. Aubry*

5:10 Peristaltic Transport in a Tapered Channel of a Magneto-Fluid Through a Porous Medium, *E. S. F. El-Shehawey, W. A. F. El-Sebaei*

Computational Geomechanics I

Organizer: M. S. Gutierrez
Session: F2O, Fri., June 28, 9:30 am-12:00 pm
Room: SQ 236
Chairs: M. S. Guitierrez, N. D. Cristescu

9:30 Large Deformation Cam-clay Theory for Granular Media, *M. Ortiz, A. Pandolfi*

9:55 Title to be announced, *L. G. Steinberg*

10:20 A Numerical Model for Soil Liquefaction at Depths, *F. Amini, Z. Duan*

10:45 A Multi-Scale Effective Moduli Model for Concrete Incorporating ITZ Water-Cement Ratio Gradients, *J. C. Nadeau*

11:10 A High-Pressure High Strain Rate Quasi-Linear Viscoelastic Model for Concrete, *O. Cazacu, N. D. Cristescu*

11:35 Localization Effects in Slope Stability Analysis, *M. T. Manzari*

Computational Geomechanics II

Organizer: M. S. Gutierrez
Session: F3F, Fri., June 28, 1:00-3:05 pm
Room: SQ 236
Chairs: V. Kaliakin, M. S. Gutierrez

1:00 Elastoplastic Constitutive Model with Vertex Effect and Anisotropic Hardening, *S. Tsutsumi, K. Hashiguchi, M. Sugimoto*

1:25 Assessment of 3-D Predictive Capabilities of Bounding Surface Model for Cohesive Soils, *V. N. Kaliakin, Z. Pan*

1:50 DSC-Based Constitutive Modeling of High Performance Concrete, *M. Zaman, A. R. Kukrati, M. P.-Y. Chin*

2:15 Analytical Solutions for the Three-Invariant CAM Clay Model: Drained Loading and Comparisons, *D. Peric*

2:40 A New Integration Algorithm for Strain-Hardening Elastoplastic Soil, *R. J. Hickman, M. S. Gutierrez*

Computational Geomechanics III

Organizer: M. Gutierrez
Session: F4F, Fri., June 28, 3:30-5:10 pm
Room: SQ 236
Chairs: M. Zaman, A. Misra

3:30 Mechanistic Model for Scale Effects in Rock Joint Behavior, *A. Misra*

3:55 Application of the Free Hexagonal Method to Stability of Tunnel Face, *P. Prochazka*

4:20 Navier-Stokes Simulations of Fluid Flow in a Rough-Walled Rock Fracture, *A. H. Al-Yaarubi, C. C. Pain, R. W. Zimmerman*

4:45 Non-Linear Finite Element Analysis of Anisotropic Shear Walls, *P. G. Asteris, D. S. Sophianopoulos*

Experimental Data and Modeling of Polymers and Polymer Matrix Composites

Organizer: R. K. Garrett, Jr.
Session: W4E, Wed., June, 3:30-6:00 pm
Room: SQ 234
Chair: J. Goldwasser

3:30 Stress Relaxation from Non-Equilibrium Deformation of Polymer Segments, *D. Z. Zhang, F. H. Harlow, C. Liu*

3:55 Physical Properties and Ballistic Data Analysis of Filled Energetic Materials, *J. Yu, L. Gabrysch, S. Armstrong, W. Shaw, S. Ritchie, W. J. Worrell*

4:20 The Temperature and Strain Rate Response of Polymeric Materials, *C. M. Cady*

4:45 Material Testing and Constitutive Modeling of PTFE 7C, *G. C. Kirby, R. K. Garrett, P. Fridley*

5:10 Fracture Toughness Evaluation of PTFE 7C, *J. A. Joyce*

5:35 Modeling the Constitutive Response of an Aluminum-Teflon Composite under High Strain Rate Loading Conditions, *P. A. Taylor*

Keynote Session
Contemporary Issues in Mechanics

Organizer: R. C. Batra
Session: R2Q, Thurs., June 27, 9:30-11:45 am
Room: DB, Rear Aud.
Chair: R. C. Batra

9:30 Research and Challenges in Applied Mechanics, *K. P. Chong , M. Y. M. Chiang*

10:15 Vibration Reduction in Helicopter Rotors Using Actively Controlled Trailing Edge Flaps, *P. P. Friedmann*

11:00 Identifying Material Constants for Viscoplastic Constitutive Equations, *E. Krempl, L. Maciucescu*

SPECIAL SYMPOSIA SESSIONS

SYMPOSIUM	HONOREE	ORGANIZER	SESSIONS
Contemporary Issues in Mechanics		R. C. Batra	R2Q
Arterial Flows: In Health and Disease		S. A. Berger	T2G, T3G, W2G, W3G
Compressible Flow with Chemical Reaction		H. Hornung	T2F, W2F
Developments in Composite Materials and Structures		M. W. Hyer	M2F
Nonlinear Dynamics and Control		J. L. Junkins	M2Q, T2Q, W2Q
Soft Actuators and Sensors		S. Nemat-Nasser	W2C, R2C, F2C
Material Failure at High Strain Rates		Y. D. S. Rajapakse	M2C, T2C
Microelectromechanical Systems (MEMS)		W. N. Sharpe, Jr.	M2B, T2B
Perturbation Theory and Computations: A Combined Approach to Mechanics	J. D. Cole	A. K. Kapila	M4F,T3F
Flow of Complex Fluids	C. G. Speziale	D. A. Signier	M2G, M3F
Recent Advances and New Directions in Mechanics, Continuum Thermodynamics and Kinetic Theory	C. A. Truesdell III	C.-S. Man	M2A, M3A, M4A, T2A, T3A, T4A, W2A, W3A, W4A, R2A, R3A, R4A
Contemporary Issues in Mechanics	M. F. Beatty	Q. Jiang, M. S. Wu and E. Baesu	M3B, M4B, T3B, T4B, W2B, W3B, W4B
General Mechanics	B. Boley	G. Dasgupta	R2G, R3J, R4J, F2G, F3G
Time Dependent Failure Phenomenon	H. Brinson, A Cardon	D. A. Dillard, C. Hiel, L. C. Brinson	T4G, W3F, W4F, R3G
Turbulence in Chemical Processing	R. S. Brodkey	G. K. Patterson, S. Kresta, C. Meinhart	W3D, W4D
Research and Education in Experimental Mechanics	J. Dally	W L. Fourney	M3M, M4M, T3M, T4M, W3M, W4M
Recent Advances in Experimental Mechanics	I. M. Daniel	E. E. Gdoutos	M2E, M3H, M4H, T2E, T3H, T4H, W2E, W3H, W4H, R2E, R3H, R4H, F2E, F3E
Mechanics of Liquid-Gas and Liquid-Solid Interfaces	S. H. Davis	G. P. Neitzel	T4E, W3E
Advances in Composite Materials	G. J. Dvorak	Z. Bazant, S. Torquato, R. M. Christensen	M3J, M4J, T3J, T4J
Stress Analysis of Composites	C. T. Herakovich	C. Lissenden, J. Beuth	W3S, W4S, R3S, R4S
Fluid Mechanics and Multiphase Flow	D. Joseph	Y. Renardy, P. Wapperom, E. B. Pittman, D. S. Khismatullin	M3C, M4C, T3C, T4C, W3C, W4C
Topics in Mechanics of Materials	W. Knauss	K. Ravi-Chandar, C. T. Liu	R2M, R3M, R4M, F2M, F3M
Structural Mechanics	A. W. Leissa	S. Ghosh, S. E. Bechtel, A. K. Noor	W2H, W3P, W4P, R2H, R3N, R4N, F2H, F3H
Solid and Fluid Mechanics Education	R. P. McNitt	N. J. Salamon	M3Q, M4Q
Plasticity and Damage Mechanics	Z. Mroz	G. Z. Voyiadjis	M3O, M4O, T3O, T4O, W3O, W4O, R3O, R4O
Continuum Mechanics and Thermodynamics	I. Müller	S. Seelecke, T. Ruggeri, H. Struchtrup	W4N, R2B, R3B, R4B, F2B, F3B, F4B
Advances in Computational Mechanics	J. T. Oden	L. Demkowicz	M3R, M4R, T3R, T4R, W3R, W4R, R3R
Turbulent Structure and Flow Control	A. Roshko	D. Papamoschou	R1F, R2F, R3F, R4F, F1F, F2F
Viscoelasticity in Composites	R. A. Schapery	D. H. Allen	M3I, M4I, T3I
Mechanics of Plasticity	Y. Tomita	H. M. Zbib, T. Hasebe, Y. Shibutani	T4I, W3I, W4I, R3I, R4I
Impact on Composites		S. Abrate	M3K, M4K, T3K, T4K, W3K, W4K, R3K, R4K
Mechanical Properties of the Thin-Films and MEMS Materials		H. D. Espinosa, R. Ballarini, W. G. Knauss	M3L, M4L, T3L, T4L, W3L, W4L, R3L, R4L
Experimental Data and Modeling of Polymers and Polymer Matrix Composites		R. K. Garrett, Jr.	W4E
Computational Geomechanics		M. Gutierrez	F2O, F3F, F4F
Advances in Three-Dimensional Flow Modeling		E. E. Khalil	M3E, M4E
Electrohydrodynamics		B. Khusid	R3C, R4C, F3C, F4C
Instability in Solids and Structures		S. Kyriakides, E. Corona	M3N, M4N, T3N, T4N
Constitutive Modeling of Shape Memory Alloys		D. C. Lagoudas, V. Levitas	R2K, F2K, F3K
Numerical Simulation of Turbulent Flows		K. Mahesh	M3D, M4D
Dynamic Fracture		T. Nishioka	W4G
Electro-Magneto-Mechanics		Y. Shindo	M3P, M4P, T3P, T4P, R3P, R4P
Mechanics of Thin Films and Other Small Structures		Z. Suo, R. Huang	M2D, M3G, M4G, T2D, T3P, T4P, W2D, W3Q, W4Q, R2D, R3Q, R4Q, F2D, F3D

PLENARY LECTURES

Bones Have Ears

Stephen C. Cowin

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The City College
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Living bones adapt their structure to meet the requirements of their mechanical environment. These adaptations require a cell-based mechanosensing system with a sensor cell that perceives the mechanical deformation of the mineralized matrix in which the cell resides, a cell-based mechanosensing system not unlike that in the ear.

One of the most perplexing features of this mechanosensory system in bone is the very low strain level that a whole bone experiences in vivo compared to that needed to produce a response in cells. The amplitudes of the in vivo strains generally fall in the range 0.04 to 0.3 percent for animal locomotion and seldom exceed 0.1 percent. These strains are nearly two orders of magnitude less than those needed (1necessary for communication of the sensing cells with the cells that deposit and resorb bone tissue. There is a paradox in the bone mechanosensing system in that the strains that activate the bone cells are at least an order of magnitude larger than the strains to which the whole bone organ is subjected.

A hierarchical model ranging over length scales that differ by 9 orders of magnitude, from the subcellular level to the whole bone level, is used to resolve this paradox. Using this extended poroelasticity-based model, it is possible to explain how the fluid flow around a bone cell process can lead to strains on the cell process structure that are two orders of magnitude greater than the mineralized matrix in which the cell resides. This mechanosensory system has features in common with the auditory system.

Cutting of Materials

Branimir von Turkovich

The University of Vermont
Burlington, VT 05405

The mechanical operations of cutting are well known. The theoretical understanding of these processes is based primarily on the mechanics of continuous media and mechanical metallurgy. The process is characterized by very large plastic strains and fracture. In addition, very high strain rates are also observed. The strains range from 1.5 to 6.5 and the rates reach 10^6 - 10^7 sec^{-1} or even higher. The speed of cutting can be as low as a few millimeters per second to as high as 500 m/sec.

The typical representation of the process is embodied in a two-dimensional plane strain model.

The process is, in reality, a thermo-mechanical phenomenon, since the mechanical work is almost completely converted into heat. This model is discussed in detail to emphasize the possibility to study material properties under the conditions that cannot be reached by the standard mechanical tests.

The metallographic examination of chips reveals the complex microstructural features of the very large deformation, such as the slip lamellae and the adiabatic localization of strain. The range of strain rates is very broad. The temperature of the material can be readily varied. The implication for the development of constitutive relations based on direct observation of the evolution of structural features is emphasized particularly with regard to the dislocation mechanics.

On the Structure of Vorticity in the Inertial Range of Turbulence

Anthony Leonard

Caltech

Turbulence governs the rate of transport of momentum, heat and material species, and the rate of mixing of different species in many flow processes. For moderate Reynolds numbers and beyond there is a range of length scales, termed the inertial range, separating the larger scales of the energy-containing modes and the smaller dissipation scales. This talk will focus on the vortex structures in the inertial range and will attempt to answer the questions - What are they? and Why should you care?

Influence of Surfaces on the Mechanics of Thin Films

Robert C. Cammarata

Department of Materials Science and Engineering and
Department of Mechanical Engineering
Johns Hopkins University
102 Maryland Hall
3400 North Charles Street
Baltimore, MD 21218

One of the characteristic microstructural features of thin solid films is the high density of surfaces relative to conventional bulk materials. In addition to the film free surface and the film-substrate interface, examples of other

important surfaces include the grain boundaries of polycrystalline films and the interlayer interfaces in multilayered thin films. Associated with every solid surface are two types of thermodynamic quantities: the surface free energy and the surface stress. The surface free energy is a scalar quantity that represents the reversible work per unit area to create or destroy a surface, while the surface stress is a tensor quantity associated with the reversible work to elastically deform a pre-existing surface. These parameters depend on the surface structure and can critically affect the mechanical behavior of thin films.

The influence of surfaces on thin film mechanics will be discussed with emphasis on recent developments. First, the thermodynamics of surfaces will be reviewed and applied to thin film systems. This will be followed by a survey of experimental and theoretical aspects of thin film mechanical behavior (elastic and plastic properites, adhesion) for which surfaces play a central role. Finally, a detailed examination of the surface effects on the generation of thin film stresses will be presented.

Some Structural Mechanics Research Experiences at NASA Langley Research Center

J. H. Starnes, Jr.

Senior Engineer for Structures and Materials
NASA Langley Research Center
Hampton, VA

Discussed will be three important recent studies at the NASA Langley Research Center in which various aspects of mechanics played a pivotal role in understanding the outcome. The studies discussed are: 1 - aging aircraft, in particular the interaction of geometric nonlinearities with the mechanics of fracture; 2 - the results of testing to failure the all-composite wing section; and, 3 - thermally-induced problems with the X33 liquid hydrogen fuel tank. The presentation will conclude with a discussion as to how mechanics will contribute to future activities of the agency.

KEYNOTE LECTURES

Keynote

Contemporary Issues in Mechanics

Organizer:
Professor Romesh C. Batra
(Virginia Tech)

CONTEMPORARY ISSUES IN MECHANICS
SESSION R2Q

Research and Challenges in Applied Mechanics

Ken P. Chong[1]* and Martin Y.M. Chiang[2]

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U.S. pursues diligent funding of basic research because it confers a preferential economic advantage**. NSF and NIST have supported basic research in engineering and sciences for more than half a century and will continue this mandate in the future. NIST also has the additional missions of providing a variety of standards services in reference materials and data, and technology transfer to U.S. industry and the public. Considerable research funding will be directed towards nanoscale, IT, and bioengineering, so the challenge to the research community is to determine the most needed and/or fruitful avenues of research within these areas. One of the needs is to model material behavior over the full range of length and time scales, from short-term nano/micro-scale behavior, through meso-scale and macro-scale behavior into long-term structural systems performance. Important problems in nanomechanics arise, for example, in thermo-mechanical behavior of nano-films; nano-indentation; nano-tribological response of solids; and failure processes of MEMS structures. NSF recently announced a program to catalyze synergistic science and engineering research in areas of nanoscale science and technology, including: nanoscale biosystems, nanoscale structures, novel phenomena, and quantum control, device and

system architecture, design tools and nanosystems specific software, nanoscale processes in the environment, multi-scale, multi-phenomena modeling and simulation at the nanoscale. Through industry workshops, internal initiatives and the Advanced Technology Program, NIST has research activities to develop and promote measurements, standards, and technology in nanoscale science, IT and biotechnology. In this presentation, results of relevant workshops on research needs in solid mechanics, multiscale and durability mechanics, nanoscale research and examples of cutting-edge applied mechanics projects will be given.

Keywords: nanomechanics, solid mechanics, material behavior

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**Wong, E. "An Economic Case for Basic Research", Nature, Vol. 381, pp.187-188, May 1996.

Vibration Reduction in Helicopter Rotors Using Actively Controlled Trailing Edge Flaps

Peretz P. Friedmann

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One of the primary concerns in rotorcraft design is the issue of vibrations experienced in the fuselage and its reduction. High levels of vibration may lead to passenger discomfort, fatigue of helicopter components, reduced effectiveness of weapon systems and increased noise. The largest contributor to vibrations in a helicopter is the rotor. The rotor blades transfer vibratory loads from the hub to the fuselage at harmonics that are predominantly N_b /rev, where N_b is the number of blades in the rotor. Stringent requirements for low vibration levels (less than 0.05g) imposed during the last 15 years have led to the development of active approaches to vibration reduction[1,2]. Among the active control strategies two fundamentally different strategies have emerged: higher harmonic control (HHC), where control is implemented in the hub fixed system, and individual blade control (IBC), where control is implemented in the rotating system. Three approaches have been used for IBC: actuation at the blade root, active twist of the rotor along the span, and the actively controlled partial span trailing edge flap (ACF); all attempt to control vibrations at their source (i.e. on the blade) by manipulating the unsteady aerodynamic loading in the rotating system. Among these approaches the ACF has the highest potential for alleviating vibrations and noise. This invited presentation will provide a detailed description of the research conducted by the author and his associates on the analytical/numerical modeling and development of the of an aeroelastic model for partial-span, trailing edge flaps, mounted on rotor blades. The research conducted by other investigators in this area will be also concisely summarized. It will be shown that these devices provide alleviation of vibrations due to blade vortex interaction (BVI) at low advance ratios, as well as vibrations due to high-speed forward flight. Furthermore, it will be shown that undesirable effects associated with dynamic stall, can also be reduced using the ACF. The development of a comprehensive aeroelastic response simulation code will be described, with considerable detail, together with experimental correlation. Finally, the description of a pending (before the end of 2002) flight-test program aimed at demonstrating the implementation of a piezoelectrically actuated ACF on a full-scale helicopter will be presented.

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Identifying Material Constants for Viscoplastic Constitutive Equations

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Nonlinear, algebraic and incremental material models are in use to describe the rate and path dependent inelastic deformations of ductile metals. These dependencies are the macroscopic manifestations of the internal changes that take place during deformation. The influence of stress rate, strain rate (between 1E-6 and 1E4 1/s), of short time creep and relaxation periods are considered.

Test data for 304 L stainless steel and Ta 2.5 W alloy was used to determine the material constants of the simplified viscoplasticity theory based on overstress (VBO) at room temperature where ?cold creep? is observed. The VBO model recognizes at least two ?mechanisms? of hardening; 1) viscous hardening, which depends on the flow function through the overstress, and 2)

the rate-independent or plastic hardening, similar to rate-independent plasticity, which is modeled by the isotropic stress. VBO exhibits long-time asymptotic solutions, which correspond to the ?flow stress region? of the stress-strain diagram. For this condition an Excel trend line analysis provides an approximation of the flow function and a R2-value to record the goodness of fit. The flow function and five constants are needed for the simplest version of VBO, which can model nonlinear rate dependence, creep, relaxation as well as cyclic neutral behavior.

Stress-strain diagrams at different strain rates are sufficient to determine the flow function. However, the isotropic stress is only established to lie between a maximum and minimum value. A simple test like a creep or relaxation test may be sufficient to uniquely determine the isotropic stress.

One flow function is determined for each material and the experimental stress-strain curves are well matched between 1E-6 and 1E4 1/s for every chosen isotropic stress. The behaviors for jumps in strain or stress rate ? either a reduction or an increase ? are predicted with satisfactory results.

Keywords: Constitutive equation, material constants, creep, relaxation.

Keynote

Arterial Flows: In Health and Disease

Organizer:
Professor Stanley Berger
(University of California, Berkeley)

ARTERIAL FLOWS: IN HEALTH AND DISEASE
SESSION T2G

The Role of Fluid Mechanics in Healthy and Diseased Arteries*

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For decades the motivation for simulations of arterial flows was to explore the relationship between flow in these vessels and atherogenesis, especially the focalization of plaque development. Most interest focused on the wall shear stresses, there being theories and supporting evidence that susceptible sites were where shear stresses were low, or, where, or when, they changed spatially or temporarily most rapidly, conditions most likely to occur where the vessels had sudden changes in flow geometry, and/or when the flow was unsteady. Consequences of atherosclerosis are potentially most severe in the cerebral and coronary circulations. Our hemodynamic simulation efforts have emphasized flows in the first of these, particularly the carotid arterial bifurcation, and have included extensive numerical studies of the fully three-dimensional unsteady flow in realistic normal and stenosed carotid bifurcation geometries. Calculated flow fields for normal vessels allow us to identify the more dangerous sites for plaque development. For the latter stages of progression of atherosclerotic disease the relevant issues become vessel occlusion, embolic events, or plaque rupture, especially since recent clinical investigations have suggested that the danger posed by a particular plaque depends both on the degree of occlusion *and* on the "vulnerability" of the plaque, the tendency of the plaque, to fracture and rupture. To address all these issues we have simulated flow in normal and realistic severely stenotic carotid bifurcations, solving the unsteady, three-dimensional Navier-Stokes equations, using structured grids for the normal arteries and unstructured grids, made up of tetrahedral cells, for the stenotic vessels. The numerical method is based on a finite-volume formulation of the governing flow equations and flows were calculated for a range of representative Reynolds numbers (of the order of hundreds). Calculations are carried out for Newtonian and non-Newtonian flow behavior. Because MR images and co-joint experimental studies indicate that the flows might not be laminar calculations were also carried out using various two-equation turbulence models. Transitional, intermittent flow models have also been explored, since the flow is more likely to exhibit this behavior rather than having the character of fully-developed turbulence. The computed flow patterns and fluid stresses are used to identify critical features of plaque geometry and "risk factors" for plaque disruption. These simulations for the normal and the diseased vessels have also been used to improve resolution and interpretation of magnetic resonance angiographic images of these vessels.

Keywords: stenotic vessels, atherosclerosis, arterial flow, carotid arterial flow

*Supported by NIH Grant HL61823

Realistic Modeling of Arterial Hemodynamics from Anatomic and Physiologic Image Data

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Introduction

Detailed hemodynamics information of healthy and diseased arteries obtained *in vivo* non-invasively is valuable for understanding the genesis and progression of vascular disease, to complement diagnosis and to improve therapies.

Methods

Realistic anatomical models are constructed from contrast-enhanced magnetic resonance angiography (MRA) images using a tubular deformable model along each of the desired arterial branches. A watertight surface model is then created by merging the triangulations of each arterial branch using an adaptive voxelization method. An unstructured grid of tetrahedral elements is then generated using this triangulation as the definition of the computational domain, i.e. as a support surface. Element sizes are specified via adaptive background grids.

The blood flow is mathematically modeled using the incompressible Navier-Stokes equations. A stabilized finite element method is used to solve these equations implicitly in time. Physiologic flow conditions are derived from phase-contrast MR measurements of flow velocity at selected slice locations.

Wall compliance is included into the models via an implicit fluid-structure interaction algorithm and a simplified ring model for the wall elasticity. Pressure waveforms are estimated from changes in the measured flow waveforms.

Results

The methodology was tested on image data of normal subjects and subjects with moderate carotid artery stenosis. Finite element models with physiologically correct boundary conditions were successfully constructed. Visualizations of the complex pulsatile flow patterns and wall shear stress distributions were produced (see figures 1 and 2). The computed and the measured velocity profiles at intermediate slice locations in the region of the bifurcation are in good agreement. Regions of low shear stress, high oscillatory shear index and of flow separation and reversal were identified.

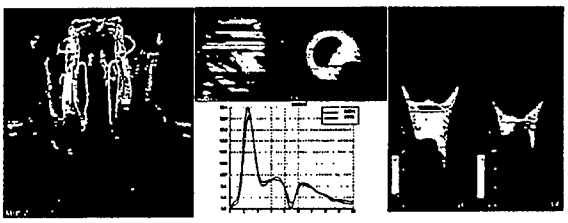


Figure 1: Normal subject

Figure 1: Normal subject

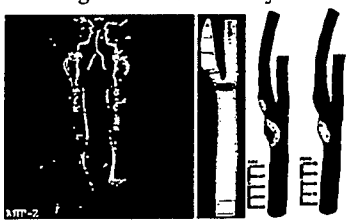


Figure 2: Subject with moderate stenosis

Figure 2: Subject with moderate stenosis

Conclusions

A method to model arterial blood flows from anatomical and physiologic image data has been presented. The methodology has been successfully applied to blood flows through healthy and stenotic carotid arteries. Maps of hemodynamics quantities of importance to study the genesis and progression of vascular diseases have been obtained. Pending further validation, these methods will be used to study the restenosis problem after carotid angioplasty and stenting.

Keywords: computational hemodynamics, fluid-structure interaction, medical imaging, arterial blood flow.

Computational Biomechanics to Guide and Interpret vascular Biology Experiments

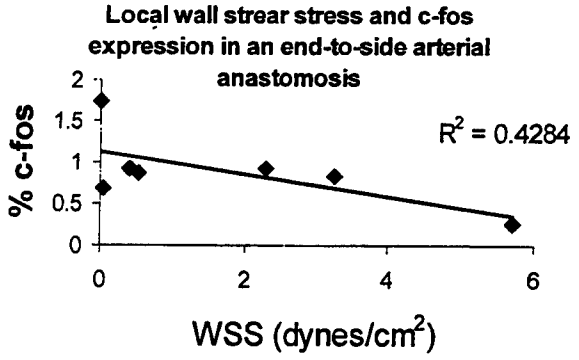
David A. Vorp

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It is well known that blood vessels and their constituent cells are biologically sensitive to mechanical forces. For example, wall shear stress and wall shear stress gradient are thought to play a role in atherogenesis and development of intimal hyperplasia. Likewise, transmural stresses and strains are thought to play a role in these and other pathologies. To fully understand the role of normal and abnormal physiologic forces and deformations on vascular disease processes, it is necessary to first *estimate* their magnitude, and then *simulate* them accurately in-vitro. We are using computational methods to estimate these forces and deformations to guide and interpret

whole-vessel perfusion experiments. Three examples of ongoing research using this approach will be presented. In one ongoing project, we perfuse an arterial end-to-side anastomosis within our vascular perfusion apparatus and utilize computational fluid dynamics to evaluate the wall shear stress and wall shear stress gradient distributions within these experimental vessels. Tissue from the experimental vessels is then sampled at regions dictated by computational fluid dynamics results to evaluate regional differences in protein expression via immunohistochemistry. Our results to date are consistent with cell culture and in-vivo studies, suggesting that there is an inverse relationship between local wall shear stress and expression of both c-fos (Figure) and c-jun, two early markers of intimal hyperplasia. In a second application, we make use of previous work, which has shown that the coronary arteries undergo cyclic flexure, elongation and twisting due to their attachment to the beating heart. Such motion may directly influence atherogenesis. We have designed an apparatus that couples with our in-vitro perfusion system that may apply these motions to perfused vascular segments. We have shown that cyclic bending of arterial segments alters their gene expression and are currently evaluating changes in intimal permeability and endothelial cell morphology in response to this stimulus.

Keywords: vascular biomechanics, biofluid mechanics, vascular biology, ex-vivo experimentation

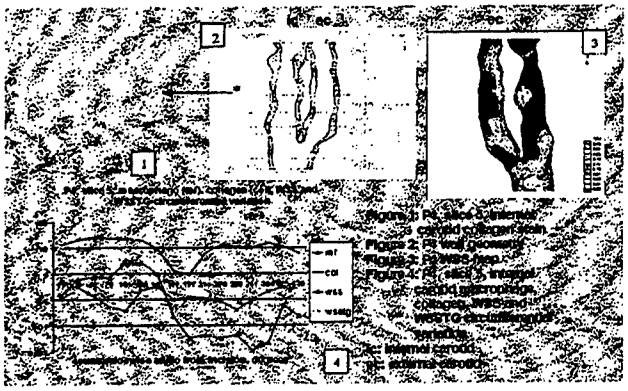


ARTERIAL FLOWS: IN HEALTH AND DISEASE
SESSION T3G

Correlations Between Fluid Shear Stress or Tissue Tensile Stress and histological markers in Advanced Carotid Artery Disease

A.G Isasi, H.F Younis, M.R Kaazempur-Mofrad, R.C Chan, and R.D Kamm

While the correlations between fluid dynamic shear stress or stresses borne by the vessel wall and the early stages of arterial disease is well established, the relationship in end-stage, when the artery is severely diseased, is less well understood. In order to examine this relationship in advanced cases of arterial disease, we examined four patients (P1-P4) who were about to undergo surgical removal of an arterial blockage (endarterectomy) in the carotid artery. This provides a unique opportunity to image and model the artery in its natural, *in vivo*, condition prior to surgical removal, and to subsequently perform histological studies of the same vessel. Carotid arteries of patients about to undergo endarterectomy were imaged by magnetic resonance with an in-plane resolution of 0.39mm in approximately cross-sectional planes each 2mm thick. The inner and outer wall contours were extracted, then used to generate a 3D model using a base loft function to interpolate across the 2D cross-sections. Unstructured meshes were generated for the fluid and solid domains and flows simulated using finite element analysis (ADINA, version 7.4). Distributions of average wall shear stress (WSS), maximum temporal gradients of wall shear (WSSTG), and an oscillatory shear index (OSI) were computed. Histological specimens from the excised tissue were sectioned and stained for lipids, smooth muscle cells, macrophages, and collagen. These were quantitatively analyzed and compared to the hemodynamic factors to determine correlations in the axial and circumferential directions. Correlations using OSI were not evaluated given its small variation within slices and across slices in all patients. Increasing WSS and WSSTG were found to be associated with decreasing concentrations of collagen in 11 out of 16 cases studied, and with decreasing concentrations of macrophages in 9 out of 16 cases studied. No correlations between hemodynamic factors and lipid concentrations were observed.



Hemodynamics Changes by Endoluminal Stents in Treatment of Cerebral Aneurysms

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Endovascular bypass of aneurysms by stenting appears to be an attractive alternative to surgical clipping. It is less invasive and advances in micro and nano devices will make it possible to access more remote locations in the cerebral circulation. Stenting not only provides the means of impeding flow in the aneurysm itself, but it also provides the parent artery with a scaffold over which the artery can remodel itself. The rational is to impede the flow inside the aneurysm such that spontaneous thrombosis can be triggered. Therefore, it is important to tailor the stent to the local hemodynamics that prevail at the site of the aneurysm.

A cylindrical artery with a spherical sidewall aneurysm was chosen to elucidate the effects of stenting on the local hemodynamics of stented arteries using laser induced fluorescence, particle image velocimetry, and computational fluid dynamics. While seldom encountered in vivo, this configuration is very useful in developing experimental models and methodologies as well as the computational methods that can be easily extrapolated to more frequent encounter aneurysm configurations in vivo. We previously demonstrated that stenting can significantly reduce the average hydrodynamic circulation inside the aneurysm ($> 95\%$).

Since accurate flow field measurements cannot be applied in vivo, we developed a simplified model based on the combined convection/diffusion washout of angiographic contrast media from the aneurysm. This model, that is currently undergoing further investigation, can predict interplay between these competing processes before and after stenting. Therefore, it is feasible to predict the efficacy of stenting in impeding intraaneurysmal flow immediately after stent placemet in vivo.

Keywords: Hemodynamics, Cerebral Aneurysms, Endovascular bypass

Simulation of Flow in Stented Saccular Aneurysms

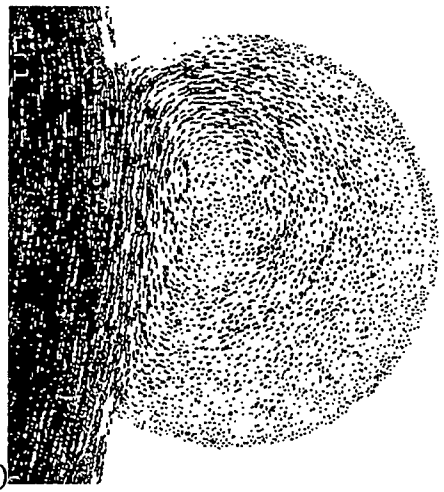
Liang-Der Jou

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Stents, wire-frame structures, are very effective devices in the treatment of vascular diseases, such as stenoses and aneurysms. One-third of patients who have stent placements develop restenosis over a six-month period, with the cause thought to be hemodynamic-related. The use of stent grafts to treat aneurysms often leads to exclusion of smaller vessels adjacent to the aneurysm from the circulation, and success of this procedure may therefore depend on the size of small vessels being occluded. An open stent is preferred to preserve the blood supply to neighboring vessels, but is considered to be less effective in aneurysm thrombosis and in reducing the pressure inside the aneurysm. In addition, the stent may still affect the flow into adjacent vessels.

The effectiveness of a generic stent placed at a saccular aneurysm adjacent to a curved vessel is analyzed by studying the flow before and after stent placement. Both the influence of the orientation and the location of the struts are investigated. Flow simulations indicate that the flow rate into the aneurysm is very sensitive to the orientation and location of the struts. The strut disrupts the pattern of flow entering the aneurysm, and a single vortex inside the aneurysm before the treatment is replaced by several smaller vortices after the treatment. The shape and area of the first opening at the entrance of the aneurysm may determine the strength and orientation of the post-treatment vortices. An individual strut can reduce the flow rate by half, but a change of the location of the strut intersection can increase the flow rate by as much as 50 percent. It appears that optimal performance can be achieved by positioning the intersection of oblique struts accurately.

Keywords: Biological Flow, Arterial Flow, Aneurysm, Stent.


(a)

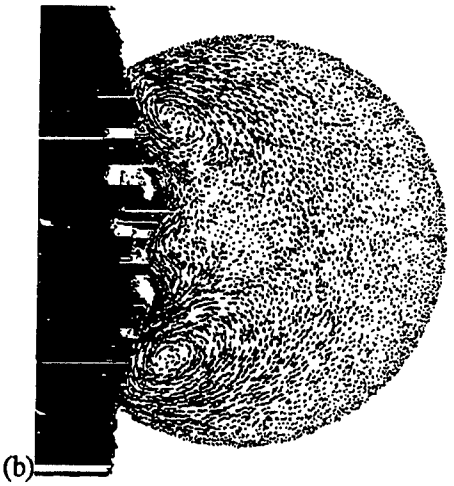


Figure 1. Velocity vector plot of flow in the aneurysm (a) before and (b) after the treatment. The vortex is broken into several vortices after the stenting.

ARTERIAL FLOWS: IN HEALTH AND DISEASE
SESSION W2G

Flow Disturbance Induced by Endovascular Stents - Whole Vessel and Cellular Considerations

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Although the use of endovascular stents has significantly reduced the incidence of restenosis following balloon angioplasty, restenosis rates remain unacceptably high (20-35% of all angioplasty procedures). Placement of a stent within an arterial segment locally injures vascular endothelium thereby stimulating thrombotic responses that contribute to in-stent restenosis. The success of a stenting procedure depends centrally on a sufficiently rapid rate of vessel re-endothelialization following stent-induced injury. Various studies suggest that this rate is likely affected by the local fluid mechanical environment in the vicinity of the stent. For instance, in vitro data demonstrate that endothelial repair after injury is sensitive to fluid mechanical forces and that endothelial cell (EC) migration is slower at the edges of flow separation zones where spatial gradients of wall shear stress are large. Furthermore, recent in vivo data suggest that in-stent restenosis preferentially develops in arterial regions exposed to low and/or oscillatory shear stress. Therefore, it is essential to establish the detailed flow environment in the vicinity of a stent and to investigat e the impact of this environment on EC function.

The presence of a stent within an artery may lead to local flow disturbance. We have used computational fluid dynamics to investigate the nature and extent of flow disturbance induced by a stent within straight and curved arterial segments under both steady and pulsatile flow conditions. Our results demonstrate that under steady flow conditions for a stent idealized as a series of circular rings, a flow separation and recirculation zone within which wall shear stress is very low occurs immediately downstream of the stent. The size of this separation zone is highly sensitive to stent wire thickness but is more weakly dependent on the spacing between stent struts. A stent placed within a curved vessel segment leads to flow separation along both the inner and outer vessel walls with the relative sizes of the separation zones along these two walls exquisitely sensitive to the angle of vessel curvature. Flow pulsatility leads to periodic appearance and disappearance of the separation zones exposing underlying ECs to purely oscillatory flow. The detailed stent geometry has a profound impact on the nature of flow disturbance. For instance, in stents modeled as continuous spirals instead of a series of circular rings, the flow separation zone downstream of the stent is occupied by forward-moving helical flow instead of recirculating flow.

To elucidate the potential impact of different types of steady and pulsatile flow on EC function, we have investigated the effect of different magnitudes of steady and purely oscillatory flow on flow-sensitive ion channels, various shear stress-responsive genes, and cell morphology in cultured bovine aortic ECs. Our results have demonstrated that ECs respond differently to the different types of flow. Although the mechanisms by which ECs distinguish among different flow waveforms remain to be elucidated, this differential responsiveness likely plays a key role in the preferential development of vascular restenosis in regions of low and/or oscillatory flow.

Keywords: stents, endothelial cells, disturbed flow, restenosis

Transitional Flow at the Venous Anastomosis of an Arteriovenous Graft*

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Individuals with end-stage renal disease would die within a few weeks or months if not sustained by some

form of dialysis therapy or a kidney transplant. Nearly 200,000 Americans currently receive some form of dialysis. Arteriovenous (AV) dialysis grafts are often constructed from an artery to a vein to provide an access site for hemodialysis patients. By bypassing the high resistance vessels (arterioles and capillaries), high flow rates can be achieved that are necessary for efficient hemodialysis. These grafts often fail within three years of construction and the majority of these failures are caused by occlusive venous anastomotic intimal hyperplasia (VAIH), which is a stenosis or narrowing of the vein downstream of the graft. The stenoses are predominately located near the venous anastomosis. While the natural healing response after surgery causes some intimal thickening, the biomechanical environment appears to be important in the development of occlusive VAIH. The biomechanical forces in the AV graft are unique with the mean Reynolds number (Re) ranging between 1000-2000, transitional (weakly turbulent) flow, generally high wall shear stress acting on the vein, a region of flow separation, and pressure fluctuations that vibrate the vein wall and surrounding tissue.

We present experimental and computational results that describe the level and distribution of velocity fluctuations within the venous anastomosis of an arteriovenous graft. Steady-flow in vitro studies (Re = 1060 and 1820) were conducted within a graft model that represents the venous anastomosis to measure velocity by means of laser Doppler anemometry. Numerical simulations with the same geometry and flow conditions were conducted by employing the spectral element technique. We also report results of a porcine animal study in which the distribution and magnitude of vein-wall vibration on the venous anastomosis were measured at the time of graft construction. Preliminary molecular biology studies indicate elevated activity levels of the extracellular regulatory kinase ERK1/2, a mitogen-activated protein kinase involved in mechanotransduction, at regions of increased vein-wall vibration. These findings implicate velocity fluctuations and the associated turbulence-induced vein-wall vibration in the development of intimal hyperplasia in arteriovenous grafts. Further research is necessary, however, in order to differentiate the vibration effect from that of flow separation.

Keywords: hemodynamics, arteriovenous grafts, transitional flow, CFD, vibration

*Supported by the Whitaker Foundation and W. L. Gore & Associates, Inc.

Stent Restenosis and Arterial Mechanics

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Stents are tiny metallic tubes intended to prop open arteries diseased with atherosclerosis. While they offer advantages in cost and patient trauma over surgical treatment, stents suffer from relatively high failure rates of 20% - 30% due to restenosis. The development of restenosis may be related to the mechanical conditions in the stented artery. Stents provoke the development of strong secondary flow patterns due to compliance mismatch, and near-wall flow stagnation. Computational flow studies have demonstrated that the degree of flow stagnation depends strongly on the stent strut spacing. Flow stagnation and low wall shear stresses affect the artery wall response, including platelet adhesion and endothelial cell regrowth. Stent implantation also creates non-physiologic stress concentrations in the artery wall. Computational modeling has revealed that the artery is subjected to very high stresses at the ends of the stent, although elevated stresses appear throughout the stented segment. Arteries respond to stress concentration by building up additional tissue. The responses of the artery wall to changes in the mechanical environment are all related to stent design. A new stent has been designed that minimizes compliance mismatch, thus minimizing the mechanical trauma to the artery wall. Initial tests confirm the beneficial effects of this new design.

This work was supported by NHLBI/NIGMS MBRS SCORE grant (S06 GM08205), the Florida International University Foundation, and a Research & Education Fund Seed Grant from the RSNA.

ARTERIAL FLOWS: IN HEALTH AND DISEASE
SESSION W3G

Predicting Outcomes of Cardiovascular Surgery: Mathematical Models and Experimental Validation

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A new approach for cardiovascular treatment planning has been proposed in which the physician utilizes computational tools to construct and evaluate a combined

anatomic/physiologic model to predict the outcome of alternate treatment plans for an individual patient [1]. In order to ensure that these predictive tools are clinically relevant, they must faithfully represent the anatomy and physiology of individual patients. Computational simulations involve solving the governing equations of blood flow on a domain and prescribing boundary conditions to account for the vasculature downstream. These outflow boundary conditions have been generally limited to prescribed velocity, pressure or traction. The limitation of this approach lies in the fact that this necessitates a priori knowledge of the distribution of the blood flow or the outlet pressure for the branch vessels. This information is rarely known in most practical situations and depends upon the solution within the modeled domain. A new approach to obtain boundary conditions applicable to blood flow is described whereby a finite element method is used for the region where the governing equations are nonlinear or not amenable to analytic solution and a lumped parameter model or linear wave equation is used for the vasculature downstream. We adopt a variational multiscale method to derive a variety of consistent boundary conditions.

Experimental validation studies were performed using data collected from experiments involving eight pigs. In each animal, we created an aortic constriction, or stenosis, by tying polyester (Dacron) umbilical tape around the descending thoracic aorta to restrict blood flow and create a simulated diseased state. A 10 mm diameter polyester (Dacron) graft was attached to the thoracic aorta proximal and distal to the constriction to provide an alternate path for blood flow. Blood is divided between the native aorta and the bypass graft and combines downstream of the stenosis. Magnetic resonance angiography was used to acquire three-dimensional anatomic images, while phase contrast MRI (PC-MRI) was used to collect velocity data at four different locations: the proximal aorta (inlet), the mid-aorta (aorta), the graft, and the distal aorta (outlet). The experimental protocol is shown in figure 1. Numerical predictions of flow rate were compared with magnetic resonance imaging data in eight pigs. Excellent agreement is obtained for both the three-dimensional method and the one-dimensional method with empirically-derived stenosis and branch loss terms.

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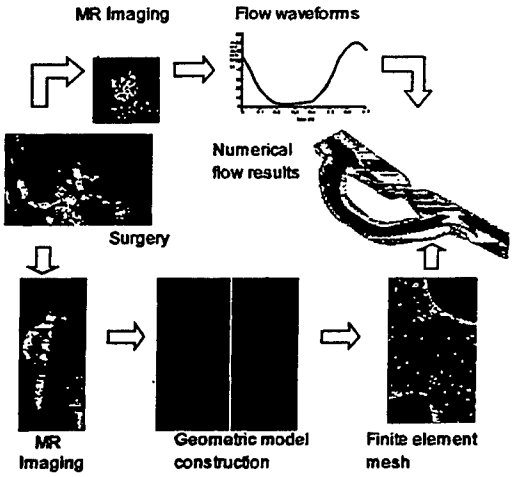


Figure 1. Procedure to combine anatomic and physiologic data for blood flow computations.

Keynote

Compressible Flow with Chemical Reaction

Organizer:
Professor Hans Hornung
(California Institute of Technology)

COMPRESSIBLE FLOW WITH CHEMICAL REACTION
SESSION T2F

Computational Methods for Hypersonic Flows: Application to Double-Cone Flows

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We summarize the current approaches for the numerical simulation of hypersonic reacting flows. We then apply one of these methods to a double-cone test case to illustrate some of the key issues associated with the simulation of hypersonic flows. Double-cone flows are characterized by a large region of separation, a strong shock interaction, and a leading-edge viscous-inviscid interaction. These flow features have very strong gradients, requiring high accuracy shock-capturing methods with extremely

fine grids. In addition, we find that to obtain good agreement with the experiments, we must simulate the flow in the hypersonic nozzle to predict the degree of vibrational and chemical nonequilibrium in the test section.

Effects of Boundary Layers and Wakes on Shocks and Flames

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This presentation describes some of our latest simulations of interactions of shocks, flames, and boundary layers in open channels and shock tubes. Solutions of the two- and three-dimensional reactive Navier-Stokes equations are performed for low-pressure acetylene-air or ethylene-air mixtures. The problem of a flame propagating in a small channel and its interaction with its self-induced boundary layer is considered first. Subsequent more complicated shock-tube simulations, involving interactions of shocks, flames and boundary-layer, show a complex sequence of events, starting from the interactions of an incident shock with an initially laminar flame, formation of a flame brush, deflagration-to-detonation transition, and, finally, the with cellular structure. The latest simulations show that the presence of a boundary layer or a wake in the flow can have a similar and significant influence on flame acceleration behind reflected shocks.

* This work was done in collaboration with James Ott, Alexei Khokhlov, and Vadim Gamezo.

Miniaturization of Explosive Technology

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Condensed phase explosives have traditionally been used in military, mining and demolition applications that have a charge size on the order of a meter or a sizable fraction of a meter. Less traditional applications include explosive cladding, welding, forming, precision cutting and drilling of recovered materials. The predominant bulk of these non-traditional applications use charges whose smallest dimension is at least a sizable fraction of a meter in width, length or extent. In either case, the corresponding length of the Chapman-Jouguet, ZND, detonation reaction zone in the explosive is a small fraction of a millimeter so that the scale ratio of the device size to the reaction zone length is huge. This size discrepancy of the device size, to the width of the controlling power generating front (the detonation reaction zone) presents difficult and fascinating scientific and engineering challenges. One successful attack has been to use asymptotic considerations about the reaction zone to understand the dynamics of the front in the limit that the inverse scale ratio (zone thickness to device size) goes to zero. This theory, which lies in the domain of quasi-one dimensional, quasi-steady theory, forms the basis of almost the entirety of what is well-known about detonation and the design of explosive systems.

Recent interests in miniaturized explosive systems, and the introduction of explosive elements into micro and nano-scale devices is forcing us to confront the limits of the well-understood theory and revisit and possibly reinvent detonation theory at scales that are well below the sizable fraction of a meter scale. In the newly envisioned applications of miniaturized system (which I will define as being at one millimeter and below), one lives in an entirely new realm. While the energy density of the explosive element is unchanged from the large scale, the quantities of explosive used and total energy released (proportional to the total mass) diminish typically by the cube of a charge dimension, when examined against a geometrically similar, but larger, traditional system. Steady detonation is paramount in the larger traditional systems and transient detonation is of a secondary concern. In the miniaturized system this situation is entirely reversed. Criteria for initiation and propagation of detonation and classical concepts used in engineering traditional (larger) systems are not always appropriate for miniaturized systems since the events under consideration are inherently transient and often multi-dimensional.

In this talk I will attempt to lay out a set of issues that are required to construct a corresponding theory of detonation for miniaturized devices and discuss some of the tools that need to be engaged for the explosives community to design small reliable devices. Specifically we will discuss the critical role played by geometry and shock diffraction in the ignition and propagation of detonation in small system. We will discuss how the numerical design tools developed in the engineering method of detonation shock dynamics might be applied to miniaturized systems with models for real equation of state and multiple layers of materials. Also we will talk about how one might model solid to liquid to gas phase transitions in energetic materials, and how those consideration may impact our understanding of ignition and propagation in very small systems.

COMPRESSIBLE FLOW WITH CHEMICAL REACTION
SESSION W2F

The Role of Transverse Waves in Gaseous Detonation

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The nature of the detonation front in gases has been the subject of investigation and speculation since the very first detonation experiments. Many unresolved issues remain but recent experimental and numerical studies have more sharply focused the inquiries onto the role of the transverse waves in maintaining the chemical reaction process. I will describe recent experimental work in our laboratory using simultaneous visualizations of a chemical species (OH) and density gradients in the reaction zones of propagating detonations. We are able to visualize the reaction zone structure associated with leading shock velocity oscillations and the associated transverse waves. Comparisons with direct numerical simulations and detailed considerations about the flow near the triple points, i.e., intersection of main shock and transverse waves, are used to investigate the role of the transverse waves. The connection to cellular regularity, to the formation of unreacted pockets, and to cellular substructure is discussed.

Mechanisms of Detonation Formation

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Emergence of a detonation in a homogeneous, exothermically reacting medium can be deemed to occur in two phases. The first phase processes the medium so as to create conditions ripe for the onset of detonation. The actual events leading up to preconditioning may vary from one experiment to the next, but typically, at the end of this stage the medium is hot and in a state of nonuniformity. The second phase consists of the actual formation of the detonation wave via chemico-gasdynamic interactions.

This talk will concentrate on the second phase. It will explore, via accurate and highly resolved numerical computations, the variety of scenarios by which initial nonuniformities in temperature and/or reactant concentrations can lead to the establishment of a detonation. We shall consider planar as well as annular configurations, and single as well as multistep kinetics. An attempt will be made to identify key mechanisms that persist across configurational or kinetic variations.

Isolating a Global Mechanism for Self-Initiation of Detonation

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The ability of an initially laminar flame to transition to a detonation is distinguished from direct "blast" initiation of detonation in that the condition required for the onset of detonation is self-generated by the accelerating flame and not by the initiation source. Since flame acceleration mechanisms involve the entire spectrum of gasdynamical and chemical processes (i.e., diffusion, interface instability, turbulent mixing, and shock-induced combustion), it is unlikely that a single fundamental theory for DDT can be formulated. However, the final stage of DDT, namely the appearance and amplification of shock waves from discrete explosion centers, appears to be a universal phenomenon in all initiation modes, even for direct "blast" initiation at the critical condition. Thus, this mechanism of the final onset of detonation may be more amenable to developing a single theory for the origin of a detonation wave.

In order to create a well-defined condition that captures the features of the final onset of DDT, a turbulent, sonic jet of combustion products may be used. While this approach appears promising, the results of jet initiation of detonation reported in the literature vary widely. In comparing the diameter of the jet, djet, to the critical diameter of the mixture, which is indicative of the chemical length scale, the results to date vary in djet/dc from 0.5 to 5. This wide variation is likely a result of the different conditions used to create the turbulent jets (constant volume explosions, turbulent flames, shock-accelerated flames, etc.). In order to provide a better-quantified jet, a constant volume explosion state is desired to drive a choked-orifice jet. The study reported here uses a reflected detonation from a perforated orifice plate of variable hole geometry, which is correlated to the fundamental characteristic length scale of the mixture (e.g., cell size). Results with both fuel/oxygen and fuel/air mixtures are reported. These results are compared to theoretical calculations of the induction time resulting from the mixing of burned products and unburned reactants. Discussion of these results suggests a more universal criterion upon which a theory of self-initiation could be based. Miniaturization of Explosive Technology

Keynote

Developments in Composite Materials and Structures

Organizer:
Professor Michael W. Hyer
(Virginia Tech)

DEVELOPMENTS IN COMPOSITE MATERIALS AND STRUCTURES
SESSION M2F

Self-Healing Composites

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Thermosetting polymers, used in a wide variety of applications ranging from microelectronics to composite airplane wings, are susceptible to damage in the form of cracking. Often these cracks form deep within the structure where detection is difficult and repair is virtually impossible. Inspired by biological systems in which damage triggers a healing response, a new structural polymeric material was recently developed [1] with the ability to *autonomically* heal cracks. Whenever damage occurs in a self-healing polymer, the repair process is triggered and after sufficient healing time, the inherent strength and toughness of the material is recovered. Self-healing polymers are designed to heal the microcracks that occur naturally during fatigue, thereby preventing large-scale cracks from forming. As a result, the fatigue life of these materials is expected to be significantly extended. The future of autonomic materials systems will include both self-regulatory and self-generating processes integrated in one materials system. New directions of research in this area will be discussed.

1. White, S.R., Sottos, N.R., Morre, J., Geubelle, P., Kessler, M., Brown, E., Suresh, S., and Viswanathan, S. (2001), *Nature*. **409**, 794.

On the Structural Mechanics of Sandwich Structures of Composite Materials

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The use of sandwich structures is increasing exponentially with time. Today one finds sandwich structures in aircraft, spacecraft, missiles, helicopters, automobiles, trucks, naval vessels, pleasure boats, bridges, buildings, housing, skis, wind energy blades, boxes and many other applications.

Sandwich structures are so superior to other architectures in bending stiffness and increased load carrying capability that it more than makes up for the increased cost and manufacturing complexities that these structures require.

There are primarily four different sandwich architectures involving namely honeycomb core, solid or foam core, truss core and web core configurations.

To fully utilize sandwich structures it is imperative to develop and use the best methods of analysis and design to make the most efficient, lightweight structures that employ the best of the available composite materials for the faces and the best available core materials.

Various aspects of analysis, design and minimum weight optimization methods will be discussed for sandwich beams, plates and shells subjected to mechanical, thermal, hygrothermal, forced vibration, impact and buckling loads, including high strain rate effects.

Some historical aspects, present status and future opportunities and challenges for the increased use of composite material sandwich structures will also be presented.

Keynote

Nonlinear Dynamics and Control

Organizer:
Professor John L. Junkins
(Texas A&M University)

NONLINEAR DYNAMICS AND CONTROL
SESSION M2Q

Extrapolation of On-Orbit Nonlinear Flexible Dynamics Based on Ground Test Model Updating

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The MIT/MACE-II flight experiment, which flew on the International Space Station from August 2000 to August 2001, is an investigation of high authority control

techniques for geometrically nonlinear flexible structures. In this context, geometric nonlinearity indicates changes in dynamics (modal frequencies and residues) under joint configuration changes. The structure is assumed to move slowly, so that rate-dependent terms are negligible. A modeling technique is needed to predict on-orbit nonlinear dynamics, based on 1g testing. Hence, a physical model is needed, so that gravity effects can be accommodated while updating the model to test data, and then removed for prediction of 0g response. The ground tests cannot encompass the entire configuration space, since gravity torques overpower the available control torques, requiring extrapolation of dynamic response from the nominal, tested configuration. The models are intended for development of high authority control, encompassing tens of flexible modes within a 100Hz bandwidth, requiring model accuracy on a par with state of the art measurement modeling techniques (modal frequencies captured to within a few percent). The paper describes a parameter-varying (PV) modeling approach to capturing variations in physical model stiffnesses, masses and inertias. The PV approach allows the closed form computation of parameter dependent frequency response matrices, which are used as the basis for an iterative, nonlinear model updating algorithm. Experimental results from application of the approach to MACE-II are presented to demonstrate that the resulting quality of fit to the experimental data is on a par with state of the art system identification techniques.

Vibrational Characteristics of an Outrageously Long, Incredibly Weak, Rotating Flexible Beam

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In this paper we concern ourselves with the vibrational characteristics (natural frequencies and mode shapes) of a long, rotating, flexible beam with small stiffness. The governing partial differential equation of motion leads to a linear differential eigenvalue problem that produces the natural frequencies and mode shapes. For the special case of a long beam with small stiffness, a small perturbing factor is introduced so that the differential eigenvalue problem takes the form of a singular perturbation equation with a turning point. An approximate solution is found that satisfies the problem up to the order of the perturbing factor. The approximate solution is found to depend upon odd integer Legendre polynomials and the Airy functions. The results are compared against those obtained using traditional modal methods. Keywords: Natural Frequencies, Mode Shapes, Rotating Beam, Singular Perturbation.

The Application of Clifford Algebras for Computing the Sensitivity Partial Derivatives of Linked Mechanical Systems

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The calculation of sensitivity partial derivatives is a frequently occurring task during the engineering design and control process. The problem begins with the development mathematical model of the physical system. Traditionally there have been two ways of developing the sensitivity partial derivatives: (i) analytical models, and (ii) numerical models using finite difference-like techniques. The analytical models are preferred when available, though the additional modeling and software develop and checkout may be expensive. The numerical methods frequently require iterative strategies to maintain the required numerical accuracy. This paper presents a Clifford algebra approach for generating: (i) sensitivity partial derivatives, and (ii) state and parameter state transition matrix partial derivatives. Clifford algebra is used to embed the Cartesian c oordinates of vector models into spaces of higher dimension, where the higher dimensions represent hyper-complex directions. By embedding small perturbations in the hyper-complex parts of the embedded coordinates, the paper demonstrates that one recovers one partial derivative column or state transition matrix column for each hyper-complex direction. Clifford algebra generalizations of normal engineering functions and integration algorithms are presented. Several applications using quaternion versions of Clifford algebra are presented. The quaternion applications demonstrate that one can recover three columns of the partial derivatives for each calculation. No explicit coding for the partial derivatives or state transition matrix is required; one only codes the function to be evaluated, and the partial derivatives are recovered from the hyper-complex part of the function. The applications demonstrate that high-accuracy is possible and that no differences of functions need to be computed to generate the partials.

Keywords: Sensitivity Derivatives, Multibody, Clifford Algebra, Numerical Methods

NONLINEAR DYNAMICS AND CONTROL
SESSION T2Q

Feedback Stabilization of a Rolling Sphere: Application to a Spherical Mobile Robot

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Feedback stabilization of a spherical mobile robot refers to the task of converging a sphere, rolling without slipping on a horizontal surface, from any initial configuration to an arbitrary final configuration. The configuration of the sphere is represented by the two Cartesian coordinates of the center of the sphere and the three Euler angles of the orientation of the sphere. This is a challenging problem since the kinematic model of the sphere cannot be reduced to chained form and hence all established non-holonomic motion planning and control algorithms are rendered inapplicable. In this paper we address this problem by presenting a control algorithm that utilizes two control actions that are applied alternately. The individual control actions cause trajectories of the sphere that are circular arcs or straight line segments. Through judicious sequence of the individual control actions based on state feedback, we construct a control strategy that stabilizes the sphere to a desired configuration. We first present the algorithm for four-dimensional reconfiguration of the sphere, where the two Cartesian coordinates and two orientation coordinates are converged to desired values. The inherent flexibility of this algorithm enables us to additionally achieve the complete five-dimensional reconfiguration of the rolling sphere. The results are presented for the two general categories of motion that arise from initial conditions of the sphere, discussed under $n > 1$ and $n < 1$ cases. Special cases that do not belong to either category can be dealt by transforming them into one of the two general categories by applying stable preliminary control actions. Simulation results are presented to demonstrate the efficacy of the strategy.

Rigid-Body Output Feedback Attitude Control Subject to Actuator and Rate Saturations

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In our paper, we consider the feedback control problem associated with attitude tracking for a rigid body subject to torque and rate saturation limits. This problem is motivated by the recent interest in control of low-cost walking robots and virtual reality gadgets. Whereas no rate-gyro measurements are utilized, the controller rigorously enforces any/all actuator constraints present within the system. Our proof is constructive and accomplished by developing a passivity based dynamic estimator that enables globally stabilizing feedback mechanisms. We place no additional restrictions on the body angular rates or other small angle assumptions. All the theoretical results will be illustrated through numerical simulations. Finally, we will discuss extensions to our controller formulation when inertia parameter uncertainty is present within the system model.

NONLINEAR DYNAMICS AND CONTROL
SESSION W2Q

Concurrent Feedforward/Feedback Controller Design for Uncertain Structures

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This work discusses the concurrent design of a feedforward time-delay filter and a linear state feed-back controller. The optimization is carried out using a cost function which weights both, disturbance rejection and control tracking performance. A minimax optimization scheme is employed to achieve robustness with respect to parameter deviations. Analytical gradients of the cost function are exploited to expedite convergence of the optimization procedure. The proposed technique is illustrated on the Floating Oscillator benchmark problem.

Spacecraft Relative Orbit Geometry Description Through Orbit Element Differences

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The relative orbit geometry of a spacecraft formation can be elegantly described in terms of a set of orbit element differences relative to a common chief orbit. For the non-perturbed orbit motion these orbit element differences remain constant if the anomaly difference is expressed in terms of mean anomalies. A general method is presented to estimate the linearized relative orbit motion for both circular and elliptic chief reference orbits. The relative orbit is described purely through relative orbit element differences, not through the classical method of using Cartesian initial conditions. Analytical solutions of the relative motion are provided in terms of the true anomaly angle. By sweeping this angle from 0 to 2π, it is trivial to obtain estimates of the along-track, out-of-plane and orbit radial dimensions which are dictated by a particular choice of orbit element differences. The main assumption being made in the linearization is that the relative orbit radius is small compared to the Earth relative orbit radius. The resulting linearized relative motion solution can be used for both formation flying control applications or to assist in selecting the orbit element differences that yield the desired relative orbit.

Vision-Based Control of Robots on Unconstrained Platforms in Space

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Consider the practical problem of applying image information from two or more cameras that are fixed to an unconstrained (say, orbiting) platform in order to control a high-degree-of-freedom robot arm whose base is also fixed to the same platform. Consider, in particular, the situation where the object of the manipulation resides on a separate unconstrained platform. How will the internal degrees of freedom of the on-board robot be guided in order, robustly, to bring about precise closure of the end-of-arm tool with selected junctures on the target body? The paper details a robust means by which the strategy of Camera-Space Manipulation [1,2] can be employed together with an Extended Kalman Filter on an analogous terrestrial problem: the bringing to precise closure of a mobile-base-mounted arm with a separate "target" body using on-board cameras. In particular, the paper discusses the identical roles of the holonomic degrees of freedom of the on-board arm in the two kinds of problem. More importantly, it illustrates the analogy between the control of kinematically nonholonomic degrees of freedom of the two drive wheels of the mobile base and the control of the dynamic response of the arm-bearing space platform in response to exercise of the internal degrees of freedom of that arm. The method is based upon the estimation of "camera-space kinematics" – that is, the response in a given 2-Dimensional image plane, or "camera space" to incremental movement of the holonomic degrees of freedom of the robot arm – even as the maneuver ensues. Experimental results from the terrestrial analog to the space-based system are presented and the inherent robustness and precision of the presented control strategy is illustrated.

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Keynote

Mechanics of Soft Actuators and Sensors

Organizer:
Professor Sia Nemat-Nasser
(University of California, San Diego)

MECHANICS OF SOFT
ACTUATORS AND SENSORS
SESSION W2C

Modeling of Swelling/Deswelling Kinetics of Hydrogels: A Chemo-Electro-Mechanical Approach

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Ionic hydrogels are composed of cross-linked polymer networks containing ionizable groups immersed in

an aqueous solution. Hydrogels are capable of undergoing large reversible deformations in response to changes in several environmental factors. In this paper, we develop models based on partial differential equations for predicting the swelling/deswelling kinetics of hydrogels in buffered pH solutions. The concentration profiles of the different ions within the hydrogel at different time instants are computed using coupled Nernst-Planck and Poisson equations. The deformation of the gel is then computed using an analytical mechanical equation for the cylindrical hydrogels modeled. The time evolution of hydration (ratio of volume of fluid to volume of solid) inside the gel is obtained.

The numerical simulations have been compared with experimental data. Swelling and deswelling experiments have been performed on cylindrical hydrogel of different diameters in glass channels. The pH of the solution was changed from 3 to 6 and the change in the diameter of the hydrogel was observed with respect to time. The height remains the same due to constant channel height. The experimental value of hydration was obtained from the diameter. The numerical simulations were done on the hydrogels for pH change from 3 to 6 and compared with the experimental data and they matched well. Comparison was also made with the kinetic model developed earlier based on the Donnan Theory and where the electrical coupling between the ions was neglected. Figures 1 and 2 show the comparison between the experimental data, the new kinetic model (model 2) and the older kinetic model (model 1) for the swelling and deswelling of a hydrogel of diameter 150 (m. It is seen that although both the models predict the kinetic well, the new model (introduced in this paper) can predict the process more accurately. However, similar comparisons with larger gels show that both the models give the same results, which is very close to the experimental data. Hence, it can be concluded that the effect of the electrical coupling between ions becomes more important in smaller gels as compared to larger ones.

The mechanical equation for deformation is a simple analytical one. Future work involves replacing it by a more general equation of motion for getting the deformation. The model has been developed in a general sense, and by incorporating some changes, it can be used for predicting kinetics of bio-responsive and electro-responsive gels. Future works in that area is also going on.

Keywords: modeling, hydrogels, kinetics, experiments.

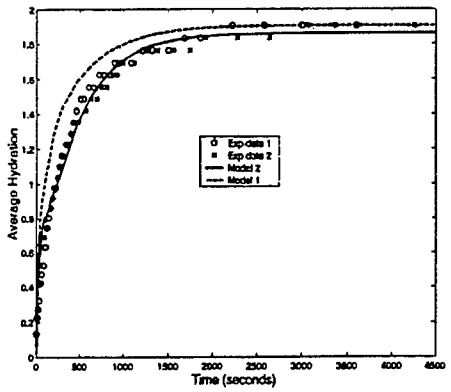


Fig 1. Swelling of 150 (m gel for pH change 3 to 6.

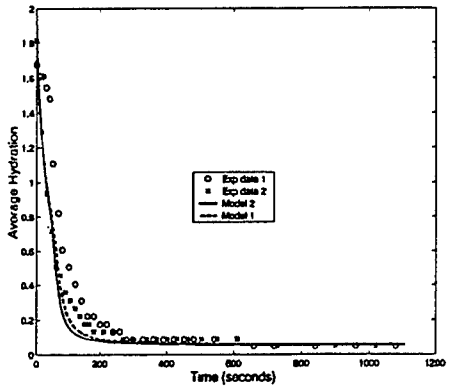


Fig 2. Deswelling of 150 (m gel for pH change 6 to 3.

Fundamentals of Ionic Polymer Composites As Biomimetic Sensors, Soft Actuators and Artificial Muscles

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This presentation will cover first a brief summary of the fundamental properties and characteristics of Ionic Polymeric-Conductor Composites (IPCC's) as biomimetic sensors, soft robotic actuators and artificial muscles. It will then address such fundamentals in more details. In particular, it will discuss the manufacturing techniques including a comparison between chemical plating and physical loading of a conductor phase, the electronic and electromechanical characteristics of IPCC's, the phenomenological modeling of the underlying sensing and actuation mechanisms in IPCC's as well as some potential industrial and medical application areas for IPCC's, respectively. It will also discuss a number of manufacturing methodologies in developing high force

density IPCC's, as well as, dry IPCC's. This presentation will include videos as well as live demonstrations.

Electromechanical Modeling and Control of Ionic Polymer Materials

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Two different types of modeling techniques for ionic polymer materials will be discussed. An empirical approach based on measurements of the input-output response of cantilever samples will be introduced. This modeling technique enables simultaneous modeling of electromechanical sensing and actuation. The model is based on the experimental observation that charge flow in the polymer is directly related to the induced strain in the material [1]. The model can be scaled to account for changes in sensor and actuator geometry. A second modeling approach based on charge and water transport within the ionic polymer is introduced. This model relates the motion of charged and uncharged species within the polymer to the mechanical deformation. The internal state variables of the model are the species concentration, water velocity, pressure gradient, current density, and electrical potential. Analysis of the model demonstrates that it predicts the existence of a relationship between charge and strain in the polymer. Furthermore, we demonstrate that this model reduces to the static model proposed by de Gennes, et a [2], in the case when the unsteady terms are neglected and the concentration gradient in the material is zero. Both modeling techniques are applied to the development of control algorithms for positioning of ionic polymer materials. The advantages and disadvantages of each modeling technique are discussed.

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[2] de Gennes, P., Okumura, K., Shahinpoor, M., Kim, K., 2000, "Mechanoelectric Effects in Ionic Gels," Europhysics Letters, vol. 50, no. 4, pp. 513-518.

MECHANICS OF SOFT
ACTUATORS AND SENSORS
SESSION R2C

Theoretical and Experimental Investigations of Polymer Gels as Adaptive Materials

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The increasing precision of shapes and displacements required by structures in both, aerospace and precision mechanics, as well as the desire of health monitoring of damaged components, lead to the concept of structures with actuatoric and sensoric capabilities. The basis for the adaptive structures are multi-functional materials.

One very promising representative of these materials are polyelectrolyte gels. These gels - consisting of a polymer network with fixed ionizable groups and a liquid phase with mobile ions - are distinguished by enormous swelling capabilities under the influence of external physical or chemical stimuli. These properties make them very attractive for a new generation of "pseudomuscular" actuators.

In the present work we investigate chemically and electrically stimulated polymer gels. Based on the theory of Flory [1] as well as on a coupled multi-field formulation involving chemo-electro-mechanics, different mathematical models describing the swelling and bending behavior of these gels are presented. For the numerical simulation, space-time finite elements are used.

The numerical results of the electric potential, conducted on a multigrid, show a promising correlation with experiments in which the Donnan potential has been registered in PAAm/PAA gels with a new microelectrode technique. For anionic gels, in both theory and experiment "hyperpolarisation", i.e. increased negativity, can be found on the anode-side of the gel and "depolarisation" on the cathode-side. These changes in the electric potential which are supposed to affect swelling or deswelling of polyelectrolyte gels lead to bending motions of the gel.

As a sample application, a short video sequence of an EAP gripper in action [2] is presented demonstrating the

opposite bending behavior of anionic and cationic polymer gels under the influence of an electric field.

Keywords: polyelectrolyte gels, numerical simulation, potential measurement, EAP gripper

[1] P.J. Flory, Principles of Polymer Chemistry, Cornell University Press, Ithaca, New York, 1953

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Design and Optimization of Electrostrictive Polymer Based Composites

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We present a micromechanical approach for the optimal design of electrostrictive composites based on ferroelectric polymers. Electrostrictive response is inherent in any solid, but is usually too small for practical applications. This could be overcome by composite technology, where a second phase with high permittivity is added to the ferroelectric polymers. In this work, the connection between macroscopic properties of composites and their microstructural details will be established, and the optimal volume fraction and morphology of the second phase will be identified.

Nafion Based Smart Membrane as an Actuator Array.

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Actuator arrays have been the object of great research effort in the last decade. Some key applications are positioning system for small objects using distributed manipulation, micro mirror devices and microwave antenna of slotted wave-guide type. In search of an alternative to piezoelectric and micro-machined thermal/mechanical actuator arrays, we developed an actuator array based on Nafion. Where the electrode metal can be gold or platinum and the use of a copper layer on top of the base metal (platinum) proved to enhance the deformation of the actuator. We prepared 3 composites from Nafion 117 (180-micron-thick), Nafion 115 (125-micron-thick) and Nafion 112 (50-micron-thick) to study the influence of the membrane thickness on actuation. We prepared a 3x3 actuator array using Nafion 112 and electrode patterning. We used hydrophobic masks sandwiching the Nafion membrane to geographically selectively exchange the metal complex. The cells in this array showed a large deformation followed by relaxation because the actuation strain has a short lifetime after the polarity change and the deformed shape was not a mechanical equilibrium. We are trying to modify this array to achieve switching of the cells between 2 stable positions

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MECHANICS OF SOFT
ACTUATORS AND SENSORS **SESSION F2C**

Tailoring Actuation Response of IPMC's

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Ionomeric polymer-metal composites (IPMCs) are soft actuators and sensors. They consist of a thin polyelectrolyte membrane of Nafion, Flemion, or Aciplex, plated on both faces by platinum, gold, or both to improve surface conductivity, and is neutralized with the necessary amount of counter-ions, balancing the charge of anions covalently fixed to the backbone membrane. When a thin strip of an IPMC membrane in the hydrated state is stimulated by an application of a small alternating potential, it undergoes a bending vibration. Under a suddenly applied DC voltage, the composite quickly bends towards the anode then the strip slowly relaxes in the opposite direction for metallic cations but not for TBA. The speed of the initial deflection depends on the cation and it is rather slow for TBA. Through a systematic exploration and quantitative experimentation, we have developed techniques to incorporate combined ions in order to tailor the response of the IPMC for given application. Micromechanical models are used to understand the basic phenomena and to identify critical parameters. These and related issues will be discussed.

Keynote

Material Failure at High Strain Rates

Organizer:
Professor Y. D. S. Rajapakse
(Office of Naval Research)

MATERIAL FAILURE AT HIGH STRAIN RATES
SESSION M2C

Dislocation Mechanics Based Description of Dynamic Deformation and Fracturing

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Dislocation model descriptions of polycrystalline material strength properties have improved hand-in-hand with improved experimental test methods and diagnostics being applied to a wide spectrum of structural materials over the full range of imposed strain rates from conventional laboratory tests to shock wave loading. Under dynamic loading, strain rate (and temperature) influences are interpreted mainly through averaged response of dislocations (within slip bands) overcoming point-like obstacles within the polycrystal grain volumes [1]. Brittle and ductile fracturing behaviors are gauged, respectively, by the grain-size-determined microstructural stress intensity characterizing the grain boundary obstacles to embryonic slip band egresses [2] or by the imposed deformations necessary to bring particle hole-joining separations to smaller critical distances [3,1]. The development of such model plasticity descriptions, that are employed in current hydrocode computations, has an interesting history based on analogy of slip band, or twinning, stress concentrations and fracture mechanics analyses [4], even extending in the latter case to a continuous indentation stress-strain method of evaluating the elastic, plastic, and cracking behaviors of materials [5].

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Some Experimental Aspects of Dynamic Fracture Mechanics

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Experimental dynamic fracture mechanics addresses phenomena that occur on a very short time scale, typically of the order of a few microseconds. In this talk, we will present specific experiments that were developed in our laboratory, as follows :

1. A framework for the investigation of dynamic mode II fracture
2. Some facts about one-point bend impact experiments
3. The importance of thermomechanical couplings in fracture.

Dynamic mode II crack initiation can be studied using one-point impact applied to an unsupported precracked plate. The addition of fatigue precrack suppresses the negative mode I component that would develop in a notched plate. It can be shown that the crack-tip experiences essentially mode II loading. The applicability of this approach to the investigation of dynamic failure mode transitions will be illustrated by experimental results.

Next, we address the one-point bend impact experiments, as a tool to investigate dynamic mode I fracture, generally, or as an extension of the Charpy test for notched specimens. The accurate sequence of specimen fracture and loss of contact with the impacting bar will be discussed. The feasibility of this technique will be discussed in the light of results obtained for A508 steel tested in the lower shelf regime.

Finally, we will present some results on the extent of thermomechanical couplings, with emphasis on polymers. It will be shown that a small thermocouple embedded close to the crack-tip can provide reliable information of the transient temperature changes that accompany crack initiation. Two cases will be exposed: first, mode I fracture in a brittle polymer to illustrate the thermoelastic coupling effect. Next we will show results concerning the thermoplastic effect ahead of an adiabatic shear band.

Analysis of Failure Mode Transition Speeds in an Impact Loaded Prenotched Plate

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Kalthoff and Kalthoff and Winkler tested pre-notched plates made of an C-300 maraging steel and impacted on the notched side by a cylindrical projectile made of the same material as the plate and moving parallel to the axis of the notch. For a fixed radius of the notch tip, they found that at low impact speeds the material failed due to the initiation of a crack from a point on the surface of the notch tip and propagated at an angle of 70 degrees to the notch axis. However, at higher impact speeds, a shear band initiated from a point on the surface of the notch-tip and propagated essentially parallel to the notch axis. Mason et al. and Zhou et al. performed experiments similar to those of Kalthoff. For impact speeds and the notch-tip radius used, they found that only a shear band initiated from a point on the notch surface.

The problem has been analyzed numerically by Zhou et al., Needleman and Tvergaard, Batra and Nechitailo, Batra and Gummalla, Batra and Jaber, and Batra, Jaber and Malsbury and analytically by Lee and Freund. These authors have assumed that a plane strain state of deformation prevails in the plate. Three dimensional analysis of the problem by Batra and Ravisankar has shown that deformations at the midsurface of the plate correspond to those obtained from the plane strain analysis of the problem. However, deformations of the midsurface of the plate are quite different from those of it's front and back surfaces where test observations are made. Brittle failure, as indicated by the maximum principal tensile stress attaining a critical value, and ductile failure in the form of an adiabatic shear band ensue first from a point on the midsurface of the plate and propagate outwards.

Assuming that a shear band initiates at a point when the effective stress there has dropped to 90% of it's peak value there, and brittle failure ensues when the maximum principal tensile stress at a point equals 2.34 times the quasi-static yield stress of the material in simple tension or compression, Batra and Jaber have ascertained the failure mode transition speed for four different thermoviscoplastic relations. They calibrated these against the same torsion test of Marchand and Duffy by solving the corresponding initial -boundary-value problem, and found values of material parameters so that the computed shear stress-shear strain curve matched closely with the experimental one. Batra, Jaber and Malsbury found that for an elliptic notch tip, a shear band always preceded the brittle failure. However, for other shapes of the notch-tip, the failure mode transitioned from brittle to ductile with an increase in the impact speed. The presence of a circular hope in front of the notch tip strongly influences where a failure mode initiates and which failure mode occurs first.

Some of the papers cited above may be found in the special issue, "Failure Mode Transition Under Dynamic Loading", of the *Int. J. of Fracture*, Vol. 101, 1-180, 2000; others are cited in papers of this issue.

Support of the work by the ONR is gratefully acknowledged.

MATERIAL FAILURE AT HIGH STRAIN RATES
SESSION T2C

Intersonic Shear Rupture Along Weak Planes: From Earthquake Fault Rupture to the Rupture of Atomic Planes

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Intersonic shear cracks propagating along weak planes in otherwise constitutively homogeneous linear elastic solids were first modeled by Freund through a steady state elastodynamic analysis. Experimental confirmation of the existence of such a process followed twenty years later through the direct observation of intersonic shear rupture of two identical, weakly bonded, Homalite plates subjected to asymmetric impact. These shear cracks which

propagated at speeds between the shear and the dilatational wave speeds of the material also featured clearly visible shear shock waves structures, of small but finite width, emitted from a diffuse crack tip region. Within a finite distance behind the growing shear crack tip a secondary set of opening (Mode-I) micro-cracks was also observed. These microcracks initiated on the upper crack-face (tension side of the main shear crack faces) and propagated a finite distance in a direction approximately 11 degrees off the vertical to the shear crack faces. Motivated by the above experimental observations, we explore the validity of a slip-rate weakening cohesive zone model of intersonic shear fracture. Direct comparison of this model with experiments allows for the estimation of the cohesive parameters of the slip-rate weakening law, addresses questions of preferable crack tip speed regimes, and elucidates a possible, rate controlled, mechanism describing intersonic shear failure. The laboratory studies of shear rupture are then correlated to crustal earthquake events where intersonic rupture along weak fault planes has been surmised and to field observations of fault complexity related to the generation of secondary tensile microcracks of the type described above. In the final part of this lecture, recent evidence of intersonic shear rupture of atomic planes is reviewed. The amazing similarities of intersonic rupture processes occurring over a 12 order of magnitude difference in length scales are discussed.

Multiscale Modeling of Material Failure at High-Strain Rates

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We present a modeling approach to bridge the atomistic with macroscopic scales in crystalline materials. We show that the meticulous application of this paradigm renders truly predictive models of the mechanical behavior of complex systems. In particular we predict the hardening of Ta single crystal and its dependency for a wide range of temperatures, strain rates. The feat of this approach is that predictions from these atomistically informed models recover most of the macroscopic characteristic features of the available experimental data, without a priori knowledge of such experimental tests. This approach provides a procedure to forecast the mechanical behavior of material in extreme conditions where experimental data is simply not available or very difficult to collect.

The present methodology combines identification and modeling of the controlling unit processes at microscopic level with the direct atomistic determination of fundamental material properties. This modeling paradigm is used to describe the mechanical behavior of Ta single crystals at *high-strain* rate. In formulating the model we specifically consider the following unit processes: double-kink formation and thermally activated motion of kinks; the close-range interactions between primary and forest dislocations, leading to the formation of jogs; the percolation motion of dislocations through a random array of forest dislocations introducing short-range obstacles of different strengths; dislocation multiplication due to breeding by double cross-slip; and dislocation pair annihilation. The model is found to capture salient features of the behavior of Ta crystals such as: the dependence of the initial yield point on temperature and strain rate; the presence of a marked stage I of easy glide, specially at low temperatures and high strain rates; the sharp onset of stage II hardening and its tendency to shift towards lower strains, and eventually disappear, as the temperature increases or the strain rate decreases; the parabolic stage II hardening at low strain rates or high temperatures; the stage II softening at high strain rates or low temperatures; the trend towards saturation at high strains; the temperature and strain-rate dependence of the saturation stress; and the orientation dependence of the hardening rate.

Closed Trans-scale Approximation to Wave-induced Damage

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It is well known that for time-dependent failure under impact, like spallation, quantitative/ predictive models based on continuum measure of spalling are needed. In this review, we introduce a closed trans-scale approximation of statistical microdamage mechanics to describe the wave-induced damage evolution.

For the time-dependent damage process, an associated equations of continuum, momentum and microdamage evolution should be formed. The trans-scale formulation

can be approximately closed by introducing a dynamic function of damage, which links continuum damage evolution to mesoscopic kinetics of microdamage. So, as long as the mesoscopic kinetics of microdamage are known, the wave process with damage evolution can be properly calculated, based on the trans-scale approximation. Also, there are several time scales, i.e. imposed and intrinsic ones. In particular, they form two important independent dimensionless parameters: Deborah number $ac^*/(LV^*)$ and intrinsic Deborah number $D^* = \frac{n_N^* c^{*5}}{V^*}$, where a, L, c^*, V^* and n_N^* are wave speed, sample dimension, microdamage size, the rate of microdamage growth and the rate of microdamage nucleation density, respectively. Physically, Deborah number $ac^*/(LV^*)$ indicates the ratio of the characteristic time taken by intrinsic process over the imposed time scale and then governs the process within the imposed time. Whereas, the intrinsic Deborah number D^* indicates the characteristic transition from damage accumulation to damage localization.

Experimental measurements of spallation show that the intrinsic Deborah number D^* and the time to failure are in good agreement with the calculated critical damage to localization and the corresponding critical time, respectively.

Keywords: microdamage, trans-scale, Deborah number, localization

Keynote

MEMS (Microelectromechanical Systems)

Organizer:
Professor William N. Sharpe, Jr.
(The Johns Hopkins University)

MICROELECTROMECHANICAL SYSTEMS
SESSION M2B

A Twilight Zone in Fluid Mechanics - Nano and Micro Flows -

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With the recent advancements in nano/micro fluidic devices, it has become possible to handle minute amounts of fluid in the pico liter range or less. This capability enables us to develop a collection of processes for moving bulk fluid mass and controlling the paths of selected particles, cells or molecules, embedded in flows. Length scale matching warrants the efficient momentum and energy transfers of the desired fluid motions. Molecules can then be directly manipulated by the flow patterns inside the micro device, which provides a pathway to exploit the nano world.

In the macro world, the continuum assumption prevails, where the flow length scale is much larger than that of molecules. The inertia of fluid mass is usually much larger than the viscous force resulting in the large Reynolds number. The most interesting phenomena are the manifestations of non-linear effects associated with the inertial forces. In micro flows, the typical Reynolds number is much less than one due to the small transverse length scale, which results in a high velocity gradient and thus high viscous force. Low Reynolds flows, Stokes flows, are linear in nature. However, linearity may not guaranty a simple solution. The force field is enriched by many other possibilities such as electrophoretic, dielectrophoretic or electro-osmotic forces. When the scales of the flows are further reduced, we are in the twilight zone between continuum and molecule dominated conditions, because the transition regime is not obvious and is especially complicated by the intricate structures of the macromolecules used in bio-molecular flow studies. Proteins and genomic molecules retain large size and complex mechanical as well electrical properties. In addition, the surface to volume ratio of a device is inversely proportional to the transverse length scale of the device and becomes very large in micro systems. Thus, a much larger portion of the fluid molecules in nano/micro devies will have the chance to interact with the surface versus those in macro flows. In other words, the properties of surface molecules can dominate the flow behaviors. Furthermore, in the case of molecular recognition processes on surface, e.g. self-assembly monolayer (SAM), the molecular near field force becomes the driving source.

During the last decade, micro-nano technologies have enabled us to reach the world of macromolecules through better length scale matching. This capability not only provides a paradigm shift in bio-technology, but also leads to a wide spectrum of challenges in fundamental research issues.

Data Storage using MEMS Technology Recent Research Results and Future Trends

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FANUC Chair for Mechanical Systems
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Recent research results and future trends for new approaches to data storage will be presented in this talk. Data storage techniques using MEMS technology take several forms, from the incorporation of MEMS actuators into conventional disk drives, to the totally new construction of high-bandwidth, planar, non-rotating data storage techniques. Before serving as the MEMS program manager at DARPA, Prof. Pisano had lead a large research team at UC Berkeley to design, fabricate and test MEMS positioners, suspensions and entire disk drive arms made of polysilicon and nickel-iron alloy. These devices were all applied to 2.5-inch magnetic disk drives in order to increase servo bandwidth and radial track pitch. All methods described in this talk use a non-volatile storage media that is scanned by a probe tip or read/write head of some form. Various techniques are described and their relative advantages and disadvantages are described. These various approaches include 1) MEMS disk drive arms and MEMS positioners that make possible articulated arms for "conventional" magnetic disk drives, 2) MEMS probe tips that are scanned linearly over memory media, 3) memory media that is scanned over a stationary set of MEMS probe tips and 4) comparisons between the competing approaches.

Materials Issues in MEMS

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This paper reviews the status of MEMS technology with particular emphasis on materials issues therein. The materials issues in MEMS are divided into three categories, the MEMS material set, microfabrication processes and material characterization and design. The MEMS materials set is slowly evolving away from its origins in CMOS microelectronics technology. However, the ability to select materials at will for a given application is usually highly constrained by the availability of appropriate fabrication methods. Conversely it is also apparent that the available materials (i.e. silicon, silicon dioxide, silicon nitride) are outstanding candidates based on objective performance metrics for sensor and actuator applications, both on account of their intrinsic properties and also the direct and indirect effects of application at small scales. The expansion of the MEMS material set is considered in the light of quantitative measures of material performance.

Microfabrication processes inevitably are closely linked to the materials that they act on. This relationship is explored and the limitations it places on materials that are viable candidates for MEMS applications is discussed.

A key reason for the sustained growth of the microelectronics industry is the speed and confidence with which complex products can be designed without the need for extensive prototyping. Design in microelectronic devices is largely enabled by the reliability of the simulation tools available and the extremely well characterized electronic properties of the materials being utilized and the processes with which the products are created. In this light, the need for high accuracy time-efficient materials characterization, and the development of models for the process-dependence of properties is discussed. The paper concludes with a discussion of the future of MEMS and the role of materials in that future.

MICROELECTROMECHANICAL SYSTEMS
SESSION T2B

Gas and Vapor Bubbles in Microdevices

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A wealth of information is available on the behavior of gas and vapor bubbles in liquid volumes with characteristic lengths far exceeding the bubble size. Much less is known, however, about situations in which the two length scales are comparable, as in the case of a bubble large enough to occupy the cross section of a small tube or chamber. In particular, such is the situation encountered in the use of bubbles as pumps, valves, and actuators in small fluid-handling devices. The strong potential of bubbles for these applications consists in their intrinsic simplicity, short time scale, and high power density. Among

others, they offer the advantage of actuation without mechanical moving parts and the ability to convert acoustic into mechanical energy.

The paper will focus on several examples and will demonstrate some effects of potential practical interest, including:

1. A vapor bubble growing and collapsing in a small channel under the action of periodic heating may, under suitable conditions, generate a d.c. flow and thus operate as a pump. The effect is found to be surprisingly strong, being capable of pumping heads of the order of tens of kPa in channels of the order of 100 to 200 μm.

2. In suitable conditions, several vapor bubbles operated in sequence may reinforce each other's effect, and also permit a reversal of the flow, thus giving rise to a bi-directional pump.

3. Resonant gas bubbles strongly respond to an applied sound field thus permitting remote actuation of a device. Results of experiment, computation, and simplified analytical modelling will be described.

In addition to presenting experimental results, the paper will also address the numerical modeling of such situations. Suitable mathematical formulations will be derived, numerical methods described, and illustrative results shown. [Supported by NSF]

The Strength of Polysilicon at the Micron and Submicron Levels

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This presentation focuses on two strength issues of MEMS-type materials, illustrated on polysilicon. The first issue relates to the influence of the manufacturing process on "properties" as determined in standard mechanical testing concepts. The second is concerned with the characterization of such "strength properties" as a function of the size of the stressed region The mechanical strength of thin polycrystalline silicon films has been examined in connection with varying exposure to 49% Hydrofluoric Acid (HF). It is found that surface roughness (groove formation along grain boundaries) depends on the HF release time. Such surface undulations and crevasses can induce errors into the determination of (effective) elastic moduli. Short times of exposure to HF can result in the delamination of a thin surface layer, which is sufficient to initiate an "early" failure. Longer exposure allows HF permeation into the intergranular domains, thus degrading the body of the "material" significantly. On the other hand, suppression of this degrading process results in film strengths that are higher by a factor of three than routinely manufactured polysilicon structures.

Apart from these manufacturing issues the strength of polysilicon has been examined as a function of domain size by introducing stress concentrations possessing various magnitudes and stress gradients through elliptic perforations. By varying the radius of curvature and the size of the ellipses, the effects of domain size and stress concentration amplitude could be assessed separately to the point where the size of individual grains (0.3 microns) becomes important.

The "local failure strength" at the root of a notch clearly increases as the radius of curvature becomes smaller, which is in agreement with probabilistic considerations of failure. The statistical scatter also increases. When the notch radius becomes as small as 1 micron (about three times the size of a grain) the failure stress increases by a factor of two relative to the tension carried by non-perforated specimens. A Weibull analysis shows for surface-micromachined specimens a dependence of the strength on the specimen length but not its width, which implies that the sidewall geometry, dimensions and condition are dominant in the failure process.

Integrated Micromechanism Design, Fabrication, and Characterization

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A new generation of silicon and non-silicon micromechanisms have been developed with the ability to interface effectively between the microscale and macroscale worlds. MEMS-based micromotors and micromechanisms have traditionally been limited to low force applications at the microscale, where there is no need to affect the macro-scale world. While previously demonstrated MEMS technology is certainly capable of meeting the demands for precision positioning in microscale systems, the high forces and large displacements required for many real world meso- and macro-scale applications often cannot be satisfied with these devices.

In this work, high force electrothermal micromotors have been developed and integrated into planar and spatial parallel manipulators. These devices have been shown to be capable of providing tens of millinewtons of force,

with sub-micron resolution and millimeter-scale displacements. Micromotors have been successfully fabricated using a variety of methods, include polysilicon surface micromachining, high aspect ratio silicon-on-insulator technology combined with silicon fusion bonding, and multilayer electroplated nickel using SU-8 polymer molds. When coupled with integrated micromechanisms, the technology enables novel functionality for a host of applications including adaptive optics, robotic locomotion and end effectors, and surgical systems.

This talk will describe recent results and ongoing efforts in the development of high-force micromechanisms. Several specific micromotor and micromechanism systems will be introduced. The design of multi-degree-of-freedom planar and spatial platform manipulators at the microscale will be discussed, particularly in terms of compliant micromechanism design issues. Systems fabricated using both silicon and non-silicon microfabrication methods will be detailed. Testing and characterization results will be provided, including micromotor and micromechanism performance, and reliability measurements from selected devices.

SPECIAL SESSIONS

Symposium on

Perturbation Theory and Computations: A Combined Approach to Mechanics

In Memory Of
Professor S. Cole

Organizer:
Professor A. Kapila
(Rensselaer Polytechnic Institute)

PERTURBATION THEORY AND COMPUATIONS:
A COMBINED APPROACH TO MECHANICS

In Memory of Professor Julian D. Cole

SESSION M4F

Modeling the Discharge of Alkaline Batteries

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In the spirit of using asymptotic methods to understand complicated practical situations, issues arising from an Australian industry are examined using analytical results from a mathematical model. In particular a model will be developed to aid in understanding the behavior of alkaline batteries as they discharge. The active part of such batteries is the manganese dioxide (EMD) contained within the cathode. In the current technology the oxide is broken into very small porous pellets that are coated with a small amount of graphite before being immersed in a strong electrolytic solution of potassium and then pressed into the cathode as a paste. There is considerable interest in understanding how much of the chemical energy stored in the EMD is used and how changes in cathode design, both to the geometry of the cathode and to the processing of the EMD mixture can influence the performance of the battery.

This paper will introduce a model of such batteries that considers the electrical conduction mechanisms within the electrolyte, at the interface between the electrolyte and the EMD, within the EMD and through the graphite. This complicated model will be systematically simplified to produce a reduced model. This simpler model will be studied with the aim of extracting generic behavior. The main tools will be asymptotic analysis with both regular expansions and multiple timescale techniques. There is a natural response time of a battery to fluctuations and in most practical instances this is short compared to the time to discharge the battery. This is exploited to produce simplified expressions for the behavior. Comparison of these analytical methods against numerical solutions of the full model will be presented.

Desorption of Saturated Polymers: Asymptotic and Numerical Results

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Due to their wide industrial applicability, much experimental work has been devoted to the study of desorbing polymer-penetrant systems. One unusual feature of such systems is the change in the polymer from a rubbery state when it is nearly saturated to a glassy state when it is nearly dry. As part of the drying process, a glassy skin often forms near the exposed surface. This phenomenon, called literal skinning, has many industrial applications. When drying wood, foods or other agricultural products, the hardening of the exterior"case" can lead to residual stresses that can cause buckling and warping. The glassy

skin can be exploited for the production of more effective protective clothing, equipment, or sealants from polymer materials. However, polymer skinning is undesirable in coating processes due to a decrease in drying rates and the formation of nonuniformities.

There are many different theories for why the skinning process occurs, but most scientists agree that one important factor is a viscoelastic stress in the polymer entanglement network. The size of this stress is related to the relaxation time of the viscoelastic polymer matrix, which changes drastically from very small in the rubber to finite in the glass.

The model consists of a set of coupled partial-differential equations for the concentration and stress. Numerical and analytical solutions are derived. For the numerical case,the parameters are assumed to vary smoothly with concentration, and hence the glass-rubber interface is simply an isocline of concentration. For the asymptotic solutions, the parameters are assumed to be piecewise constant in the rubber and glass. Thus, a moving boundary-value problem similar to a Stefan problem results. In each of the regions a different partial differential operator holds, and continuity conditions at the glass-rubber interface dictate its motion.

One defect of previous studies of the model was the appearance of negative concentration values when the concentration at the boundary was forced faster than the relaxation time scale of the rubbery polymer. The present study eliminates the negative concentration field by focusing on a more realistic flux boundary condition with mass transfer coefficient k.

The problem examined is desorption of an initially unstressed saturated polymer film of finite thickness, insulated at one end and exposed at the other. Series and transform techniques are used to derive analytical solutions in the limit of small and large k. The analytical approach yields the variance of the front speed and the crossing time as a function of k.

Global Analysis - Beyond Asymptotic Methods and Numerical Simulation

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Current methods used to study problems in engineering and physics rely heavily on numerical simulations and asymptotic techniques. These methods provide important knowledge about the nature of the problem but are typically limited to either certain values or certain limits of the physical parameters characterizing the problem and do not provide the complete picture of the system's behavior. Global analysis, on the other end, attempts to study the complete set of equations and boundary conditions that describe the problem and, using methods from variational analysis and the theory of nonlinear PDEs, identify the number of steady-state solutions of the problem at any given set of parameters and the characteristics of these solutions. Moreover, using asymptotic methods to investigate the stability of the steady states and numerical simulations to demonstrate the results, this approach provides a complete understanding of the dynamics of the system studied. The use of global analysis in the study of the vortex breakdown phenomenon is described. Results show the existence of this phenomenon, the sensitivity of the flow dynamics to initial conditions, and the effect of various parameters on the flow behavior.

A Perturbation Based Numerical Method for Solving a Three Dimensional Axisymmetric Indentation Problem

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Indentation testing is a well-established method for measuring the mechanical properties of materials. The analysis of this testing procedure remains of interest and current applications include nanoindentation testing for thin films and micro-indentation of biological materials using an atomic force microscope.

The indentation problem considered here comes from the study of mechanoreceptors in tissue. Such receptors, which are generally distributed through the depth of the tissue, are responsible for transducing a component of the deformation field at the receptor location into a neural or chemical signal. In the case of tactile sensors, it is still an open question as to what component of the field is transduced. One hypothesis is that the vertical strain plays a central role in the transduction process. To address this question it is essential to know the deformation throughout the depth and this brings us to the objective of this talk. In particular, we will demonstrate the effectiveness of an analytical approximation of the deformation, both as a relatively simple expression in studying the deformation at the receptor location as well as its effectiveness in producing an accurate numerical method to solve the problem.

We consider the three dimensional axisymmetric problem of the indentation of a thin compressible linear elastic layer bonded to a rigid foundation, using a cylindrical flat ended rigid indenter. Using perturbation arguments

based on the thinness of the layer, we derive an analytical approximation of the solution that incorporates the singular deformation gradients near the edge of the indenter. Besides providing an accurate closed-form expression for the deformation and deformation gradient throughout the layer we demonstrate the effectiveness of the approximation in helping to solve the problem numerically. We do this by incorporating the analytical solution into a numerical scheme and we exhibit the fact that the convergence rate and accuracy of the modified scheme are dramatically better than the original scheme.

Singular Perturbation Problems Arising in Mathematical Finance

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The seminal work of Black & Scholes (1973) and Merton (1973) has led to an explosion of ideas in the theory of the pricing of financial derivatives, in particular options (and a joint Nobel price for economics). A put (call) option is a contract between two parties, in which one party (the holder) has the right to sell (buy) an asset from the other party (the writer). Obviously the *right* implies some value to this contract, and this is what option pricing theory is all about. In this talk a very brief overview of the subject is given, and a short derivation of the now well known Black-Scholes equation is presented. This equation, which is pivotal in numerous studies of this kind is of backwards parabolic type, although a series of routine transformations can reduce the basic form to the heat-conduction equation.

Of particular concern in this talk is that the highest *spatial* derivative is multiplied by the square of the volatility (a measure of the risk/uncertainty of a particular asset). In many practical systems this parameter (which is generally calculated from historical data analysis) is typically $(O(0.4))$ (units: per (annum)$^{\frac{1}{2}}$), suggesting the classical conditions for a singular perturbation problem.

The first example tackled is that of European put and call options (in which the options can only be exercised on a prescribed date). The smallness of the volatility leads to flow solutions which take on a form analogous to shear layers in fluid dynamics contexts. Our solutions compare extremely favourably with the well-known exact solution for these problems.

The second example concerns a down and out barrier put option (in this case if the asset falls to/below some prescribed value, the option becomes worthless); in this case the asymptotic structure (which can take on up to three regions) can, in some circumstances, be regarded as being analogous with that of a shear layer colliding and coalescing with a wall boundary layer.

Finally the case of American options is treated. This class of option is one where the holder of the option has the right to exercise at any time during the lifetime of the option. These lead to free boundary problems (basically the location in asset space where the option should be exercised), and as such these are nonlinear problems. Nonetheless these remain amenable to singular perturbation analysis, leading on from that described above for European options, albeit with computations necessary to treat the location of the unknown free boundary. Again, asymptotic results are found to compare very favourably with 'exact' numerical results, even for $O(1)$ values of the volatility parameter.

PERTURBATION THEORY AND COMPUATIONS:
A COMBINED APPROACH TO MECHANICS

In Memory of Professor Julian D. Cole

SESSION T3F

Microwave Joining of Two Long Hollow Tubes: An Asymptotic Theory and Numerical Simulation

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A nonlinear heat equation which models the microwave assisted joining of two large SiC tubes is analyzed. By exploiting the small fineness ratio of the structure and disparate time scales an asymptotic theory for this problem is systematically deduced. Specifically, a one-dimensional nonlinear heat equation is described which governs the temperature in the outer region. This is a numerically well posed problem and it is efficiently solved using standard methods. This solution is not valid in the inner region which includes the microwave source. An inner asymptotic approximation is derived to describe the temperature in this region. This approximation yields two unknown functions which are determined from matching to the outer solution. The results of the asymptotic theory are compared to calculations done on the full problem. Since the full problem is numerically ill conditioned, the asymptotic theory yields enormous savings in time and computational effort. Examples are given to make this point.

On the Formation of Curvature Singularities in Free-Surface Flows

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Many interfacial flows lead to the formation of curvature singularities in finite time: Examples include dendritic growth, Kelvin-Helmholtz instability, two-fluid Rayleigh-Taylor instability. Progress in understanding how these singularities occur has been possible through a combination of asymptotics and numerics. Using the Kelvin-Helmhotz instability as a specific example, I'll show how the motion of branch-point singularities in the complex plane of the arclength coordinate account for the formation of curvature singularities. Neglected physical effects presumably ameliorate singularity formation. Progress in understanding how physical effects, such as surface tension, no matter how small, can change the presence and/or the nature of curvature singularities will be described.

A Hybrid Method for Low Reynolds Number Flow Past an Asymmetric Cylindrical Body

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Low Reynolds number fluid flow past a cylindrical body of arbitrary shape in an unbounded, two-dimensional domain is a singular perturbation problem involving an infinite logarithmic expansion in the small parameter ϵ, representing the Reynolds number. We apply a hybrid asymptotic-numerical method to compute the drag coefficient, C_d, and the lift coefficient, C_l, to within all logarithmic terms. The hybrid method solution involves a matrix M, depending only on the shape of the body, which we compute using a boundary integral method. We illustrate the hybrid method results on an elliptic object and on a more complicated profile.

Effect of Thermal Nonhomogeneity on the Evolution of Detonation in an Annulus

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This computational study is inspired by recent experiments on cookoff in annular configurations (Asay, Dickson et al., JANNAF PSHS Meeting, Cocoa Beach, FL, 1999). In the experiments, a confined annular charge is heated carefully so as to produce, nominally, a uniform radial thermal gradient. In the absence of any circumferential asymmetries, the end result is a wave of reaction, essentially a weak detonation, travelling from the hot outer boundary of the sample to the cold inner boundary. In practical situations, however, material inhomogeneities and the inevitable experimental imperfections can lead to small nonuniformities in the temperature profile producing one or more hot spots where ignition may occur preferentially. This study examines a model homogeneous explosive with strongly state-dependent kinetics in an annular, two-dimensional geometry. The initial condition corresponds to a weak radial temperature gradient, upon which is superimposed a local temperature nonuniformity. Accurate and well-resolved numerical computations are carried out to determine the mode of evolution to explosion or detonation. The purpose of the study is to understand and classify the manner in which the behavior of the system is determined by the geometry, the size of the nominal radial temperature gradient, and the location and size of the imposed temperature nonuniformity. Various scenarios will be described, ranging from a perturbed wave of thermal explosion to radially and/or circumferentially travelling detonations. Results will be contrasted with our recent study of detonation evolution (Kapila et al., Combustion Theory and Modelling, in review) in planar configurations.

Intermediate Asymptotics for Richards' Equation in a Finite Layer

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Perturbation methods are applied to study an initial-boundary value problem for Richards' equation describing vertical infiltration of water into a finite layer of soil. This problem for the degenerate diffusion equation with convection and Dirichlet/Robin boundary conditions exhibits several different regimes of behavior. Boundary layer analysis and short-time asymptotics are used to describe the structure of similarity solutions, traveling waves, and other solution states and the transitions connecting these different intermediate asymptotic states.

Symposium on

Symposium on Topics in the Flow of Complex Fluids

In Memory Of
Professor Charles G. Speziale

Organizers:
Professor D. A. Siginer
(Wichita State University)

TOPICS IN THE FLOW OF COMPLEX FLUIDS

In Memory of Professor Charles G. Speziale

SESSION M2G

Turbulence Modeling for Intermittent Pulsatile Flows

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Flows in undiseased arterial vessels are, under normal flow conditions, generally laminar. This is often not the case in diseased vessels, particularly ones that are severely stenosed. The flows in these vessels are often transitional and turbulent, albeit for relatively small Reynolds numbers. This change in the character of the flow has potentially significant implications, ranging from effects on non-invasive diagnostic imaging to the stresses on the walls of the vessels. The difficulty in predicting the behavior of flow in these vessels stems in part from the severe requirements placed on the turbulence model chosen to close the time-averaged equations of fluid motion. In particular, a successful turbulence model should: (a) correctly capture the 'non-equilibrium' effects wrought by the interactions of the organized mean-flow unsteadiness with the random turbulence, (b) correctly reproduce the effects of the laminar-turbulent transitional behavior that occurs at various phases of the cardiac cycle, and (c) yield good predictions of the near-wall flow behavior in conditions where the universal logarithmic law of the wall is known not to be valid. These requirements are not immediately met by standard models of turbulence that have been developed largely with reference to steady, fully-turbulent flows in approximate local equilibrium. The purpose of this paper is to report on progress made in the development of a turbulence model suited for use in arterial flows. The model used is of the two-equation eddy-viscosity variety with dependent variables that are zero-valued at a solid wall and vary linearly with distance from it. The effects of transition are introduced by coupling this model to the local value of intermittency, obtaining the latter from the solution of a modeled transport equation. This approach is shown to produce substantial improvements in the prediction of important parameters such as the wall shear stress. A demonstration of the relevance of this approach to real-life problems is provided by predictions obtained for fully-developed flow in a circular pipe driven by flowrate oscillations measured in an actual diseased carotid artery. The results show that intermittency plays an important role in determining the behavior of the wall shear stresses and that its effects should therefore be considered in future predictions of arterial flows in such vessels.

Keywords: intermittent flows, turbulence modeling, oscillatory flows, stenotic vessels

A Generalized Nonlinear Two-Equation Turbulence Model: Development and Applications

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A generalized nonlinear two-equation turbulence model based on extended thermodynamics has been proposed recently by Huang and Rajagopal[1]. In this approach, a non-Newtonian fluid model is first developed within the context of extended thermodynamics and the analogy between the constitutive equation for the non-Newtonian fluid and the Reynolds stresses in turbulent flow of a Newtonian fluid is used to formally derive a closure model.

The model is cast in a frame indifferent form and is shown to incorporate the relaxational effect of Reynolds stresses. The linear form of the model is similar to that proposed by Yoshizawa and Nisizima[2], while the steady form is similar to the nonlinear two-equation model of Speziale[3,4].

The model of Huang and Rajagopal1 has been refined and the coefficients are estimated using available experimental and computational results. Computations are performed for selected benchmark test cases and compared with available experimental and computational findings to

validate the model. Test cases considered in this study include: homogeneous shear flows subject to rotation, turbulent channel flows subject to span-wise rotation, flows in curved channels and separated flow over backward facing step. The model performance and its potential applications are discussed.

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Prediction of Equilibrium States in Turbulence Models for Flows Induced by Rayleigh-Taylor and Richtmyer-Meshkov Instabilities and in Oceanic and Atmospheric Applications

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One of the many important contributions that Charles Speziale made to turbulence modeling is the application of fixed-point analysis to RANS turbulence models[1]. Indeed, the two-equation turbulence model can be simplified to an initial-value problem for a set of coupled nonlinear ordinary differential equations - a dynamical systems problem. Speziale and Mac Giolla Mhuiris[2] studied the physical implications of the results obtained from various models as applied to homogeneous turbulence.

We apply the fixed-point analysis to a two-scale, two-equation turbulence model developed for flows induced by Rayleigh-Taylor and Richtmyer-Meshkov instabilities[3]. The investigation is performed on a numerical test-bed based on an ALE scheme4. A special emphasis is to determine the optimum initial conditions for the two-scale, two- equation model, for which a methodology due to Orszag (private communication) was found to be particularly helpful.

We have also introduced the fixed-point analysis to turbulence mixed layer models for geophysical applications[5]. Specifically, we found that the results of the fixed-point analysis provided improved prediction when applied to the model of Kantha and Clayson[6] (1994), which has been widely used in oceanic and atmospheric applications.

Keywords: Mix, Turbulence, Fixed-point, Two-equation

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The authors dedicate this work to honoring the memory of Charles Speziale and in respectful acknowledgment of his exemplary scientific career. This work was performed under the auspices of the U.S. Department of Energy by the University of California Lawrence Livermore National Laboratory under co ntract No. W-7405-Eng-48.

Optimal and Robust Control of Thermal Convection in Porous Media [1]

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In earlier works, the feasibility of utilizing linear, feedback control strategies to postpone the transition from the no-motion to the motion state in a liquid layer heated from below and cooled from above (the Rayleigh-Benard problem) has been demonstrated both in experiments and theory [1]. These investigations indicated that the critical Rayleigh number (Rc) at transition could be increased by as much as an order of magnitude. For these control strategies to be useful in applications, it would be necessary to increase Rc by many orders of magnitude. In this theoretical investigation, we utilized optimal (LQG) and robust (H_∞) control strategies to control the onset of convection in a saturated porous layer (the Lapwood problem). Both sensing and actuation were done non-intrusively at the cell's boundaries. We demonstrated that (at least in th eory) we can increase Rc by many orders of magnitude. Unfortunately, nonlinear numerical simulations revealed that the basin of attraction of the stabilized state was quite small. Weakly nonlinear analysis revealed that the controller preserves the direction of the supercritical bifurcation. Further studies of the linear operators revealed that while the uncontrolled system is "normal", the controlled system is highly non-normal [2]. Thus strongly

amplified disturbances may provide a by-pass mechanism for transition. The magnitude of the basin of attraction of the stabilized state was investigated as a function of R-Rc, where R is the Rayleigh number. This investigation indicates the need to develop non-linear control strategies to achieve any desired level of stabilization.

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[1] The work was supported, in part, by the National Science Foundation.

The Generation And Structure Of High Reynolds Number Homogeneous Turbulence

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This paper describes the design and development of an active grid system to generate large-scale high Reynolds number homogeneous turbulence. The system is being developed at Virginia Tech, ultimately for the purpose of studying the flow of turbulence through cascades of blades for the case of where the scale of the turbulence is comparable to the chord and spacing of the cascade blades. This paper includes details of the grid and a comparison of its turbulence characteristics with previous studies of homogeneous turbulence. The present design is based upon the rotating vane grid of Makita (1991) which consisted of 8 horizontal and 8 vertical rows of diamond-shaped vanes attached to rotating bars. The rotation of each bar is controlled using a separate stepper motor. The stepper motors operate independently and, under computer control, change direction randomly. Makita (1991) and Mydlarski and Warhaft (1996, 1998) built active grids using this design for 3 fairly small wind tunnels with square cross sections 0.46, 0.71, and 0.91-m on edge. Mydlarski and Warhaft found the turbulence generated in this way to be closely homogeneous, to decay in the same manner as grid turbulence, and to have spectral and statistical properties closely consistent with the fundamental expectations of homogeneous turbulence theory. They also found that, despite the small size of the wind tunnels, the turbulence had very large integral scales (up to 20cm), quite high intensity and thus big Taylor Reynolds (of over 730). These are some of the highest Reynolds number homogeneous turbulent flows ever generated in a wind tunnel.

The new active grid system has been built in the Virginia Tech Stability Wind. The test section of this facility is particularly well suited to the generation of large-scale turbulence. The section width and height of 1.83m (twice that of the largest tunnel used by Makita or Mydlarski and Warhaft) are sufficient to accommodate very large integral scales without compromising homogeneity. The section length, plus a short length of contraction to improve isotropy, allows about 9m of distance over which grid turbulence is allowed to develop. The active grid is sited in the contraction at a location where the cross sectional area is 32% greater than that of the test section - the remaining contraction following the grid should be just sufficient to remove the 20% anisotropy recorded in earlier studies. We chose to use a grid form from 10 sets of horizontal and 10 rows of vertical vanes. The grid is powered by twenty 2140 oz-in stepper motors controlled by 40 TTL digital signals output by two coupled National Instruments 6534 digital output cards. The bars is constructed from aluminum tubing, and the vanes from Luan plywood. These materials were chosen because of their stiffness and low mass. Low mass was important to minimize the inertial loads associated with changes in the direction of rotation of each vane set. Table 1 shows the design maximum rotation rate (5Hz) and test-section flow speed (30m/s) and compares the expected turbulence properties. Note the expected integral scale of about 12 inches, and the expected Taylor Reynolds numbers of about 1000. This facility will therefore allow the study of homogeneous turbulence and Reynolds numbers considerably larger than previously possible. The presentation will include details of the grid design and operation and measurements of the mean flow field and single and two-point 3-component turbulence properties. These measurements will be used to establish the level of isotropy and homogeneity of the turbulence and compare with the fundamental expectations of homogeneous turbulence theory.

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Paper	Grid	Rotation rate	x/M	U (m/s)	u'/U (%)	L(in)	Re(lam)	Section size	u'/v'
M&W98	8x8	1 or 2Hz	62	3.3	9.1	5.9	306	36x36''	
M&W98	8x8	1 or 2Hz	68	11.4	8.9	3.1	407	36x36''	
M&W98	8x8	1 or 2Hz	62	7	10.9	8.5	582	36x36''	
M&W98	8x8	1 or 2Hz	31	6.9	17.4	7.9	731	36x36''	
Makita	8x8	2Hz	50	5	16.4	3.9	387	28''x28''	1.22
M&W 96	8x8	1 or 2Hz	68	13.3	10.4	3.3	469	18x18''	
M&W 96	8x8	2Hz	68	7.1	7.4	2.3	262	18x18''	1.21
M&W 96	8x8	2Hz	68	10.4	8.6	2.8	377	18x18''	
M&W 96	8x8	2Hz	68	14.3	9.5	2.9	473	18x18''	
Present	10x10	to 5Hz	to 54	to 30		~2	~1000	72x72''	1

Table 1 Comparison of conditions (flow velocity U, rotation rate) and turbulence characteristics (integral scale L, Taylor Reynolds number $Re(lam)$, anisotropy u'/v') from the studies of Makita (1991) and Mydlarski and Warhaft (1996, 1998), with those expected for the present grid.

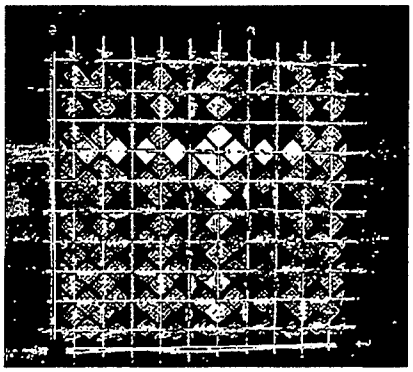


Figure 1 Present grid

Keywords: Homogeneous Turbulence, High Reynolds number

The Physics of the Secondary Flows of Viscoelastic Fluids in Straight Tubes

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A survey of secondary flows of viscoelastic liquids in straight tubes is given including recent work pointing at striking analogies with transversal deformations associated with the simple shearing of solid materials. The importance and implications of secondary flows of viscoelastic fluids in heat transfer enhancement are explored together with the difficulties in detecting weak secondary flows (dilute, weakly viscoelastic solutions) in a laboratory setting. Recent new work by the author and colleagues which explores for the first time the structure of the secondary flow field in the pulsating as well as steady flows of constitutively nonlinear simple fluids of the multiple integral type and of the Phan-Thien-Tanner type, respectively, in straight tubes of arbitrary cross-sections is summarized. Arbitrary conduit contours are obtained through a novel approach to the concepts of domain mapping and perturbation. Time averaged , mean secondary flow streamline contours are presented for the first time for triangular, square and hexagonal pipes in the case of the pulsating flow. The secondary flow structure of Phan-Thien-Tanner fluids in steady flow in cross-sections of industrial importance such as tear shape and other arbitrary contours is also studied.

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TOPICS IN THE FLOW OF COMPLEX FLUIDS

In Memory of Professor Charles G. Speziale

SESSION M3F

Continuous Models: Variants of LES

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The objective of this work is to develop and test what we call continuous models of turbulence which interpolate in some sense the unsteady Reynolds Averaged Navier-Stokes (RANS) computations and large-eddy simulations (LES). These models would provide a unified treatment of the three computational approaches. They would depend on the resolution of the computation in such a way that they would mimic, progressively, RANS models, LES models and no model (for DNS) as the resolution is made finer. Such a concept was suggested by the combined time-dependent RANS and VLES approach of Speziale1.

The analysis is based on two rather bold assumptions. Let Λ represent the wavenumber that characterizes the magnitude of the filter cut-off: $\Lambda \to \infty$ corresponds to no filtering and yields a DNS; and $\Lambda \to 0$ corresponds to filtering virtually everything and yields a RANS. The first assumption is that the generalized subgrid Reynolds stresses $\mathbf{R}_\Lambda$ may be represented for arbitrary Λ as a function of Λ times an ideal RANS model $\mathbf{M}$ (which is, by definition, independent of Λ):

$$\mathbf{R}_\Lambda = f(\Lambda)\mathbf{M} \tag{1}$$

Consider what happens to $\mathbf{R}_\Lambda$ when Λ is varied and the velocity field simultaneously varies in such a way that $\mathbf{U}_\Lambda$ is independent of Λ. While somewhat contrived, there is no reason why it should not happen. This leads to the second assumption under this special situation: The increment to $\mathbf{R}_\Lambda$ is some function of Λ, $g(\Lambda)$ (assumed to be positive), times $\mathbf{R}_\Lambda$:

$$d\mathbf{R}_\Lambda = -g(\Lambda)d\Lambda\mathbf{R}_\Lambda \tag{2}$$

Various expressions for $f(\Lambda)$ are discussed, including one in terms of the energy spectrum of the field. Of

course, one may also determine $f(\Lambda)$ directly, by forming the Reynolds stresses both from the subgrid velocities (filtered from the DNS data) and from the Smagorinsky model (using the filtered resolved velocities) and taking the ratio[2]. This has been done for a velocity field from a 96^3 DNS of decaying homogeneous isotropic turbulence, and it was found that $f(\Lambda)$ formed from the ratios of the diagonal components and from the ratios of the off-diagonal components fell, respectively, on two curves. The expression in terms of energy spectrum of the field was also used to predict $f(\Lambda)$. The predicted $f(\Lambda)$ is found to have a slope quite similar to those of the observed $f(\Lambda)$'s.

Keywords: Turbulence, Modeling, Simulation, and Navier-Stokes Equations

*Boston University, deceased.

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Internal Constraint Theories for the Thermal Expansion of viscous Fluids

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Many fluids in many processes are effectively mechanically incompressible but experience significant thermally-induced volume change. We focus here on models for viscous fluids that exploit this observed behavior to produce governing equations that are both easier to solve than the full Navier-Stokes equations and simplify the required material characterization. We derive the four possible models for thermal expansion available from the theory of internal constraints, in which the primitive mechanical variable (density ρ or pressure p) is slaved to the primitive thermal variable (temperature θ or entropy η). We then show that each of these four models is equivalent to a specific constitutive limit of the compressible theory, namely two of no pressure dependence of density and their duals of no density dependence of pressure. Based on this connection, we deduce that two constraints, namely $\rho = \rho(\eta)$ and $p = p(\theta)$, offer physically viable candidates fqqor the modeling of thermal expansion, whereas two others (the customary density-temperature constraint $\rho = \rho(\theta)$, as well as $p = p(\eta)$) are unphysical in the absence of any other conditions on the process, predicting catastrophic instability of the rest state.

Yield Stress Measurements of Suspensions

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This contribution will address the problem of yield stress measurements in multiphase systems. Following a critical review of existing practice, we will discuss a new slotted-plate technique that allows for the direct measurement of the static yield stress of a suspension. Possible wall effects associated with our original yield-stress plate instrument have been minimized. Yield-stress experiments were conducted on both high-concentration (TiO_2) and low-concentration (bentonite) aqueous suspensions. Our new setup avoids the disadvantages of the vane instrument, possible secondary flow between the blades as well as a non-uniform stress distribution along a virtual cylindrical surface. Yield stress values of TiO_2 suspensions were compared with the values obtained via a variety of other methods, including indirect extrapolation from steady-shear data, vane creep testing, and vane stress-ramp measurements using an SR-5000 rheometer. Very small yield stress (up to $\sim 10^{-4}$ Pa) measurements of low-concentration (2 wt.%) bentonite suspensions could be determined only with our slotted-plate device. The vane method could not measure yield stress values of bentonite suspensions of less than 7 wt. % concentration. Relaxation tests on high-concentration suspensions indicated that these suspensions may not be purely elastic below yield stress. We will also discuss results of a finite element analysis.

Stokes' Mechanism of Drag Reduction

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The mechanism of drag reduction due to spanwise wall oscillation in a turbulent boundary layer is considered. Published measurements and simulation data are analyzed in light of Stokes' second problem. A kinematic vorticity re-orientation hypothesis of drag reduction is first developed. It is shown that spanwise oscillation seeds the near-wall region with oblique and skewed Stokes vorticity waves. They are attached to the wall and gradually align to the freestream direction away from it. The resulting Stokes' layer has an attenuated nature compared to its laminar counterpart. The attenuation factor increases in the buffer and viscous sublayer as the wall is approached. The mean velocity profile at the condition of maximum drag reduction is similar to that due to polymer. The final

mean state of maximum drag reduction due to turbulence suppression appears to be universal in nature. Finally, it is shown that the proposed kinematic drag reduction hypothesis describes the measurements significantly better than what current Direct Numerical Simulation does.

Spreading Liquid Layers onto Moving Substrates: How does Ambient Air Affect the Contact Line?

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Spreading a liquid layer on a moving solid substrate leads to many industrial applications, for example: paper industry, mag. tape industry or photo industry. This process resorts of dynamic wetting which has long been studied. This three phase (solid / liquid / air) problem is classically reduced to a two phase (solid / liquid) one. Within that framework, the flows induced in the surrounding air are neglected. In such conditions, one is faced with a singularity at the contact line, i.e. the friction force tends to infinity (Huh & Scriven). Several solutions have been proposed to relax the singularity, among which wall slippage which is questionable. Since the pioneering work of Deryaguin and Levi, numerous experimental studied were carried out and lead to the evidence of air entrainment in the vicinity of the contact line (Burley et al., Blake, Scriven, Telezke and others).

We propose here a model which takes into account the effect of the ambient ai r on the liquid sheet: the problem is governed by two coupled differential equations where the unknown functions are the shape of the free surface and the pressure generated in the air wedge close to the contact line.

Having prescribed adequate boundary conditions, the problem is solved in the steady case. A linear stability analysis is carried out in the spirit of Savage's and allows the spatial oscillations of the contact line to be described in various conditions. The temporal stability of the contact line is also considered by studying the response of the contact line to fluctuations generated upstream. It is shown that there is a sub-critical Hopf bifurcation, which offers good qualitative agreement with experimental observations done separately.

Symposium on

Mechanics, Continuum Thermodynamics and Kinetic Theory

In Memory Of
Professor C. A. Truesdell

Organizer:
Professor C. S. Man
(University of Kentucky)

MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY I

In Memory of Professor C. A. Truesdell

SESSION M2A

Clifford Truesdell and Thermodynamics

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In this talk the speaker will attempt to describe the depth and impact of the contributions that Clifford Truesdell made to the science of thermodynamics, beginning with his publication in 1952 of what he later called, with great generosity, the Clausius-Duhem inequality.

Keywords: Clifford Truesdell, Thermodynamics

A Nonequilibrium Theory of Epitaxial Growth that Accounts for Surface Stress and Diffusion

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We develop a general dynamical theory for the epitaxial growth of an elastic film, a theory that accounts for both

stress and diffusion within the growth surface. Our approach relies on recent ideas concerning configurational forces. In addition to an equation that expresses the balance of classical Newtonian forces, our theory gives rise to equations for the growth surface that impose the balance of atoms for each species and a normal configurational force balance. The latter balance can be viewed as a generalization, to a dynamical context involving dissipation, of a condition that would arise in equilibrium by considering variations of the total free-energy with respect to the configuration of the growth surface. It is the counterpart of similar conditions that arise in theories for dislocation, crack, and interface propagation. A key and somewhat surprising result of our theory is that, for sufficiently small or large values of the interfacial stretch, a convex dependence of the surface free-energy on the interfacial stretch may be destabilizing.

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The Lavrentiev Phenomenon in Nonlinear Elasticity

Mikil Foss, William Hrusa, Victor J. Mizel

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In response to a challenge delivered by Tonelli in a lecture in Moscow, M. Lavrentiev produced in 1926 an example of a one dimensional variational problem in which the infimum of the functional over Lipschitz functions was strictly greater than the infimum over absolutely continuous functions. This example was later improved upon by Mania' and others. However it was until the 1980's that examples were provided involving strictly regular integrands. The existence of such one dimensional examples led Ball and Mizel to raise the question of whether a similar gap phenomenon could arise for multi- dimensional boundary value problems involving an elastic material with a physically natural stored energy function. The present work describes such examples in two dimensions. Moreover the stored energy functions are objective and isotropic. The significance of such results for applications is also discussed.

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Constitutive Relations of Textured Polycrystals

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As masterfully presented by Truesdell and Noll in their monumental treatise "The Non-Linear Field Theories of Mechanics", among the major advances brought to bear by the renaissance of continuum mechanics in the years 1945-1965 are an awareness of the important role played by constitutive relations in mechanics, a general approach to their study, and the formulation of some underlying principles (e.g., material frame-indifference) that they should satisfy. Recently, in my study of the elastic and plastic anisotropy of polycrystalline materials, I introduced the orientation distribution function (ODF), which characterize the preferred orientations of the constituting grains, as an independent variable in the elastic and plastic constitutive relations of polycrystals, treated it on a par with other variables (e.g., stress and strain) in macroscopic continuum mechanics, and applied general principles that govern constitutive relations to derive representation formulae which show explicitly how the constitutive functions depend on the ODF up to terms linear in the texture coefficients. In this talk I will highlight some of the formulae derived and their applications.

Keywords: polycrystals, mechanical anisotropy, crystallographic texture

MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY II

In Memory of Professor C. A. Truesdell

SESSION M3A

Tensile Waves in a Rubberlike Material

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This paper is concerned with the propagation of impact-generated tensile waves in a one-dimensional bar made of a rubberlike material. Because the stress-strain curve changes from concave to convex as the strain increases,

the governing quasilinear system of partial differential equations, though hyperbolic, fails to be "genuinely nonlinear" in the sense of Lax. As a consequence, the governing boundary-initial value problem fails to be well-posed in a certain range of loading. When the problem fails to be well-posed, it does so by exhibiting a massive loss of uniqueness, even though an entropy-like dissipation inequality is in force at moving strain discontinuities. Because the breakdown in uniqueness is reminiscent of a similar phenomenon that occurs in continuum-mechanical models for impact-induced phase transitions, a mathematically suitable, though physically unmotivated, selection mechanism naturally suggests itself. We describe the solutions determined by two special forms of this selection mechanism, which takes the form of a kinetic relation at certain propagating strain discontinuities. The solutions arising from these two special kinetic relations provide upper and lower bounds on the solution corresponding to an arbitrary kinetic relation.

Keywords: rubber, impact, genuine nonlinearity, kinetic relations

Kinetic Relations for Phase Boundaries - Computations and Proposed Experiments

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It is now well known in continuum mechanics that the classical balance laws of mass, momentum and energy cannot fully describe the motion of phase boundaries in martensitic solids. Additional information is needed as phase boundaries are material defects. An approach that has found wide acceptance is to identify a thermodynamic driving force and to postulate that the rate of evolution of the phase boundary is related to the corresponding driving force through a constitutive function known as the 'kinetic relation'. This paper examines this framework first through atomistic considerations and then through proposed experiments. We first obtain a kinetic relation starting from a simple atomistic model by viewing the kinetic relation as a manifestation of the atomic level physics that is averaged out in a continuum theory. We perform several simulations with a one-dimensional atomic chain with double-well interaction potentials – each well being a stable phase, and observe propagating phase boundaries. We determine the driving force across the phase boundary as a function of the phase boundary velocity and hence obtain a kinetic relation. Although one-dimensional simulations like these are an excellent device to furnish a proof of concept, they shed little light on the kinetic relations for actual materials. For obtaining them one has to resort to experiments. This has proved to be extremely tricky. Here we propose some simple experiments for single crystals. The experiments are designed using a bending theory for phase transforming materials. The basic equations in the theory are classical but the constitutive equations are completely non-classical and have been derived using principles of continuum thermodynamics. The constitutive parameters in our theory are related to the underlying crystallography and we demonstrate how this information can be used for constructing experiments.

Keywords: Phase transformations, Kinetic realtions, Strings, Beams.

Non-Isothermal Kinetics of a Moving Phase Boundary

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In this paper we derive an explicit formula for a kinetic relation governing the motion of a phase boundary in a bilinear thermoelastic material capable of undergoing solid-solid phase transitions. To obtain the relation, we study traveling wave solutions of a regularized problem that includes viscosity, heat conduction and convection. Both inertia and latent heat of transformation are taken into account. We investigate the effect of material parameters on the kinetic relation and calculate the range of parameters for which the relation becomes non-monotone, in agreement with recent numerical [1] and asymptotic [2] calculations. The non-monotone kinetic relations lead to an irregular propagation of phase boundaries, as shown in [3], where such non-monotonicity was postulated. The model predicts a nonzero resistance to phase boundary motion, part of which is caused by thermal trapping, also observed in [1], and captures local self-heating, in qualitative agreement with recent experiments on shape-memory-alloy wires [4,5].

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Thermal Effects in Dynamics of interfaces

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The continuum thermodynamic method is applied to the study of thermal effects of motion of interfaces that appear after different phase transitions. These effects stem from the existence of the surface thermodynamic properties and temperature gradients in the interfacial transition region. Thermal effects may be explained by the introduction of a new thermodynamic force exerted on the interface and the internal energy density flux through the interface. The evolution equations for the interfacial motion are derived. For the experimental verification of the thermal effects during continuous ordering the expression is derived for the amplitude of temperature waves.

Interface Evolution in Three-dimensions with Curvature-dependent Energy and Surface Diffusion

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When the interfacial energy is a nonconvex function of orientation, the anisotropic curvature flow equation becomes backward parabolic. To overcome the instability thus generated, a regularization of the equation that governs the evolution of the interface is needed. In this paper we develop a regularized theory of curvature flow in three-dimensions that incorporates surface diffusion and bulk-surface interactions. The theory is based on a superficial mass balance; configurational forces and couples consistent with superficial force and moment balances; a mechanical version of the second law that includes, via the configurational moments, work that accompanies changes in the curvature of the interface; a constitutive theory whose main ingredient is a positive-definite, isotropic, quadratic dependence of the interfacial energy on the curvature tensor. Two special cases are investigated: (i) the interface is a boundary between bulk phases or grains, and (ii) the interface separates an elastic thin film bonded to a rigid substrate from a vapor phase whose sole action is the deposition of atoms on the surface.

MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY III

In Memory of Professor C. A. Truesdell

SESSION M4A

About Clapeyron's Theorem in Linear Elasticity

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According to Love (Love, A.E.H., "A Treatise on the Mathematical Theory of Elasticity", 4th ed. Cambridge, 1927, p. 173), "The potential energy of deformation of a body, which is in equilibrium under given load, is equal to half the work done by the external forces, acting through the displacements from the unstressed state to the state of equilibrium." This is commonly known as Clapeyron's theorem in linear elasticity theory, first noted in 1833. In particular, this theorem implies that the accumulated elastic stored energy for a body in equilibrium accounts for only half of the work that is spent to distort the body. The remaining half of the work done to the body by the external forces is unaccounted for and apparently is lost somewhere in achieving the equilibrium state. It is natural, then, to question the whereabouts of this lost work. In this paper, we consider the richer dynamical theories of elasticity, viscoelasticity and thermoelasticity in order to shed light on the seemingly paradoxical and incomplete conclusion that is implicit in this classical and important theorem.

E. Frola (1906-62): An Attempt Toward an Axiomatic Theory of Elasticity

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In a sequence of papers written in the 1940's, the Italian mathematician Eugenio Frola (1906-1962) sketched a program for the foundation of the Mathematical Theory of Elasticity in which he took into account finite deformations and thereafter he tried to include also the influence of thermodynamics.

Unfortunately, he did not formulate his ideas in a strict mathematical form and gave only some general principles and a few hints, without obtaining any definite axiomatic structure. Frola proposed also an axiomatic formulation of the linear elasticity, as an autonomous branch of mathematics.

Comparison of Frola's theory with the conceptions proposed some years later by C. Truesdell and W. Noll shows that he anticipated some of the deeper issues of modern Rational Continuum Mechanics. Thus, for example, Frola distinguished between geometrical mechanical and physical hypothesis, but did not consider any specific axiom for the constitutive equations.

Even if unknown to the specialists in this field, Frola was part of the movement which "in the middle 1940's began a revival and renascence in rational continuum mechanics as a whole" (Wang & Truesdell, *Introduction to Rational Elasticity*, Noordhoff , 1973, Preface). His attempt of refounding and recasting of classical elasticity must be recognised, from an historical point of view, as one of the first step toward the construction of a rational structure of the theory.

F. Frola, *Sull'elasticità non globalmente lineare. . Principi e fondamenti delle teorie*, Atti Acc. Sc. Torino, LXXV, p.10

F. Frola, *Sui fondamenti logici della teoria dell'elasticità*, Atti Centro Studi Metodologici, I, p. 12

Keywords: history of elasticity - axiomatic theory .

Complex Variable Displacement Method in Plane Isotropic Elasticity

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Both the stress and displacement formulation methods are used in plane isotropic elasticity. The stress formulation starts with the two equilibrium equations in terms of stress and introduces a potential (Airy's stress) function. The displacement method begins by solving the two equilibrium equations in terms of displacement (i.e., Navier's equations) directly. The two Navier equations can be solved either simultaneously or separately. When the latter approach is taken (Gao, 2000), a displacement formulation similar to the afore-mentioned stress method can be obtained. Both the Airy stress function method and the displacement function approach discussed in Gao (2000) are based on an extended version of Green's theorem and, therefore, are mathematically equivalent. The same is shown to be true for the two formulations in planar anisotropic and orthotropic elasticity theories (Gao and Rowlands, 2000a,b; Gao, 2001).

The complex variable formulation of the stress function method has been available for a long time (Muskhelishvili, 1963). However, no similar displacement formulation has been found in the literature. A displacement method in terms of complex variables is hereby presented, which gives the displacement components in terms of two analytic functions. This displacement formulation is shown to recover the Kolosov-Muskhelishvili complex variable solution based on the stress function method, thereby verifying the equivalency noted in Gao (2000) using a different (real variable) approach.

Keywords: Plane elasticity; Complex variable theory; Displacement method; Stress method

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Anisotropic Elasticity and Multi-material Singularities

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Stress singularities generally occur at a point of convergence of discontinuity lines in composite structures, such as interfaces, cracks, free or fixed boundaries. A multi-material wedge is composed of dissimilar anisotropic material sectors perfectly bonded along one or more radial interfaces. Such a wedge possesses an infinite number of real and complex eigenvalues, and eigenfunctions which join the equilibrium fields in the various sectors through interfacial continuity relations. The eigenfunctions may be combined to form an eigenseries that matches remote loading.

The formulation of the wedge problem is omplicated by the cases of degenerate (D) and extradegenerate (ED) material sectors, which require special representations of the 2-D general solutions. There are five types of anisotropic materials, each having a distinct form of representation. A symbolic algebraic program is developed to discriminate the material types, to calculate the material eigenvalues and eigenvectors of all sectors, the inter-sector transfer matrices, and to derive the characteristic equation of the wedge eigenvalues and eigenfunctions. Boundary collocation of the remote loading data determines the eigenseries.

The eigenseries generally show rapid convergence. However, the coefficient of the dominant eignfunction ("asymptotic solution") cannot be accurately evaluated unless the collocation scheme involves a sufficient number of nonsingular eigenfunctions. Furthermore, the elasticity solution may deviate significantly from the asymptotic solution, even as one approaches the singularity to within a distance of subatomic scale. Such disturbing discrepancies often happen when the lowest eigenvalue is very close to the next one. Hence the asymptotic solution, and its associated stress intensity factors, may inadequately or misleadingly represent the intense physical stress near the singularity.

Constitutive Relation of Elastic Polycrystal with Quadratic Texture Dependence

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Polycrystalline materials are said to carry crystallographic texture if their constitutive crystallites show preferred orientations. Since single crystals are naturally anisotropic, crystallographic texture clearly could exert a strong influence on the directional properties of polycrystals. To give a crude but quantitative description of grain orientations in a polycrystal, the orientation distribution function (ODF) was introduced independently by Bunge and by Roe in the 1960s. Since then, efforts have been made to delineate the effects of the ODF on various material properties of polycrystals. When the ODF is expanded into an infinite series in terms of the Wigner D-functions, the expansion coefficients of the anisotropic part of the ODF are called texture coefficients. Recently Man pointed out that, without going into any detailed micromechanical modelling, general representation formulae could be derived which show explicitly the effects of the ODF on various material tensors up to terms linear in the texture coefficients. Empirical evidence has so far suggested that these formulae would work well in practice for materials such as aluminum, whose single crystal has weak anisotropy. On the other hand, it is doubtful whether these same formulae would suffice for materials such as copper, whose single crystal is strongly anisotropic. In the present paper we restrict our attention to linear elasticity. We introduce two simple models by which we derive expressions for the elastic stiffness and compliance tensors pertaining to aggregates of cubic crystallites with orthorhombic texture symmetry. These expressions, each of which carries an undetermined material constant, delineate the effect of crystallographic texture on elastic response and are quadratic in the texture coefficients. There is a unique choice of the two undetermined material constants so that the two constitutive relations agree with each other up to terms linear in the texture coefficients.

MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY IV

In Memory of Professor C. A. Truesdell

SESSION T2A

A Strain Averaged Statistical Mechanical Model for Rubber Elasticity

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Zuniga and Beatty [1] have shown recently that constitutive equations for isotropic rubberlike materials that are based on the Kuhn-Grn probability distribution function, or any of its amended forms for non-Gaussian statistical mechanical network models, are described by a strain energy function $W(\lambda_r)$ that depends on only the relative

chain stretch λ_r, the ratio of the current end-to-end chain vector length to its fully extended, locking length. All network chains are identical, with the same undeformed length r_0. The well-known 4-chain tetrahedron model and the 8-chain cubic model are members of this class. In each of these cases, the relative chain stretch is determined from the deformation kinematics of a single network chain. These important models, however, are members of a much larger geometrical class of ν-chain models described by uniform polyhedra of ν vertices. For the 8-chain model, $\nu = 8$, for example. Here I consider a ν-chain polyhedron model whose center C is fixed at one cross-link junction. The end points of the chains radiating from C, all having the same undeformed chain length, form cross-links situated at the vertices of a uniform polyhedron of type ν, all vertices being situated on the surface of a sphere of radius r_0. In the deformed state, the chain structure is distorted with varying degrees of relative chain stretch. It is shown that the "volume" averaged relative stretch $< \Lambda_r >$ of this cell model is a function $< \Lambda_r >= \lambda_r(I_1)$ of the first principal invariant of the Cauchy deformation tensor $\mathbf{B}$. The strain energy is determined from the configurational entropy for a "full network" of such chains. As a result, the constitutive equation for all such non-Gaussian network models of rubber elasticity is described by the familiar law

$$\mathbf{T} = -p\mathbf{1} + \aleph(I_1)\mathbf{B}$$

for the Cauchy stress $\mathbf{T}$, in which the isotropic elastic response function is defined by

$$\aleph(I_1) = (1/3N\lambda_r)\partial W(\lambda_r)/\partial_r,$$

N being the number of rigid links of the molecular chain structure and p an arbitrary pressure reflecting incompressibility of rubbers. This model includes, for example, the 4-chain and 8-chain non-Gaussian network models, and all amended forms described in [1]. The Gaussian (neo-Hookean) network model is a special case for which $\aleph(I_1) = \mu 0$, the constant shear modulus.

Keywords: rubber elasticity, constitutive equation, non-Gaussian network, statistical mechanics

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An Elementary Molecular-statistical Basis for the Mooney and Rivlin-Saunders Theories of Rubber-Elasticity

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By relaxing the assumption that the end-to-end vectors of molecules transform as macroscopic material line elements, we arrive at a generalization of the molecular-statistical theory of rubber elasticity. This generalization includes as special cases continuum-mechanical theories proposed by Mooney and by Rivlin and Saunders as improvements upon the classical neo-Hookean theory.

Rivlin's Approach to Rubber Elasticity is Ill-Suited for a Rational Experimental Method

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Following Rivlin, strain-energy W for rubber is defined in terms of the principal invariants I1 and I2 of C, the left Cauchy-Green deformation tensor. Use of I1 and I2 is nonetheless arbitrary, and experimental problems arise. Toward this end, consider biaxial stretching of a rubber sheet by the ratios l1 and l2. Assuming homogeneity, isotropy and hyperelasticity, in-plane loads f1 and f2 should be such that: (1) f1 is single valued for each l1 and l2, (2) f2 is single valued for each l1 and l2,(3) values of f1 and f2 are interchanged when the values of l1 and l2 are interchanged, and (4) the derivative of f1 wrt l2 is equal to the derivative of f2 wrt l1. The first two conditions relate to elasticity, the third to isotropy, and the last to conservation of strain-energy. However, rubber is slightly inelastic. If one strain state is retested multiple times, different f1 or f2 data are often obtained for each test. (The variance is much greater than that due to measurement, whereby the error is primarily "error of definition" [1] and not "error of measurement"). It is nonsensical to use data sets that violate isotropic hyperelasticity to calculate response functions and determine an average or typical W for rubber. Response functions cannot exhibit inelasticity, but stress values can. Averaging must be done on f1 and f2 to first define an adjusted data set [1] that satisfies hyperelasticity. With well-dispersed data, it is easy to fit a surface to f1 and f2 subject to the above 4 hyperelasticity constraints. However, when the I1 and

I2 response functions are subsequently calculated, their derivatives are singular. Singularities arise because I1 and I2 are quadratic order in strain. The hyperelasticity approaches of Ogden and of myself [2] use strain parameters that are first order in strain magnitude. When this rational experimental method is used in conjunction with first order strain parameters, singularities in response function plots are absent.

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Analysis of J.F. Bell's Research on the Finite Twist and Extension of Cylindrical Tubes

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I examine James F. Bell's empirical result regarding the rotation factor in the polar decomposition of the deformation gradient for the finite twist-extension of a cylindrical tube. The correct expression for the rotation is derived and used to show how Bell's result should be interpreted. Some implications for his incremental plasticity equations are also discussed. In particular, they are shown to satisfy appropriate invariance requirements when cast in terms of the variables measured by Bell in his experiments. Further consequences of his equations consistent with his data are also derived. Finally, it is shown that his theory furnishes a consistent constitutive statement about the response of isotropic solids provided that the Cauchy stress is constrained to be symmetric.

Some New Advances in the Theory of Dynamic Materials

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Dynamic materials are defined as composites assembled from ordinary materials on a microscale in space and time. These formations are thermodynamically open: to be maintained, they require energy exchange with the environment. A spatio-temporal material mixing is discussed in the context of electrodynamics of moving dielectrics. I distinguish between the stable and unstable mixtures, i.e., between the composites that do or do not allow the long electromagnetic waves travel through them without damping and formation of shocks. A stable G-closure of original materials is defined as the union of all stable mixtures, regardless of their microstructure. For one spatial dimension and time, I give attainable bounds for the effective properties specifying a G-closure generated by two isotropic dielectrics differing in the (positive) values of their dielectric and magnetic constants. Particularly. a stable G-closure includes the mixtures that may be identified as isotropic dielectrics with both effective material parameters negative.

MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY V

In Memory of Professor C. A. Truesdell

SESSION T3A

Invariance, Computation, and Regularity

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Many of the numerical methods designed for capturing shocks in nonlinear hyperbolic equations are inspired by the equations of gas dynamics in their spatial formulation. When these methods are routinely adapted to the equations of solid mechanics, they lose their invariance under rigid motion and can produce serious errors. These errors are exhibited, methods for removing them are developed, greatly improved numerical results are exhibited, and deep connections of the theory with the regularity of solutions of the governing equations are discussed.

Generalized Hessian and External Approximations in Variational Problems of Second Order

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We introduce a suitable notion of *generalized Hessian* and show that it can be used to construct approximations

by means of piece-wise linear functions to the solutions of variational problems of second order. An important guideline of our argument is taken from the theory of the Γ-convergence. The convergence of the method is proved for integral functionals whose integrand is convex in the Hessian and satisfies standard growth conditions.

Equilibria of a Class of Tensegrity Structures

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Tensegrity structures are a class of cable and bar constructions which date to sculptures by Kenneth Snelson in 1948 and were popularized by Buckminster Fuller. For an arbitrary topology (the structure as a graph) characterization of the stable positions is an open question. We study a class of structures which we call Snelson structures, whose atructural matrix has a minimal form which is characteristic of Snelson's sculptures. For this class of structures we present results which delimit the stable positions more precisely than is possible for the general class of tensegrity structures. We also outline and illustrate a numerical algorithm which enables construction of the stable positions of a structure of a given topology.

Keywords: Tensegrity, Stability, Structures, Algorithm

Identification of Crack by Boundary Measurement

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The theory of fracture mechanics can be thoroughly applied to predict the danger or guarantee the safety of the material if the location and shape of crack can be identified. Hence, it is very important to provide a method for identifying crack. In our paper we will show that the probe method can be successfully applied to reconstruct the location and shape of crack by many boundary measurements measuring the current and voltage at the boundary of the material. Also, a similar reconstruction procedure will be discussed for identifying crack by using mechanical measurements at the boundary of the material.

Keywords: crack, identification, probe method, many boundary measurements

On Cavitation, Configurational Forces and Implications for Fracture in Nonlinear Elasticity

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Sufficient tensile stress in an elastomer induces cavitation, the appearance of voids that were not previously evident. These voids can be regarded as either the growth of preexisting infinitesimal microvoids or, alternatively, as the spontaneous creation of new holes. In this lecture both views are adopted concurrently. An elastomer is modeled, on a macroscale, as a void-free material and, on a microscale, as a material containing certain defects that are the only points at which hole formation can occur. This is accomplished, mathematically, by the use of deformations whose point singularities are constrained. One consequence of this viewpoint is that cavitation may then take place at a point that is not energetically optimal. We show that this disparity will generate configurational forces, a type of force identified previously in dislocations in crystals, in phase transitions in solids, in solidification, and, most relevantly to this work, in fracture mechanics. In addition we consider the problem of determining the energetically most favorable point for a solitary hole to form in a homogeneous and isotropic elastic ball. We show that the center of the ball is the unique optimal point. Finally, we speculate that the configurational force generated by cavitation at a non-optimal material point may be sufficient to result in the onset of fracture. Our analysis utilizes the energy-momentum tensor, the asymptotics of an equilibrium solution with an isolated singularity, and the linear theory of elasticity at the stressed configuration that the material occupies immediately prior to cavitation. [1] [2] [3]

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MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY VI

In Memory of Professor C. A. Truesdell

SESSION T4A

An Approach to Robust Structural Design

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Typically, the optimal constructions are designed to work against a prescribed loading condition and are very sensitive to variations of the loading. The very nature of optimality forces the optimally designed structure to become anisotropic and concentrate its stiffness in the direction of the loading, hence weakening the stiffness in other directions. However in many engineering applications, the loading is either variable or not completely known; accordingly, the structure should be designed to work in a variety of conditions.

This talk discusses a robust formulation of an optimal design problem that accounts for possible variations and uncertainties in the loading applied to the boundary of the designed domain. The loading itself is not specified, only a quadratic constraint for a class of loadings (the norm of the loading) is given. The design problem is to find the optimal structure from minimization of the energy stored in the structure under the most unfavorable (the most destructive) loading; this problem results in a min-max game "Design versus Loading".

Specifically, we consider a problem of robust design of an optimal structure from linear elastic materials. The most destructive loading turns out to be an eigenfunction of a Steklov eigenvalue problem: At each boundary point, the most destructive traction is proportional to the generated displacement; the coefficient of proportionality is the Steklov eigenvalue. The design problem becomes the problem of minimization of the maximal eigenvalue. Solving the last problem, we face multiplicity of the eigenfunctions: More than one critical load may correspond to the maximal eigenvalue. Similar phenomenon of multiplicity was noticed in the optimization of eigenfrequencies and buckling load. Here, the multiplicity of the eigenfunctions means that the optimally designed construction should equally well resist several mutually orthogonal and evenly destructive loadings. The optimal structure that evenly resists several loadings is either the "third-rank matrix laminate" (in 2D) or "sixth-rank matrix laminate" (in 3D); the stiffness tensors of these structures are explicit functions of their geometry. Also, we observe that a symmetry of possible loadings results in the same symmetry of the optimal shape or structure.

Minimum Elastic Energy Configurations of DNA Torus Knots and Catenanes

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In research of Bernard D. Coleman, Irwin Tobias, and the speaker on the theory of the idealized elastic rod model for DNA exact analytical representations have been obtained for equilibrium configurations of DNA segments showing both isolated points and intervals of self-contact. Criteria have been derived for determining whether an equilibrium configuration is stable in the sense that it gives a strict local minimum to elastic energy. In recent joint research with Coleman these results have been applied to knotted DNA plasmids, with emphasis placed on the dependence on excess link of minimum elastic energy configurations of knotted DNA plasmids. Among the results to be presented are: the bifurcation diagram for supercoiled DNA trefoil knots and a theorem to the effect that the minimum bending energy configuration a (2, q) torus knot shows self-contact along a circle. The theorem remains valid even when the integer q is even, i.e., when the "knot" reduces to a link of 2 unknots.

Keywords: elastic rod, DNA topology, elastic stability, knots

Global Bifurcation of Barrelling States of Cylindrical Columns

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For many years one of the most difficult open problems of non- linear elasticity theory has been the use of global

continuation methods (via degree theory) to study the governing partial differential equations of three-dimensional models. Recent results by Healey and Simpson based upon the construction of a degree which has the same important properties of the classical Leray-Schauder degree, makes it possible to do rigorous global bifurcation analysis of problems in non-linear three- dimensional elasticity. In this talk we prove the existence of local and global bifurcation of nontrivial barrelling states for the boundary value problem of columns undergoing uniaxial compression. We will also remark on the corresponding lateral compression problem.

Global Bifurcation and Continuation in Nonlinear Elasticity

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We consider a general class of boundary value problems governing the equilibrium of forced, three-dimensional nonlinearly elastic bodies. In spite of the age of the subject, the current state of existence theory in nonlinear elastostatics is quite poor. Local existence of classical solutions, based upon the implicit function theorem, is well known. For a broad class of conservative problems, J. Ball proved the existence of absolute energy minima in 1977. However, it is not known if such minima correspond to weak solutions of the Euler-Lagrange equations (momentum balance), and the results do not address the existence of other critical points - including local energy minima.

We impose strong ellipticity and pay careful attention to the constraint of local injectivity and the accompanying growth of the stored energy function. These physically natural restrictions rule out *uniform* ellipticity. In addition, the presence of traction boundary conditions renders the problem fully nonlinear. Consequently, a conventional Leray-Schauder-Rabinowitz approach to global analysis is precluded. We present recent results, overcoming these difficulties in global bifurcation and continuation problems of nonlinear elastostatics. Physically reasonable constitutive restrictions and growth conditions play a crucial role. In the absence of a-priori bounds, however, we fall short of general existence theorems. Nonetheless, these are the first results in our subject addressing classical, locally injective solutions "in the large".

The Hanging Rope of Minimum Elongation for a Nonlinear Stress–Strain Relation

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We consider the problem of determining the shape that minimizes the elongation of a rope that hangs vertically under its own weight and an applied force, subject to either a constraint of fixed total volume or fixed total mass. The constitutive function for the rope is given by a nonlinear stress-strain relation and the mass-density function of the rope can be variable. For the case of a constant mass-density function we show that the optimal cross-sectional area of the rope is as that for a linear stress-strain relation (Hooke's Law). For the case of a variable mass-density function we use the implicit function theorem to show the existence of a branch of solutions depending on the parameter representing the acceleration of gravity. This local branch of solutions is extended globally using degree theory techniques.

MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY VII

In Memory of Professor C. A. Truesdell

SESSION W2A

The Augustinian Contuitus and Its Relevance in Natural Philosophy

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Saint Augustine in his 'Confessions' argued that (God help us!) time seems to be a void concept because, said roughly, past is gone, future has still to come and the element of separation between past and present has no duration. In fact, the latin word He used for that element (contuitus) suggests the contrary: the complex of feelings (the 'sight', as contuitus is usually translated) that makes up our 'present' depends on the time constants of our sensorial make-up.

Thus it seems appropriate that, also in studying the physical wordl, we ought to address the 'present' of bodies in a less dismissive way as is usual and not exclude the need, sometimes, to involve at least two scales for the

variable time: a contuitive and a subtuitive scale. Some phenomena that seem to require such more detailed image of 'present' are quoted (e.g., intermittency, structured deformations, body shocks) and a possible approach is suggested.

Symmetries and Hamiltonian Formalism when Material Elements do not Behave like Monads

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In the classical approach to the modeling of continuous bodies, each material element is considered to be identifiable once and for all. In Cauchy's format, the material element is a monad attached at a place in space. Then the standard job is to evaluate the crowding and the shearing of neighboring material elements. Often, real materials display a rather prominent influence of the texture on the bulk behavior and even the material element may be no more uniquely identifiable; rather, in some circumstances it is an element of the limit of a sequence of bodies in the sense of Del Piero and Owen [1].

Order parameters may be introduced to represent the prominent features of the material texture; they are true observable variables because they sense changes of observers. Then, substructural interactions must be considered, develop power in the rate of the order parameter and must be balanced. Various models fall within this scheme: multi-phase materials, liquid crystals, polymeric fluids, polycrystals etc. Sometime the order parameter may be identified uniquely, in other cases it is a statistical average of a certain property of some population of substructures. Order parameters may reduce to internal variables when they describe latent substructures in the sense of Capriz [2].

In the present paper, only the conservative case is treated and the order parameters are considered in general as elements of a differentiable manifold [2] M. Appropriate Lagrangian and Hamiltonian formalisms are considered. The consequences of requirements of invariance of Lagrangians under the actions of groups are examined first: conservation laws follow even in the form of non-usual path-independent integrals. Then, essential geometrical features of the consequent non-standard Hamiltonian formalism are discussed. The geometric properties of M influence the structure of classical Hamiltonian formalism of field theories [3]. The possible occurrence of non-local effects is also discussed.

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Smooth Categories and Microstructure

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Bodies can sometimes be considered to have infinitesimal thickness, or even to be themselves infinitesimal. To model this useful approximation by using "extra" quantities abstractly imposed on lower-dimensional space may serve immediate needs. However, more fundamentally, these quantities should rather be realized as intensively or extensively variable over the body itself as domain space. In fact, such a recognition of the role of the body itself is possible, because even a body with only one point can have non-trivial elements, as in certain categories inspired by work of Volterra, Hurewicz, and Grothendieck. Instead of containing "non-standard" ghost points and ghost maps, these categories reveal that the ordinary spaces have many subspaces. These subspaces are not distinguishable by their mere points; the topological dimension of such a space may be 0, 1, or 2, even though its intrinsic tangent bundle has fiber dimension 3. Some examples of material microstructure are also intrinsic to such space without imposing "extra" quantities. Possible constitutive relations for "part-icles" (qualitatively diminutive parts, not bare points) with such a microstructure can be surveyed by using a functional analysis of large finite (but not infinite) dimension.

Keywords: Cosserat, topos, infinitesimal body, microstructure

A Simple Class of Fit Regions for Continuum Mechanics

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At my knowledge, it was in the paper (1) that W. Noll expressed for the fist time the idea that the "set of the parts of a body" should belong to a suitable class of "nice" regions. Later, in a paper with E. Virga (2), he defined a

specific class of "fit regions". The definition was based on the concept of a set with finite perimeter, and the machinery of geometric measure theory was used in proving that the proposed class of regions satisfies a number of axioms of physical nature.

In his last textbook on Continuum Mechanics, Clifford Truesdell put large emphasis on these ideas. He set as a cornerstone the concept of a "universe of bodies", and he introduced the concept of a "universe of shapes", the set of all regions which can be occupied by the body when subject to a properly defined class of deformations.

In this contribution I present a class of fit regions which requires a simpler mathematical apparatus and which, at least in my opinion, meets more directly some requirements suggested by physics. In the proposed definition, fit regions are equivalence classes of regions which have the same interior. Thus, they need not be either open or closed. This allows to re-define the operations of "join" and "meet" between regions in a more direct and comfortable way. A second advantage is that no measure theoretic concepts are involved in the definition, which only relies upon more familiar tools from topology. Nevertheless, since the boundary of a fit region is required to have a finite (n-1) dimensional Hausdorff measure, fit regions are automatically sets with finite perimeter; therefore, they enjoy all properties of this class of sets. Finally, I prove that the proposed class of fit regions can be identified with a subset of Noll and Virga's class. The regions which are left out in the new definition seem not to be of any importance in Mechanics.

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Cauchy's Flux Theorem in Light of Geometric Integration Theory

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This work describes the theory of Cauchy fluxes in the setting of H. Whitney's abstract geometric integration theory. A basic feature of this theory, is that it addresses at the same time various issues of continuum mechanics such as the class of regions under consideration, the existence of flux, the regularity of flux, and the representation of balance by a differential equation. The fluxes one obtains are as irregular as bounded and measurable functions. The admissible domains are very general and include regions with piecewise differentiable boundaries, domains which are nowhere rectifiable, Dirac's delta and its derivatives, and fractals. In Whitney's approach to integration, one gives a Banach space structure to the collection of integration domains, called chains. Starting with the vector space of polyhedral chains, the Banach space is obtained by a completion process relative to a norm. Then, integration operators, called cochains, are defined as elements of the dual space to the space of chains. Thus, the approach links the analytical properties of cochains with the corresponding properties of the domains in an optimal way. The basic representation theorem shows that cochains may be represented by forms. The various norms used in the completion process, in particular those introduced recently by J. Harrison, give a variable degree of smoothness to the representing differ ential forms. The form representing a cochain is a geometric representation of a flux in continuum mechanics.

Some Geometric Properties of High Order Fluxes

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High order stresses, particularly tensors of order 3, are used in continuum mechanics to model phenomena like surface tension and edge interactions. The fundamental work on the subject was done by Toupin, [1], followed by Mindlin and others. While traditionally, the concept of a stress in continuum mechanics is based on Cauchy's theorem, most work on the subject introduce the high order stresses using a variational approach where an assumed elastic energy depends on the second derivatives of the configuration mapping. The only presentation of high-order stresses using an approach analogous to the classical proof of Cauchy's theorem is due to Noll & Virga, [2]. The present work, confined to fluxes for simplicity, considers some geometric properties of higher order theories in the framework of general differentiable manifolds. In particular, we do not assume the availability of a particular Riemannian metric. In addition, we study some features common to all high order theories. The presentation uses the theory of symbols of linear differential operators

on vector bundles and integration of differential forms in analogy with some recent work, [3].

Keywords: Fluxes, Manifolds, Edge, Forms.

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Truesdell's Views on the Interdisciplinariety of Certain Rigorous Works

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Painlevé's booklet 'Les axiomes de la mécanique' (1922) is widely known. In it, after the remarkable phrase "cette terminologie admise" an axiom system is "rapidly" proposed, practically capable to define general notions such as *force*.

It is *generally unknown* that the "admitted terminology" is connected with a lack of rigor which induced a remarkable rigorization work. The related rigorous articles have a threefold *interdisciplinary character: mechanics, logic, philosophy of science*. A. Bressan decided to treat this character in a meeting in April 2002 because it it had caused serious misunderstandings and even now it is increasingly important to divulge that these are due to lack of information.

The above rigorous articles include A. Bressan's monograph 'Metodo di assiomatizzazione...' (1962) (of over 150 pages) on mass points. In this, a "theorem" asserted in the booklet is shown not to be rigorously provable there; and it is rigorously proved in the monograph. This fact was appreciated by Prof. Truesdell; and in his letter to the Acc. Naz. Lincei, Rome (1984) he strongly supported the extension of the monograph to continuous media, extension to be also enriched with yet unpublished articles on mechanics, logic and philosophy of science.

M. Pitteri used *physical possibility* (a special kind of A. Burks's causal possibility) introduced in the monograph and further studied in a much reacher modal theory (1972) of A. Bressan. He knew this notion intuitively but used it correctly for motives of ease; and he correctly introduced modal axioms in an article included in Truesdell's book Rational Thermodynamics (1984). Thus Truesdell and Pitteri are the only professors of mechanics that (as far as I known) fail to ignore the above interdisciplinary character; and more they can deal with this correctly.

Several remarkable merits of Prof. Truesdell appear from his polemic book 'An idiot's fugitive essays on science' on philosophy of science (1984) and from his support letter (1984).

MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY VIII

In Memory of Professor C. A. Truesdell

SESSION W3A

Eshelby Tensor as Tensor of Free Enthalpy

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On the phase boundary between two liquids, or between a gas and a liquid, equilibrium means that, – apart from pressure and temperature, – the free enthalpy (Gibbs free energy) is continuous. This observation leads to the well-known vapour pressure curve $p(T)$ and to the Clausius Clapeyron relation.

Things are different when we consider equilibrium between two coherent solid phases, because in that case there is no pressure; rather there is the stress tensor, whose component normal to the interface is continuous along with the temperature. In addition the normal component of the Eshelby tensor is continuous which therefore play the role of the free enthalpy: from the thermodynamic point of view the Eshelby tensor may be regarded as the tensor of free enthalpy.

The paper illustrates this role of the Eshelby tensor for a circular linearly elastic thin plate subject to a fixed radial displacement. The plate material may undergo a phase transition characterized by a prescribed strain tensor. We calculate the position of the phase boundary as a function of temperature. For simplicity we assume plane stress and equal moduli of the phases.

Keywords: Phase transition, Eshelby tensor, free enthalpy tensor

Weak Phase Transitions in Multilattices

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We show that, as for simple lattices, also for essentially described multilattices generic bifurcations occur provided the tensor of moduli (second-order derivatives of

the free energy density with respect to the configurational parameters) has irreducible-invariant proper spaces, one of which is the kernel of the tensor itself.

This requires the transition to be either (purely) configurational or purely structural and, in the second case, the coupling that drives the skeleton to the same symmetry as the whole structure to be of the third order at least. Application to the alpha-beta phase transformation will be given if time permits.

The research presented is part of the activities of the TMR research project "Phase Transitions in Crystalline Solids", funded by the European Community, and of the "Cofinanziamento 2000: Modelli matematici per la scienza dei materiali".

Kinetic Theory for Collisional Grain Flows

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We consider flows of inelastic particles in which collisions dominate the transport of momentum and energy. We review the predictions of kinetic theory for steady, fully developed collisional flows of identical, nearly elastic, frictionless spheres in simple situations. These include shearing between parallel horizontal boundaries with bumpy, frictional features, vertical flow driven by gravity between such boundaries, and gravitational flow down a bumpy, frictional incline.

We indicate when simple kinetic theory for frictionless, nearly elastic spheres succeeds in describing such flows and when it fails. Usually, the simple theory fails because there being too much energy lost in collisions or because the particle interactions can not be idealized as instantaneous and binary. When it fails, we show what additional elements need be incorporated in order improve predictions.

Keywords: Kinetic, Granular, Collisional, Flows

The Atomic Level Virial Stress is not a Valid Measure of Mechanical Stress

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As one of the most commonly used definitions of stress in discrete molecular systems, the virial stress includes two parts. The first part depends on the mass and velocity of atomic particles, reflecting an assertion that mass transfer causes mechanical stress to be applied on stationary spatial surfaces external to an atomic particle system. The second part depends on interatomic forces and atomic positions, providing a continuum measure for the internal mechanical interactions between particles. The virial stress violates balance of momentum and does not possess physical significance as a measure for mechanical interaction between material points. The lack of physical significance is both at the individual atom level in a time-resolved sense and at the system level in a statistical sense. As a stress-like quantity, the virial stress has the geometric interpretation of being a measure for momentum change in a fixed spatial region. It is demonstrated that the interatomic force term alone is a valid stress measure and can be identified with the Cauchy stress. The discussions focus on historic errors made in the theoretical derivation of the virial stress that led to the inclusion of the kinetic energy term and on the conceptual flaws in the argument commonly used for including it. To further illustrate the irrelevance of mass transfer to the evaluation of stress, an equivalent continuum (EC) for dynamically deforming atomistic particle systems is defined. The equivalence of the continuum to discrete atomic systems includes (i) preservation of linear and angular momenta, (ii) conservation of internal, external, and inertial work rates, and (iii) conservation of mass. This equivalence allows fields of work- and momentum-preserving Cauchy stress, surface traction, body force, and deformation to be determined. The resulting stress field depends only on interatomic forces, providing an independent proof that as a measure for internal material interaction stress is independent of kinetic energy or mass transfer.

Some Critical Experimental Results on Polymers

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A comprehensive set of experimental results will be presented on three polymers (Adiprene L100, Teflon and Nylon). These highly non-linear measured responses are from compression tests at a wide range of strain rates and temperatures, relaxation experiments at different levels of deformation under compression, torsion and tension-torsion loading, studies of creep in these materials, and loading-unloading experiments followed by monitoring of the deformation recovery after unloading. The last set of the experiments are used to separate visco-elastic and

visco-plastic deformations. In Adiprene, the softest material of this family and which is rubber-like, the deformation is mostly visco-elastic, while in Nylon, it is predominantly visco-plastic deformation. In between, visco-elastic and visco-plastic deformations are significant in Teflon. Relaxation process will be shown to be basically an elastic one, while creep causes internal change in the material. The response of the three polymers is non-linearly dependent on strain-rate and temperature.

MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY IX

In Memory of Professor C. A. Truesdell

SESSION W4A

On the Equilibrium of Spherical Particles in a Vertical Shear Flow

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Over the last 40 years the study of the motion of small particles in a viscous liquid has become one of the main focuses of engineering research; see [1] and the literature cited therein. The presence of the particles affects the flow of the liquid, and this, in turn, affects the motion of the particles, so that the problem of determining the flow characteristics is highly coupled. It is just this latter feature that makes any fundamental mathematical problem related to liquid-particle interaction a particularly challenging one.

This talk concentrates on the mathematical analysis of one of these interesting questions. Specifically, we shall consider the motion of a spherical particle in a vertical channel filled with a Newtonian liquid. The driving forces acting on the liquid are a constant pressure drop in the axial direction, and gravity. Our objective is to determine all possible equilibrium positions of the particle at small and non-zero Reynolds number. We show that this problem may have one, more than one or no solution at all depending on whether the particle is homogeneous and/or neutrally buoyant.

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Temperature and Heat Inequalities in Process Thermodynamics

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The approach to thermodynamics fostered by Clifford Truesdell since the early 60s of the past century emphasized its application to processes, and made use of entropy and absolute temperature concepts which were taken as primitive, undefined notions. A second wave of foundational studies a decade later (by the same Truesdell, Serrin, Šilhavý, Fosdick, Ricou, and others) addressed the problem of giving meaning to (absolute) temperature and entropy in general, 'non-equilibrium' processes. In this respect the great breakthrough was the introduction by Serrin of his 'accumulation function'. Its concept needs a one-dimensional ordered manyfold of hotness levels, which is mapped onto the real line by the temperature scales. In our paper we construct this order, relating it to the asymmetry of heat exchange through an axiom imposed on a heat interaction function which generalizes Serrin's accumulation function. In particular, we define the structure of heat interaction by introducing *(i)* a notion of interaction process and of composite system, *(ii)* a non-negative biadditive heat interaction function, *(iii)* a set of axioms translating the directionality of heat exchange; with their help we *(iv)* define an order on the hotness manyfold and *(v)* obtain several *general heat inequalities* expressed in terms of Serrin's accumulation functions, which entail *(vi)* so-called 'heat-bath' inequalities. Further we prove for composite systems *(vii)* a subadditivity result of the accumulation function, and *(viii)* a general subadditivity and a special additivity result for Ricou's general entropy function.

Keywords: temperature, heat inequalities, entropy additivity

Minimum Free Energies for Materials with Finite Memory

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Finite memory viscoelastic materials are of interest because (a) they are experimentally indistinguishable form

materials with infinite memory; and (b) the assumption of infinite memory can, in certain contexts, lead to results that run counter to physical experience; and example of this - the quasi-static viscoelastic membrane in a frictional medium - is presented in the lecture.

It is shown that, for a finite memory material, the singularity structure of the Fourier transform of the relaxation function derivative is quite different from the infinite memory case in the sense that it is an entire function with all its singularities being essential singularities at infinity. The formula for the minimum free energy [1] is shown to be still valid in this case. In contrast to the work function, this quantity, and all other functions of state, depend only on the values of the history over the period when the relaxation function derivative is non-zero.

The factorization required to determine the form of the minimum free energy can be carried out explicitly for simple step-function choices of the relaxation function derivative. The two simplest cases are fully worked through and explicit formulae given for all relevant quantities.

Keywords: Viscoelasticity, thermodynamics, free energy, finite memory.

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Exponential Decay in Materials with Memory

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Consider the decay to zero of solutions of the dynamic problem of linear inho- mogeneous viscoelasticity:

$$\rho\ddot{\mathbf{u}} = \operatorname{div}\mathbf{S}, \qquad \Omega \times (0,\infty), \tag{1a}$$

$$\mathbf{S} = \mathcal{G}(0)\mathbf{E} + \dot{\mathcal{G}} * \mathbf{E}, \quad \Omega \times [0,\infty) \tag{1b}$$

$$\mathbf{u} = \mathbf{0} \text{ on } \Gamma_1 \times (0,\infty), \ \mathbf{Sn} = \mathbf{0} \text{ on } \Gamma_2 \times (0,\infty), \tag{1c}$$

$$\mathbf{u}(\mathbf{x},0) = \mathbf{u}_0, \quad \dot{\mathbf{u}}(\mathbf{x},0) = \mathbf{u}_1, \quad \mathbf{x} \in \Omega. \tag{1d}$$

Here $\mathbf{u}$ is the displacement, $\mathbf{E}$ is the infinitesimal strain, $\mathbf{S}$ is the stress, $\mathcal{G}$ is the relaxation function, ρ is the mass density, Ω is the region occupied by the body in its reference placement, $\mathbf{n}$ is the outward unit normal to the boundary $\partial\Omega$ and Γ_1, Γ_2 are complementary subsets of $\partial\Omega$ such that Γ_1 has positive measure. The body force and past history are neglected, so that the body can only gain or lose energy through its initial instantaneous displacement.

It has long been known that if the relaxation function satisfies usual physical restrictions, the damping is too weak to ensure that solutions of (1) decay to zero exponentially. If solutions of (1) do decay to zero exponentially, this reflects a property of the material. The aim is investigate this property mathematically.

We say here that a solution $\mathbf{u}$ of (1) decays to zero exponentially if

$$\int_0^\infty \int_\Omega (|\mathbf{u}(\mathbf{x},s)|^2 + |\nabla\mathbf{u}(\mathbf{x},s)|^2 + |\dot{\mathbf{u}}(\mathbf{x},s)|^2) e^{2\delta s} dx ds < \infty \text{ for some } \delta > 0. \tag{2}$$

Synchronous relaxation functions have the form $\mathcal{G}(\mathbf{x},t) = g(t)\mathcal{C}(\mathbf{x})$, where g is scalar-valued. Appleby, Fabrizio, Lazzari and Reynolds have shown that for synchronous relaxation functions which satisfy the usual convexity assumptions $\dot{g}(s) \leq 0$ and $\ddot{g}(s) \geq 0$, a necessary condition for a nontrivial solution of (1) to decay to zero exponentially in the sense of (2) is that $\int_0^\infty (|\dot{g}(s)| + |\ddot{g}(s)|) e^{\gamma s} ds < \infty$ for some $\gamma > 0$. Moreover it has been shown that, for general asynchronous relaxation functions, a strong thermodynamic condition on $\mathcal{G}$ and

$$\int_0^\infty \int_\Omega (\| \dot{\mathcal{G}}(\mathbf{x},s) \| + \| \ddot{\mathcal{G}}(\mathbf{x},s) \|) e^{\gamma s} dx ds < \infty \text{ for some } \gamma > 0. \tag{3}$$

are sufficient for the exponential decay to zero of solutions of (1) in the sense of (2).

This paper reviews these results, examines similar results in the theories of heat conduction and electromagnetism and discusses how solutions decay to zero in some cases of (3) being violated.

Universal Relations for Principal Acceleration Waves in Nonlinear Isotropic Viscoelastic Solids

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A *principal wave* in a deformed body is a wave whose direction of propagation is parallel to a principal axis of strain. For nonlinear isotropic elastic solids, several simple relations for the speeds of principal acceleration waves are known. Ericksen's (1961) formula relates the shear wave speed to the principal strains and the difference in the principal stresses in the region ahead of the wave.

Biot's (1963) formula relates the difference in the shear wave speeds along orthogonal principal axes to the difference in the principal stresses. Truesdell's formula for waves propagating into a region under hydrostatic pressure relates the longitudinal and shear wave speeds to the derivative of pressure with respect to the density. These formulas are *universal relations* in the sense that they hold for all nonlinear isotropic elastic solids and do not explicitly involve the coefficients in any particular representation of the stress-strain relation. The material need not be hyperelastic.

In this talk we will consider generalizations of the above relations to principal acceleration waves in nonlinear isotropic viscoelastic solids. The classes of constitutive models studied here are of the single integral type and include the "finite linear" viscoelastic solids of Coleman and Noll (1961) and the model of Pipkin and Rogers (1968). Some universal relations for the former class have been obtained by Schuler (1970) and Nunziato, Schuler and Walsh (1972), and their results are extended here. The implications for the experimental determination of the stress relaxation function are discussed.

Keywords: acceleration waves, nonlinear viscoelasticity, universal relations

MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY X

In Memory of Professor C. A. Truesdell

SESSION R2A

Pseudo-Plasticity and Pseudo-Inhomogeneity Effects in Materials Mechanics

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It is shown that a large variety of physical effects such as continuously distributed defects, heat conduction, anelasticity (plasticity in finite-strains, growth), phase transitions, more generally shock waves, can be viewed as pseudo- material inhomogeneities when continuum thermomechanics is completely projected onto the material manifold itself. Main ingredients in this approach are the notions of local structural rearrangements (Epstein and Maugin) and of its thermodynamical dual, the Eshelby material stress tensor. An outcome of this is the unification of the theories of inhomogeneity of Eshelby on the one hand, and of Kroener-Noll-Wang on the other hand. The notion of configurational forces as understood nowadays in solid-state physics and engineering mechanics follows necessarily from these developments. They are driving forces acting on sets of material points that correspond to strongly localized fields (in the limit, singularities), the latter being also viewed as pseudo-inhomogeneities. The second law of thermodynamics then is a constraint imposed on the time evolution of these pseudo-inhomogeneities (e.g., plastic evolution, volumetric growth, progress of a crack, advancement of a phase transition front, etc). This has very powerful applications in numerical schemes drawn directly on the material manifold (e.g., thermodynamically admissible volume-element scheme for the simulation of phase-transformation evolution).

Inhomogeneity of Generalized Media with Microstructure

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A material body with smoothly distributed microstructure can be seen geometrically as a fibre bundle M whose base manifold B is an ordinary material body (the macromedium). The nature of the fibre depends naturally on the particular physical application. Within this general framework, we define the notion of configuration as a trivialization of M, namely, a fibre-consistent embedding of M in the product bundle defined by the Cartesian product of physical space with the typical fibre of M. In order to characterize a first-grade material response of such bodies, we introduce the notion of first-order fibre jets as certain equivalence classes of configurations sharing first derivatives along entire fibres. In this way, we localize the response in terms of points in the macromedium, while leaving the fibre dependence global in principle. Material symmetries can then be defined and their rather complicated symmetry group characterized. The notion of material uniformity is then introduced and shown to confer on the body the structure of a transitive (Lie) groupoid. A precise notion of local inhomogeneity can then be established as the departure of this groupoid from flatness. Two applications are developed in greater detail. The first one considers a global response of the fibres characterized by integration of a fibre-wise volume form. An attempt to define the associated Eshelby "stress" at this level of generality is explored. As a second application, we show

that this general theory reduces to the theory of inhomogeneity of generalized Cosserat media when the fibre bundle is identified with the principal bundle of frames of the macromedium.

A Few Remarks on the Kinetic Energy in Continua with Structures

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Kinetic energy is frequently disregarded in continua with structures, as applications or macroscopic evidences are essentially concerned with static or quasi-static phenomena. Whenever dynamics happens to be relevant, people customarily appeal to a quadratic form of the kinematic variables of the microstructure, by analogy with the classical form of the kinetic energy. However, such a quadratic form may be inappropriate or even incorrect in some cases. Examples of the inadequacy of this quadratic form are illustrated in reference [1], where a systematic treatment for the dynamics of continua with microstructure is also expounded. In that context, the notion of kinetic co-energy is judiciously introduced, along with that of kinetic energy. Although the proposed treatment is irrespective of thorough variational procedures, the notion of kinetic co-energy naturally addresses to a variational formulation, if this novel notion is understood as a primitive quantity. In this view, a procedure for deriving the kinetic energy can be proposed. Other approaches are proposed in the literature. A specific Lagrangian can be introduced, for instance, whenever some of the equations that govern the microstructure are a priori known and, in addition, admit a variational formulation. Possibly, such a Lagrangian formulation may not unambiguously allow for the classical distinction between forces (in the sense of material constitutive response) and inertial forces. In this respect, the question may arise whether the notion of kinetic co-energy can be consistently introduced in such a context. Hopefully, such a consistency can be assessed for a broad class of structured materials and the novel notion can provide a qualified tool for selecting momentum and stress. Eventually, a deformable electromagnetic material is discussed hereby in this view.

Keywords: Continuum Mechanics, Microstructure, Variational methods, Electromagnetism.

Mathematical Modeling of Mesoscopic Elasticity

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This talk presents our study of mathematical modeling of elastic properties of mesoscopic materials. The primary physical properties of these materials depend on the processing history of their assembly and have common mechanical behavior, which exhibits nonlinearity, hysteresis, etc. The mesoscopic materials represent a wide class of materials, which includes damages crystalline materials, natural rocks, sand, soil, cement concrete and material of sol-gel technologies, etc. These material structures consist of rigid elastic units connected by dislocated elements that control the whole mechanics. The typical sizes of fabric defects in mesoscopic materials are of order 1ìm. We discuss a mathematical theory for that mechanical behavior. The general mathematical description includes theory of defects, which we combine with classical elasticity theory. We describe dynamics of the mesoscopic materials in terms of configurational bulk, surfaces and lines stresses. We also incorporate into these model well-known differential equations for characteristics of density and flux of the material imperfections, dislocations and other relevant to these mesoscopic dynamics characteristics. We introduce special constitutive equations, which allow us to obtain some analytical solutions. We also consider influence of the constitutive equations on the particular forms of the strain-stress relationship, which are essential in the description that mesoscopic elasticity.

This research is partially supported by the DOE EPSCOR program for Puerto Rico.

A Model of the Evolution of a Two-dimensional Defective Structure

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In pure elasticity an a-priori introduced pattern of inhomogeneities (defects, dislocations, etc.) remains unchanged. In contrast, theories such as plasticity, visco-

elasticity and material growth involve mechanisms that usually modify the distribution of inhomogeneities. Formulating such an evolution law is a difficult constitutive modelling problem. In this work, using the language of the mathematical theory of inhomogeneities, a simple model of the anelastic evolution law of a two-dimensional defective solid crystal body is proposed. Assuming that the material body is made of triclinic crystals and that the evolution process does not alter the basic material symmetry group, we postulate that in a stress free environment the evolution is driven by the density of the distribution of defects. In the theory of the continuous distribution of inhomogeneities this density is represented by the torsion of a unique material connection. We therefore propose that the evolution equation is a linear relation between the inhomogeneity velocity gradient, measuring the rate of change of the pattern of defects, and the torsion tensor. We show that this simple law is rich enough to model such phenomena as relaxation of defects, dislocation pile-up and nucleation.

MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY XI

In Memory of Professor C. A. Truesdell

SESSION R3A

Elasticity with Disarrangements as a Continuum Field Theory

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The multiscale geometry embodied in the theory of structured deformations provides decompositions of macroscopic deformation, velocity, and stress into a part due to non-smooth deformations (disarrangments) at smaller length scales and a part due to smooth deformations at smaller length scales. Corresponding decompositions of the power together provide balance laws for linear and angular momentum in which the unknown fields are the macroscopic motion χ, the deformation and velocity without disarrangements G and $\dot{\chi}_\backslash$, and the stress S. We review the derivations of these balance laws and introduce a constitutive assumption of elasticity in the context: the free energy density ψ is a function Ψ both of the macroscopic deformation $F = \nabla\chi$ and the deformation without disarrangements G. We obtain conditions on isothermal dynamical processes that are sufficient for the second law of thermodynamics to hold and that imply (i) a formula for the stress as a combination of the partial derivatives $D_F\Psi$ and $D_G\Psi$ valid on each dynamical process, (ii) a consistency relation connecting $D_F\Psi$ and $D_G\Psi$ on each dynamical process, and (iii) a formula for the internal dissipation as the inner produce of $D_G\Psi$ and $\Delta\dot{\chi}_\backslash - \dot{G}$, the latter being a measure of the submacroscopic incompatibility of a given structured motion. The balance laws and the thermodynamical relations (i), (ii), and (iii) provide the field equations and dissipation inequality for our theory of elastic bodies undergoing disarrangements. We give a preliminary study of statics in the field theory by introducing a notion of "submacroscopic stability" for homogeneous structured motions. We prove that a homogeneous, classical motion (i.e., a homogeneous motion in which $G = F$ and $\dot{\chi}_\backslash = \dot{\chi}$) is submacroscopically stable only if the Cauchy stress is hydrostatic, and we provide an example of an elastic body that can undergo infinitely many non-classical, submacroscopically stable homogeneous motions with non-hydrostatic stress.

Keywords: structured deformation, elasticity, disarrangements, multiscale geometry

A Continuum Theory for Materials with Microstructures

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A theoretical framework that combines the merits of the continuum approach and the micormechanics approach is developed for dynamics of material systems with microstructures and phase transformation properties. In particular, the dynamic behavior of porous shape memory alloys (SMAs) is studied within this framework.

Average state variables and internal variables associated with material microstructures are explicitly defined through averaging process. The concept of moving average is used in deriving the field equations for the average variables. These equations contain terms associated with pore surface effects. It is noted that these surface terms are found to occur in the continuum theory developed by Nunziato and Cowin [1] for porous elastic materials. The equations governing the evolution of the internal variables are also derived from the exact field equations. For example, by taking the scalar moment of the local equation of motion about the centroid of the void and integrating, an equation is derived, which governs the motion of pore expansion, and has been identified as the balance of equilibrated force in [1].

The constitutive equations for the internal variables are derived using variational principles via the virtue de-

formation and the generalized forces of the microstructure. This involves averaging a certain energy function and solving a series of initial-boundary value problems for a representative volume element. Both homogeneous and inhomogeneous kinematic boundary conditions are needed to obtain constitutive equations for higher order gradient of internal variables. The increment of the average energy due to the virtue displacement of the pore surfaces leads to the relation between the generalized forces on pore surface and the pore surface deformation. These generalized forces are found to be linked to the equilibrated stress and the intrinsic equilibrated body force introduced in [1].

[1] Nunziato, J. W. and Cowin, S. C. A nonlinear theory of elastic materials with voids, *Archive Rational Mech. Anal.* **72**, 175-201 (1979).

Modeling of Ferroelectric Liquid Crystals and Applications

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This presentation deals with the modeling of ferroelectric phases of chiral smectic C liquid crystals and their electro-optic properties.

The free energy that we study is that proposed by de Gennes and Lubensky for the modeling of smectic phases, but including additional terms accounting for polar interactions. We first identify energy minimizers corresponding to ferroelectric and antiferroelectric phases. In particular, we show that the model accounts for the Clark-Lagerwall effect. Secondly, we propose an evolution equation to study the transition between ferroelectric and antiferroelectric phases, and discuss estimates for the switching time among them. We will finally discuss the properties of the model in terms of modern applications to large video display devices, optical switching and telecommunications.

On Spontaneous Deformation and Internal Stress and Electric Fields

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Domain reorientation is the major character of ferroelectric materials that are in service. Spontaneous deformation associated with domain reorientation is inevitable and significantly affects behavior of ferroelectric materials when the materials are under a cyclic loading. However, in classical constitutive theories for ferroelectric materials, the spontaneous deformation is ignored, and the stress and electric fields in the materials are assumed to have a linear dependence on strain. To investigate effects of the spontaneous deformation on behavior of ferroelectric polycrystalline materials, a model based upon the assumptions that the strain energy function is domain dependent, and that the strain energy function is a quadratic function of induced strains and induced electric displacements for each domain is established. In this model, the strain energy function is a non-convex function of strains and electric displacements. As an example, the distribution of internal stresses and electric fields around a triple point of a ferroelectric polycrystalline aggregate was discussed. By enforcing the continuity conditions across grain and domain boundaries and assuming that each grain consists of either a single domain or a finite number of twinned domains, a general and analytical representation of the internal stress and the internal electric field around the triple point due to the spontaneous polarization was derived. The consequences of uncertainty of the spontaneous deformed configuration on the internal fields were discussed. The difference in distributions of internal stress and internal electric field for the triple point configuration with different electric domains and twinning structures was demonstrated, and an argument relating this difference to the fatigue behavior of ferroelectric material under the action of pure cyclic electric field was given.

Keywords: Spontaneous Deformation, Internal Stress and Electric Field, Domain, Twinning

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MECHANICS, CONTINUUM THERMODYNAMICS AND KINETIC THEORY XII

In Memory of Professor C. A. Truesdell

SESSION R4A

Rod Theories: Energy Formulations of the Theory of Slices

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Theories of rods have been devised for describing the deformations of bodies that are long and slender. While three-dimensional elasticity theory certainly provides the equations to be solved for such bodies, researchers have

long looked for ways in which the long slender nature of a rod might help to simplify the equations to be solved. Several "technical" theories have been designed with this purpose in mind and have served the researcher well. At the same time there is interest in ensuring that elasticity theory and these technical theories exhibit some consistency or overlap. Do the sharply different theories we see give rise to similar deformations for what should be the same body?

The goal of this research is to introduce a formulation of elasticity theory specifically focused on rod shaped bodies. A theory of elastic slices is developed and three-dimensional deformations are represented as a one-parameter family of slices generated through rigid-body displacements. The classical energy minimization problem for hyperelastic bodies is then reformulated in terms of this representation and shown to stratify into two coupled problems: a) a "technical" theory of rods whose constitutive relations come from b) an energy minimization problem on the space of slices. By approximating solutions of the minimization problem, the technical rod theory reduces to a theory of rods that is familiar in the literature.

Keywords: rods, elasticity, slices, minimization)

Unusual Buckling of Highly Anisotropic Elastic Materials and Rippling of Carbon Multiwalled Nanotubes

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It has been known for more than two and a half centuries that a column subjected an axial pressure force may be buckling when the force reaches a critical value, and this critical force is proportional to the inverse of the square of the column length. Such a relation, called Euler formula, is, however, valid only for slender columns. A short column under an axial pressure force may tend to be failure due to the stress (or equivalently, strain) is beyond the stress strength of the material of the column, rather than buckling. Recently, it was found that carbon multiwalled nanotubes (MWNTs) can bear extremely large bending while remain to be elastic. The microstructure of a MWNT is an assemblage of concentric cylindrical graphite sheet shells. Under increasing bending moment, a MWNT may suddenly turn to have wave-like buckling or rippling mode from the classical pure bending configuration, and such rippling mode is quite different from the traditional elastic buckling. The rippling mode has a wavelength that is only about one-fourth of the diameter of the MWNT. To the best knowledge of the authors, there would be no observation on such a phenomenon before, except for plastic or rubber materials. We show that, due to the highly anisotropy, a graphite column with the base plane parallel to the axis, will be buckling whenever the axial strain reaches a critical value. Even though the length is infinitesimal comparing with other two dimensions, the critical strain is about 4.3are obtained for bending a graphite sheet and a MWNT. With this understanding we successfully predict the dramatic drop of bending Young's moduli of MWNTs as diameters increase, as observed recently by experiments. The critical strains are theoretically found and the buckling modes for various columns as well as a rectangular graphite beam and MWNTs are numerical simulated.

We discuss a purely mechanical model for surfaces composed of two families of continuously distributed elastic fibres. The fibres are endowed with kinematical and constitutive structures that account for fibre twist in addition to extension and flexure. Among these, twist is distinguished by the fact that it is not computable from local surface geometry. A formal variational argument is used to deduce the Euler equations and boundary conditions. The resulting theory is offered as a model for the description of complex three-dimensional finite deformations of wire mesh. It may also furnish a useful generalization of the engineering plate theories frequently adopted, for want of alternatives, to model the mechanics of woven fabrics.

Equations for the Flexure, Twist and Extension of Fibre Networks

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We discuss a purely mechanical model for surfaces composed of two families of continuously distributed elastic fibres. The fibres are endowed with kinematical and constitutive structures that account for fibre twist in addition to extension and flexure. Among these, twist is distinguished by the fact that it is not computable from local surface geometry. A formal variational argument is used to deduce the Euler equations and boundary conditions. The resulting theory is offered as a model for the description of complex three-dimensional finite deformations of wire mesh. It may also furnish a useful generalization of the engineering plate theories frequently adopted, for want of alternatives, to model the mechanics of woven fabrics.

Theory of Linearly Elastic Residually Stressed Plates

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The equations of a plate for a linearly elastic monoclinic material with residual stress is here derived for the first time. By using techniques of Γ-convergence we show that also in the case with residual stress the displacements are of Kirchhoff-Love type. An improvement of the result of Man and Carlson (*Arch. Rational Mech. Anal.* **128** (1994), 223-247) on the existence of a solution for the three-dimensional problem of linear elasticity with residual stress is obtained as well.

Higher Order Shear and Normal Deformable Thermopiezoelectric Plate Theory

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We use a mixed variational principle to derive a higher order linear shear and normal deformable theory for a plate made of a piezoelectric material. The displacement field, the electric potential, and the temperature field are expanded in terms of the thickness coordinate by using orthonormal Legendre polynomials as the basis functions. The distinguishing features of the plate theory include satisfying exactly the tractions, heat fluxes and the electric charge density prescribed on its major surfaces. Also, we do not make contradictory assumptions of the simultaneous vanishing of the transverse normal stress and the transverse normal strain.

Symposium on

Contemporary Developments in Mechanics

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CONTEMPORARY DEVELOPMENTS IN MECHANICS

In Honor of Professor Millard Beatty

SESSION M3B

On Pure Torsion of a Compressible Elastic Circular Cylinder

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In this presentation we discuss the combined uniform extension and torsion of a compressible isotropic elastic cylinder of finite length. The equilibrium equations are formulated in terms of the principal stretches and also expressed in terms of the principal invariants (I_1, I_2, I_3) of the Cauchy-Green deformation tensors and the principal invariants (i_1, i_2, i_3) of the stretch tensors. The equations are applied to the special case of pure torsion superimposed on a uniform extension (an isochoric deformation). New explicit necessary and sufficient conditions on the strain-energy function for the material to support this deformation with vanishing traction on the lateral surfaces of the cylinder are obtained. Necessary and sufficient conditions for the mater ial to support pure torsion without axial extension obtained previously by Polignone and Horgan [1] without the requirement for vanishing lateral traction follow from the new conditions derived here. Some strain-energy functions satisfying these conditions

are considered, existing results are recovered as special cases and new results are obtained. Specifically, we obtain new classes of strain-energy functions, both in terms of (I_1, I_2, I_3) and (i_1, i_2, i_3), satisfying the requirements for pure torsion with zero lateral traction. We also point out how the strain-energy functions generated from the considered isochoric deformation (of a compressible material) can be used to generate energy functions and corresponding solutions for the incompressible theory.

Keywords: Compressible elasticity, Large deformations, Torsion

[1] Polignone, D.A. and Horgan, C.O. Pure torsion of compressible nonlinearly elastic circular cylinders. *Quarterly of Applied Mathematics* **49** (1991), 591-607.

Constitutive Modeling of Hyperelastic Materials with Limiting Chain Extensibility

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Many rubber-like materials and soft tissues exhibit a significant stiffening or hardening in their stress-strain curves at large strains. The development of constitutive models that can account for such phenomena and have predictive capabilities is crucial to a full understanding of the thermomechanics of rubber and the biomechanics of soft tissues. Classical constitutive models of nonlinear elasticity, such as the neo-Hookean or Mooney -Rivlin models, fail to capture this strain-hardening effect. In this lecture, we describe some recently developed constitutive models for isotropic incompressible nonlinearly elastic solids that remedy this defect of the classical models. In the molecular theory of elasticity, the models we examine are called non-Gaussian because they involve a distribution function for the end-to-end distance of the polymer chain composing the material that is non-Gaussian. In particular, we focus on constitutive models that reflect limiting chain extensibility at the molecular level. The first class of constitutive models we consider are generalized neo-Hookean materials for which the strain-energy density depends only on the first invariant of the Cauchy-Green strain tensor. Because of the limiting chain extensibility, this invariant is constrained and the resulting stresses are unbounded as this invariant approaches a critical value. A particularly attractive model of this type is the Gent material model, proposed by Alan Gent in 1996. This model gives theoretical predictions similar to the more complicated Arruda-Boyce (1993) eight chain model. We examine the behavior of the Gent material in some homogeneous deformations and discuss the modifications needed to include dependence on the second invariant. A discussion of an alternative approach using strain-energy functions depending directly on the principal stretches is also given.

Keywords: constitutive models, incompressible hyperelastic materials

Boundary-value Problems for Hyperelastic Materials with Limiting Chain Extensibility

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In the preceding lecture, we have described some constitutive models for incompressible isotropic hyperelastic materials that reflect limiting chain extensibility at the molecular level. Such models can account for strain-hardening at large strains, in contrast with classical models such as the neo-Hookean or Mooney-Rivlin models. A particularly tractable model is the Gent material, a generalized neo-Hookean model involving a logarithm of the first invariant of the Cauchy-Green strain tensor. This model was proposed by Alan Gent (1996) and gives theoretical predictions similar to the more complicated Arruda-Boyce (1993) eight chain model. In this lecture, we obtain the explicit analytic solution to some fundamental boundary-value problems of elastostatics for the Gent material. The problems first treated are those of torsion, axial and azimuthal shear. The governing equilibrium equations are nonlinear ordinary differential equations which allow for an explicit analytic solution. The effects of strain-hardening in these shearing problems are thus readily analysed. We then consider the general problem of finite anti-plane shear deformations for the Gent material and give explicitly the governing second-order quasilinear partial differential equation that arises. The anti-plane shear problem for a traction-free crack subject

to remotely applied simple shear loading is then investigated. The stress fields near the crack tip for this material are obtained. It is found that the crack-tip stress fields are bounded, in contrast to results for other strain-hardening constitutive models, such as the Knowles' power-law. Thus, the constraint of limiting chain extensibility, in the case of the Gent material, is seen to prevent the development of crack-tip singularities.

Keywords: material hardening, incompressible hyperelastic materials

A Variational Problem Modelling Modelling Behavior of Unorthodox Silicon Crystals

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Controlling growth at crystalline surfaces requires a detailed and quantitative understanding of the thermodynamic and kinetic parameters governing mass transport. Many of these parameters can be determined by analyzing the isothermal wandering of steps at a vicinal ["step terrace"] surface. In the case of "orthodox" crystals one finds that these meanderings develop larger amplitudes as the equilibrium temperature is raised [consistently with the view of meanderings as arising from atomic interchanges]. However in a 1997 series of experiments on vicinal defects of heavily boron-doped Silicon crystals [1], these were revealed to be quite "unorthodox" in the sense that a lowering of the equilibrium temperature led to increased amplitude for the isothermal wanderings of a step edge! This article examines a stored free energy model for such crystals which involves a second order Landau / de Gennes "order parameter" term and provides a proof for existence of a minimizer. Some implications of this model for dynamics are also discussed. [2]

[1] J. Hannon et. al., Step Faceting at the (001) surface of Boron Doped Silicon, Phys. Rev. Lett. 79:4226-4229 (1997)

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Non-Isochoric Bending and Shearing

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Two families of inhomogeneous deformations are treated. For each family, the governing system of second order nonlinear partial differential equations reduces to a system of first order nonlinear ordinary differential equations for homogeneous compressible elastic solids with arbitrary isotropic or anisotropic response.

CONTEMPORARY DEVELOPMENTS IN MECHANICS

In Honor of Professor Millard Beatty

SESSION M4B

Hysteresis in the Stress-Cycling of Bars Undergoing Solid-Solid Phase Transitions

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A model is presented for the response to slow, cyclic stressing of bars capable of undergoing displacive phase transitions. One-dimensional nonlinear elasticity is used, and the sharp interface between material phases bears a strain discontinuity. As a result, the theory is dissipative, in the sense that the rate of work supplied to the bar exceeds the rate of increase of stored energy. An essential part of the model is a continuum-mechanical version of a kinetic relation that controls the rate at which the phase transition takes place and therefore determines the ultimate governing dynamical system. A periodic solution of this system is constructed, from which one may determine the hysteresis loop to which the response of the bar is expected to tend after many loading cycles. The energy dissipation associated with this loop is determined for a very general class of kinetic relations. For a particular kinetic relation, the *transient* cycling problem is also solved explicitly, and it is verified that the response indeed tends to that for the periodic solution as the number of cycles tends to infinity. Several predictions of the model are in qualitative agreement with experimental results for shape-memory alloys.

Why Do Cracks in Rubber Turn Sideways?

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Calculations have been made by FEA of strain energy release rates G for a rubber sheet with a small edge crack, subjected to a far-field simple extension. Growth of the crack is considered in both forwards and sideways directions, the latter corresponding to crack splitting or turning. When the imposed extension is large, the value of G at which a small sideways crack will initiate is found to be a substantial fraction, about 60%, of that for further forwards growth. This suggests that crack splitting or turning will occur when the tear strength in the sideways direction is only slightly lower than that for forward growth. However, the value of G for a sideways crack decreases rapidly as the crack grows, indicating that it will stop after a short distance. These conclusions are shown to be in accord with experimental observations of crack splitting in filled rubber compounds and account for some aspects of reinforcement of rubber by fillers. In particular, they account for the fact that deep edge cracks are less likely to split or turn.

Modeling and Analysis of Nonlinearly Elastic Rods with Chirality

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We consider long, thin elastic structures possessing a uniform helical micro-structure in a natural state. Examples motivating our work include man-made ropes and cables, and biological filaments occurring in nature, e.g., DNA molecules and mammalian tendon. We adopt a Cosserat-rod model for initially straight filaments of such material. The helical symmetry leads to natural restrictions on the stored energy function. Assuming that the period of the helical structure is much smaller than the length of any rod under consideration, we obtain, by simple averaging, a homogeneous, hemitropic rod. We also give two other realizations of hemitropy (without averaging), exploiting the dihedral-helical symmetry of typical ropes and cables, comprising three or more helical strands. We show that that hemitropic rods have built-in chirality or "handedness". That is, in contrast to the usual isotropic rod model, the hemitropic model captures the essential difference between right-handed and left-handed helical micro-structures. In particular, hemitropic rods are characterized by mechanical coupling between extension and twist.

We consider two classes of problems for straight, hemitropic rods under end thrust, demonstrating that the post-buckling behavior depends crucially upon the end conditions. In particular, we show that a "fixed-free" hemitropic rod responds much like an isotropic one, while a "fixed-fixed" rod exhibits non-planar behavior, which is markedly different from the isotropic case.

Invariants of the Stretch Tensors and their Application to Finite Elasticity Theory

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Dedicated to Millard F. Beatty

The principal invariants of the stretch tensors in the polar decomposition of the deformation gradient stand in one-to-one relation to the principal invariants of their squares, the Cauchy-Green deformation tensors. These relations are used to obtain the derivatives of the first set of invariants with respect to the deformation gradient. The latter generate expressions for the stretch and rotation factors in the polar decomposition as explicit functions of the deformation gradient, and lead to new formulas for the stress and elastic moduli for isotropic elastic materials.

A Constrained Mixture Model for Cell Mechanics

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Significant information has become available over the past two decades that reveals the fundamental role of mechanical factors in controlling the complex structure and function of many cell types. There is a pressing need, however, to synthesize these many observations via mathematical models that have predictive capability and that suggest experiments that will provide increased insight

and thus refinement of the models. In this paper, it is suggested that some of the salient mechanical behaviors exhibited by cells, including dynamic mechano-sensitive changes in internal structure and thus mechanical properties, can be described using a simple constrained mixture model that was recently proposed for describing tissue-level growth and remodeling. That is, strong similarities in structure-function relationships at multiple length scales - cell, tissue, and organ - may allow us to exploit common constitutive frameworks, which may prove advantageous in future attempts to model across the various scales. Because of the complex structure of cells, however, composite models consisting of a separate membrane, cytoskeleton, and nucleus may be needed. The constrained mixture model presented herein can be used to model each of these three distinct materials, however.

Continuum Modeling of Cell Membranes

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The response of the living cell membranes probed with Atomic Force Microscope is investigated. The general theory of fluid membranes with local bending resistance is used to obtain the equations that describe axisymmetric equilibrium states. The membrane is assumed to enclose a fluid medium, which transmits hydrostatic pressure to the membrane, and a point load is applied at the pole of the membrane to simulate an AFM probe. Both types of loading are associated with a potential and the problem is then cast in a variational setting. The equilibrium equations and boundary conditions are obtained by applying standard variational procedures, resulting in a pair of coupled fourth-order differential equations to be solved for the shape of the meridian. Further refinements associated with global constraints on the enclosed volume and contact with a rigid substrate are introduced and a solution strategy is proposed which relies on an iterative scheme for calculating the associated Lagrange multipliers. A procedure is also given for identifying material constants for the cell membrane through correlation with AFM data.

Universal Relations for Transversely Isotropic Elastic Materials

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We adopt Hayes and Knops's approach and derive universal relations for finite deformations of a transversely isotropic elastic material. Explicit universal relations are obtained for homogeneous deformations corresponding to triaxial stretches, simple shear, and simultaneous shear and extension. Universal relations are also derived for five families of nonhomogeneous deformations.

CONTEMPORARY DEVELOPMENTS IN MECHANICS

In Honor of Professor Millard Beatty

SESSION T3B

Inflating a Rubber Balloon

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A spherical balloon has a non-monotone pressure-radius characteristic. This fact leads to interesting stability properties when two balloons of different radii are put in contact, see [1], [2]. Here, however, we investigate what happens when a single balloon is inflated by mouth (say). We simulate that process and show how the maximum of the pressure-radius characteristic is overcome by the pressure in the lungs and how the downward sloping part of the characteristic is "bridged" while the lung pressure relaxes.

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Keywords: Rubber balloons, Mooney-Rivlin material, Non-convexity, Stability.

A WKB Analysis of the Buckling of an Everted Neo-Hookean Cylindrical Tube

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It is well-known that a circular cylindrical tube may not stay cirular cylindrical after eversion and it may prefer to adopt a wrinkled configurtion. A linear analysis using the method of adjacent equilibria followed by a numerical computation shows that for a neo-Hookean tube, a wrinkled configuration is possible when the ratio of the inner radius to the outer radius is approximately less than 0.4232. The wrinkles have a circumferential mode number approximately equal to 15. In this paper, the WKB method is used to derive an asymptotic expression for the critical ratio of the inner radius to the outer radius, with the mode number used a large parameter. A turning point is found to exist in the eigenmodes, and is used to explain the difficulties experienced in previous numerical computations.

Keywords: WKB method, singular perturbation, finite elasticity, eversion of tubes

Asymptotic Analysis of an Isotropic Compressible Hyperelastic Half-Space Under a Tensile Point Load

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The nonlinearly elastic Boussinesq problem is to find the deformation produced in a homogeneous, isotropic, elastic half space by a point force normal to the undeformed boundary, using the exact equations of elasticity. For this core problem of elasticity and engineering, the 1885 linear elasticity solution of Boussinesq is still used in a variety of applications. Simmonds and Warne [1] first considered an asymptotic treatment of the tensile point load problem when the half space is composed of two particular nonlinearly elastic material models (Blatz-Ko and generalized neo-Hookean). In [2], we addressed the case of a tensile point load acting on a half-space composed of a *general* incompressible hyperelastic material. Here we consider an analogous asymptotic analysis of this problem within the context of compressible finite elasticity. Asymptotic tests are developed to determine whether an isotropic hyperelastic material can support a finite deflection under a tensile point load. The results are then applied to a variety of particular constitutive models for compressible nonlinearly elastic materials. It is found that, for many of the well-known strain energy models for compressible hyperelastic materials proposed in the literature, a tensile point load cannot be supported. For models which may sustain a tensile point load, we determine the remaining equations and conditions for the asymptotic solution, and numerically compute this solution for a particular case.

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This work was supported by the James Madison University Program of Grants for Faculty Assistance.

Numerical Computation for Singular Nonlinear Solid Mechanics Problems: the Modified Picard Method

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While a Runge-Kutta order four system solver has been a predominant numerical solution technique for differential equations, a shooting algorithm using the Picard method can potentially produce better accuracy in less time near a singularity. A theory for a more efficient Picard approach [1] requires the right hand side of an ODE to be converted into polynomial form, which is possible for nearly all systems/equations arising from continuum physical principles. This produces an effective numerical shooting technique for boundary-value problems (BVPs) and allows the Taylor polynomial to be formed at each step with each term of the series generated essentially by a single function evaluation. The algorithm allows for a smaller number of steps as the solution marches toward the singularity and provides a simple manner in which to increase (or decrease if desired) the order of the algorithm during the computation, resulting in general in more accurate solution nearby and at the singularity. The algorithm also routinely "pulls off" the coefficients of the

Taylor series to store them for later use, producing high efficiency. This modified Picard shooting method is first developed theoretically and is then demonstrated for a particular singular test problem and is compared against a standard Runge-Kutta procedure. Finally, singular nonlinear BVPs associated with modeling both concentrated loads and cavitation (void formation in solids) in finite elasticity are examined numerically via the Modified Picard and Runge-Kutta techniques.

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Eversion Problems for Nonlinearly Elastic Shells

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This lecture treats the eversion of incompressible axisymmetric nonlinearly elastic shells (described by a geometrically exact theory). The incompressiblity and the polar singularity are sources of severe technical difficulty. It is shown how to characterize the everted state by a rigorous asymptotic expansion in a thickness parameter, the boundary layer characterizing the formation of a lip near the edge. Preliminary results for nonsymmetric shells and for shells described by the 3-dimensional theory are also described. (These techniques support the construction of equilibrium states with large strains.)

CONTEMPORARY DEVELOPMENTS IN MECHANICS

In Honor of Professor Millard Beatty

SESSION T4B

An Experimental Study of the Thermo-Mechanical Response of Elastomers Undergoing Scission and Cross-linking at High Temperatures

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When an elastomeric material is held at a fixed state of stretch at a sufficiently high temperature, the applied force relaxes to zero with time. When the external force is removed, the material has a permanent deformation. The force relaxation is attributed to time dependent scission of macromolecular network junctions. The permanent deformation is attributed to the recoil of affected molecules and their cross linking to form a new network that is stress free in a new reference configuration. These phenomena have important implications when elastomeric components operate at high temperatures, either due to their environment or as a result of energy dissipation due to mechanical work. An appropriate constitutive theory is vital for the engineering analysis of such components. This work presents experimental results that have been carried out as part of the development of a constitutive theory for a commercial grade vulcanized natural rubber.

Results are presented for uniaxial extension for various conditions of deformation control, force control and temperature control. These results provide insight into the consequences of scission and cross linking for mechanical response They are also used to evaluate various constitutive assumptions.

A Pressurized Spherical Elastomeric Membrane Undergoing Temperature Induced Scission and Cross-linking

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When an elastomeric material is held at a fixed state of stretch at a sufficiently high temperature, macromolecular network junctions undergo time dependent scission and the applied force relaxes with time. The affected molecules recoil and cross link to form a new network that is stress free in a new reference configuration. A constitutive theory is presented which accounts for this process as the elastomer deforms. The material system is a time dependent mixture of molecular networks with different reference states. Using the constitutive theory, it can be shown that scission and cross linking have significant consequences for the mechanical response. Of particular interest for this presentation are time dependence and material softening.

This constitutive theory is used in a study of a pressurized spherical elastomeric membrane at a temperature high enough for the scission-cross linking process to occur. It is shown that at a constant pressure, the membrane diameter increases with time. Moreover, there can be a finite time when the membrane diameter increases at an infinite rate - 'runaway inflation' (or blow out?'). This event depends on the elastic properties of the molecular networks, the rate of formation of new networks, and the

history of the increase in the membrane diameter. Numerical results are presented for the case when the networks act as Mooney-Rivlin materials.

On Agmon's Condition for Incompressible Finite Elasticity

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The energy-functional for an incompressible hyperelastic body Ω, subject to displacement data on $\partial_1\Omega$ and to dead–load traction data on $\partial_2\Omega$, is

$$\mathcal{F}[\chi] := \int_\Omega \{W(\nabla\chi(\mathbf{X}), \mathbf{X})\}dV - \int_{\partial_2\Omega} \{\mathbf{t}\cdot\chi\}dA$$

Let $\tilde{\chi}$ be a smooth minimizer of $\mathcal{F}[\,\cdot\,]$, $\mathbf{X_0} \in \partial_2\Omega$ and choose local coordinates such that $-\mathbf{i}_3$ is the unit external normal to $\partial_2\Omega$ at $\mathbf{X_0}$. Then, for all smooth solenoidal vectorfields $\mathbf{u}$ which vanish on the curved boundary of the unit half-ball with base outer normal $-\mathbf{i}_3$,

$$\int_{HB} \{W_{\mathbf{FF}}(\tilde{\mathbf{F}}_0, \mathbf{X}_0)[(\nabla_{\mathbf{u}})\tilde{\mathbf{F}}_0]\cdot((\nabla\mathbf{u})\tilde{\mathbf{F}}_0) + p\,\mathrm{tr}((\nabla\mathbf{u})^2)\}dv := \int_{HB}\{\mathbb{K}[\nabla_{\mathbf{u}}]\cdot(\nabla_{\mathbf{u}})\}dv \geq 0 \qquad \text{(IV2)}$$

LEGENDRE–HADAMARD CONDITION
(IL–H) $\quad \mathbb{K}[\mathbf{a}\otimes\mathbf{b}]\cdot(\mathbf{a}\otimes\mathbf{b}) \geq 0$
for all vectors $\mathbf{a}, \mathbf{b}$ with $\mathbf{a}\cdot\mathbf{b} = 0$

SUPPLEMENTARY CONDITION
(IS) $\quad$ If $\quad \mathbb{K}[\mathbf{a}\otimes\mathbf{i}_3]\cdot(\mathbf{a}\otimes\mathbf{i}_3) = 0$
for some vector $\mathbf{a}$ with $\mathbf{a}\cdot\mathbf{i}_3 = 0$, then
$\mathbb{K}[\mathbf{a}\otimes\mathbf{i}_3] = h(\mathbf{a})\mathbf{1}$ $\quad$ for some scalar $h(\mathbf{a})$

AGMON'S CONDITION
Let $\xi = \xi_1\mathbf{i}_1 + \xi_2\mathbf{i}_2$ be a general tangent vector, and define linear operators $\mathbf{M}^{(i)}$, $\mathbf{N}_\xi^{(i)}$, $\mathbf{P}_\xi^{(i)}$, and $\mathbf{P}_\xi^{(i)^\alpha}$ respectively, by

$$\mathbf{M}^{(i)}\mathbf{a} = \mathbb{K}[\mathbf{a}\otimes\mathbf{i}_3]\mathbf{i}_3 \quad \mathbf{N}_\xi^{(i)}\mathbf{a} = \mathbb{K}[\mathbf{a}\otimes\xi]\mathbf{i}_3$$

$$\mathbf{P}_\xi^{(i)}\mathbf{a} = \mathbb{K}[\mathbf{a}\otimes\xi]\xi \qquad \mathbf{P}_\xi^{(i)^\alpha} = \mathbf{P}_\xi^{(i)} + \alpha^2\mathbf{1}$$

$$\left.\begin{aligned} -\mathbf{M}^{(i)}\ddot{\mathbf{z}} + i(\mathbf{N}_\xi^{(i)} + \mathbf{N}_\xi^{(i)^T})\dot{\mathbf{z}} + \mathbf{P}_\xi^{(i)^\alpha}\mathbf{z} &= iq\xi + \dot{q}\mathbf{i}_3 \\ \dot{z}_3 + i(\xi_1 z_1 + \xi_2 z_2) &= 0 \end{aligned}\right\} \qquad \text{(IE)}$$

$$\mathbf{M}^{(i)}\dot{\mathbf{z}}(0) - i\mathbf{N}_\xi\mathbf{z}(0) + q(0)\mathbf{i}_3 = \mathbf{0} \qquad \text{(IIC)}$$

AGMON'S CONDITION (IAG) :– For all ξ and every $\alpha > 0$, the only bounded solution of (IE) on $(0,\infty)$ which satisfies the initial conditions (IIC) is the zero solution.

MAIN RESULT
(IV2) $\Longleftrightarrow$ (IL – H) + (IS) + (IAG)

Keywords: Incompressible, Elastic, Agmon Condition

Rapid Mode III Interface Flaw Extension: Dissimilar Anisotropic Solids with Largely Arbitrary Orientations of their Principal Material Axes

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The dynamic failure of composites can be caused by the rapid extension of flaws along the interfaces of the constituent materials. This study considers two half-spaces that are rigidly bonded along a semi-infinite portion of their interface, but separated by a vanishingly-thin flaw along its remainder. The half-spaces are dissimilar elastic solids with only single planes of material symmetry. The symmetry planes coincide for the two solids, but their principal material axes in the common plane are of arbitrary orientation with respect to each other, and to the interface.

Anti-plane shear forces translating along the flaw surfaces are assumed to extend the flaw, thereby creating a dynamic steady-state in which flaw and forces move at the same constant speed.

Exact solutions valid for any constant speed show that the interface shear wave speeds in the two solids are sensitive to both material properties and to principal axis orientations. Moreover, the solutions show that the square-root singular behavior of classical fracture mechanics – and the finite energy dissipation rate that is associated with the behavior – can be assured only for purely sub-sonic flaw speeds.

Calculations and analytical results for the special cases in which one solid is isotropic show that the energy dissipation rate is clearly influenced by the degree of nonorthotropy of the anisotropic sold, and the orientation of its principal material axes. Thus, composite design can use anistropy and mis-alignment of principal material axes to produce effective elastic constants that are of advantage, while also limiting the possibilities for debonding.

Keywords: composite, dynamic debonding, anisotropy, principal axis orientation

Some Exact Solutions for Coharmonic Elastic Materials

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In this paper exact solutions for compressible elastic materials with strain energy functions of the form $W(i1, i2, i3) = i3f(i2/i3) + c1i1 + c2i2 + c3i3$ are exhibited. The i's are the invariants of the stretch tensor and the c's are arbitrary constants. The materials are dubbed coharmonic because they correspond to the harmonic materials introduced by John. By using Shield's inverse deformation theorem, for any deformation possible in a harmonic material, the corresponding inverse deformation is possible in the appropriate coharmonic material. The solutions for boundary value problems for both harmonic and coharmonic materials are contrasted. Representations of the displacements in terms of harmonic functions for plane and axisymmetric deformations are also used to find some new solutions for both types of material.

Mechanoelectrical Phenomena In Ionic Polymers

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Ion containing polymers, when suitably composited with a conductor phase such as a metal, a conductive polymer or graphite, sometimes called ionic polymer conductor composites (IPCC), displays certain spectacular mechanoelectrical phenomena. When subjected to a dynamic electric field they deform dynamically (actuation) and if dynamically deformed they generate a dynamic electric field (transduction or sensing). Here, we present a description of these phenomena in the linear regime, and in steady state conditions using the standard Onsager formulation. We describe the underlining principle of IPMC actuation/sensing phenomena using linear irreversible thermodynamics: when static conditions are imposed, a simple description of *mechanoelectric effect* is possible based upon two forms of transport: *ion transport* (with a current density, J) and *electrophoretic solvent transport* (with a flux, Q,). The conjugate forces include the electric field, $\vec{E}$, and the pressure gradient, $-\nabla p$. We also present some estimates on the Onsager coefficients as well.

CONTEMPORARY DEVELOPMENTS IN MECHANICS

In Honor of Professor Millard Beatty

SESSION W2B

On Modeling the Anisotropic Plastic Response of Aluminum Alloys

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Experimental evidence and polycrystal plasticity calculations show that quadratic yield surfaces cannot accurately describe yielding of materials with a FCC crystal structure. Based on results of polycrystal calculations, Hershey [1] and Hosford [2] have proposed a non-quadratic isotropic homogeneous function in the principal values of the stress deviator. Extensions of this yield function to anisotropic conditions have been proposed by Barlat *et al.*, [3,4], Karafillis and Boyce [5]. In the latter, the material symmetry is introduced by means of a linear fourth order tensor $\mathbf{L}$, which multiplicatively operates on the Cauchy stress σ acting on the material. In this approach, the anisotropy of thin rolled sheets is described by four coefficients. Yet, to accurately describe yielding under plane stress conditions, at least six independent material parameters should be taken into account, such as uniaxial yield stresses and r values (r is the width to thickness strain-rate ratio in uniaxial tension) at 0°, 45° and 90° deg from the rolling direction. An alternate method for introducing anisotropy in the expression of a given isotropic yield criterion was proposed by Cazacu and Barlat [6] within the framework of the theory of representation tensor functions. In this paper, this new method is applied to extend to orthotropy Hershey's

isotropic criterion. The ability of this new criterion to describe the anisotropy in the plastic response of aluminum alloy sheets is tested against representative sets of data, the predictions of Karafillis and Boyce [5], and simulated results using polycrystalline models.

Keywords: anisotropic yielding; generalized invariants; theory of representation; aluminum alloys

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Microstructural Analysis of Polycrystalline Ceramics Using Voronoi Tessellations

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Microstructural modeling based on Voronoi tessellations has been applied in the study of the statistical nature of strain energy distribution in polycrystalline ceramics undergoing elastic deformation. In the material structure model, crystals are treated as Voronoi polyhedra, each with a randomly assigned crystallography orientation. Each crystal is overlaid with a non-uniform tetrahedral mesh having finer cells near the grain boundaries and coarser ones near the center. Two types of calculations are used. One is the finite element analysis using each tetrahedral cell as a constant-strain element. Both three-dimensional (3D) modeling and two-dimensional (2D) approximation are studied. The other is a generalized Eshelby analysis for the generalized plane-strain conditions. Results will be presented for alpha-6H silicon carbide (SiC, hexagonal structure) and alumina (trigonal structure) and for Voronoi tessellations up to 1,000 grains. The statistical results of 2D calculations will be compared with those of 3D simulations to examine the validity of the commonly used 2D modeling. In addition, several published sets of crystal elasticity constants for the SiC will be screened by comparing the computed macroscopic response with the available experimental data. For alumina, whose crystal st ructure has often been approximated as transversely isotropic, numerical results based on the approximated crystal structure will be compared with those computed with the trigonal crystal structure to estimate the error of the approximation. The significance of these results for polycrystalline ceramic modeling and microstructural analysis will be discussed in detail.

Keywords: Microstructural analysis; Voronoi polycrystal; ceramic; numerical simulation

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On the Elliptic Balance Method

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In many practical situations a pair of coupled, damped, homogeneous nonlinear ordinary differential equations model the dynamical behavior of mechanical systems. For example, these equations arise during the process of studying the mechanical response of systems such as strings, beams, absorbers, plates, and so on. In general, the exact solution of these types of equations is unknown and hence, numerical integrations, perturbation techniques or geometrical methods have to be applied in order to obtain their approximate solution. A large number of studies of the nonlinear behavior of these systems have been made using perturbation techniques; however, the vast majority dealt with weakly non-linear systems, i.e. with small values of the non-linear parameter ε or light damping ν.

The objective of this work is to apply a novel perturbation technique developed in (Elas-Zuiga, 1994) and called the Elliptic Balance Method (EBM) to obtain the approximate solution of nonlinear two degree of freedom systems. Two examples are presented to compare the EBM solution with numerical integration. The first is related to a damped, nonlinear system with two degrees of freedom that describes the dynamical behavior of a viscohyperelastic simple shear suspension system with an undamped linear absorber, and the second is related to a proposed damped, nonlinear mechanical model. It will be shown that its amplitude-time response can be accurately described by the EBM solution even for moderate values of

the damping coefficients (i and the non-linear parameter ε.

Small Oscillations and Stability of a Thick, Highly Elastic Slab

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The problem of small oscillations of a thick slab superimposed on a finite biaxial deformation subject to both dead and hydrostatic lateral loads is investigated*. A general frequency equation is derived from which specific results are deduced for both slender and stubby slabs. The question of the stability of a thick plate is studied by aid of a kinetic stability criterion. The results for a special case are compared with others in the literature. Upon introduction of certain effective Lam moduli, correspondence with work of others is established, and some existing discrepancies are explained. Some results for the disputed problem of stability in equibiaxial finite deformation are presented.

Keywords: stability, equibiaxial, finite deformation, highly elastic

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Existence of Point Defects in Nematic Gels

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Nematic gels differ from their conventional counterparts by the presence of nematic mesogens that are included as spacers along the polymer backbone or are attached to the backbone as pendant side-groups. We consider the question of whether nematic gels are capable of sustaining point defects. As a basis for this investigation, we work with a free-energy density that extends the conventional molecular-statistically derived expression for a nematic elastomer to account for volumetric contributions. We consider the special case of a gel cross-linked in a state where the mesogens are randomly aligned and study the behavior of a spherical specimen the boundary of which s subjected to a uniform radial displacement or traction. For simplicity, we allow only for distortions in which the molecular agglomeration is uniaxial with constant anisotropy and, thus, is determined by a unit orientation field. Even for relatively mild loads or applied displacements, we observe a definitive energetic preference for states in which the orientation field is radial and, thus undefined at the center of the specimen. Such states are point-defective. The question that remains open concerns biaxial states. Specfically, it is possible that states for which the molecular agglomeration is biaxial and the material exhibits a point defect may be energetically preferred over our uniaxial solutions.

Referential Doyle-Ericksen Formulae and the Energy-Momentum Tensor in Finite Plasticity

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In a recent publication[1], a referential Doyle-Ericksen is derived in the context of the covariant theory of nonlinear elasticity. The formula indicates that Eshelby's energy-momentum tensor can be obtained by varying the current energy density with respect to the referential metric tensor defining the undeformed geometry of the material body. On the basis of the formula, a material balance equation fully reciprocal to the balance of linear momentum is also established. The significance of the referential Doyle-Ericksen formula is that, it reveals the kinetic implication of the referential metric. The result suggests that similar formulae may be obtained for a family of inelastic materials for which the inelastic deformation can be characterized by an (evolving) referential metric. An important example is the elastic-plastic material in which the referential metric is associated with the plastic deformation.

In this work, we explore the extension of the referential Doyle-Ericksen formula in the context of finite plasticity. Motivated by the physical assumption of the multiplicative plasticity, the strain energy (at fixed plastic variables) is defined as a covariant function of the Cauchy-Green deformation tensor and a plastic metric tensor. The elastic-plastic energy-momentum tensor is derived, and is related to the change of plastic tensor through the Doyle-Ericksen formula. Thermodynamical implications of these results

are discussed. The formula is compared with similar equations associated with the multiplicative plasticity.

Keywords: Doyle-Ericksen formula, energy-momentum tensor, finite elasticity, plasticity.

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CONTEMPORARY DEVELOPMENTS IN MECHANICS

In Honor of Professor Millard Beatty

SESSION W3B

Response of Viscoelastic Polymer Melts at High Shear Rates: New Experiment and Modeling

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A new experimental technique for large-strain high-rate transient rheometry has been developed utilizing a modified Kolsky torsion bar device. The technique has been applied for determining the transient response of molten low-density polyethylene (LDPE), a viscoelastic fluid, under shear rates $10^3 \sim 10^5 1/s$ and temperatures $150 \sim 210°C$. The results indicate that the material's transient response at high shear rates has a rate dependence significantly stronger than the predictions of the existing LDPE models calibrated with low-rate transient data and high-rate steady-state measurements.

A new phenomenological model is proposed to provide a more accurate description for the high-rate transient response of the molten LDPE. The material is assumed to be composed of such deformable fluid elements that the flow of the elements is non-Newtonian viscous while the deformation of each element is non-linear elastic. The effects of distribution and evolution of the representative molecular orientations of fluid elements with respect to the principal stretch directions are considered and modeled using an element stiffness distribution that evolves with macroscopic strain. Consequently, the proposed model yields the average response of an evolving spectrum of generalized Maxwell elements, each of which has a unique elastic component (non-linear spring) and an identical viscous component (non-linear dashpot) connected in series. For pure shear loading, the initial spectrum of elastic components is assumed to be Gaussian. The results of model calculations for lager-strain high-rate shearing deformation will be presented and compared with the available experimental data. The significance of the results will be discussed in comparison with the existing theory for rubber-like liquids.

Keywords: High strain-rate response; polymer melt rheology; transient rheometry; viscoelastic fluid modeling

Nonlinear Vibrations of Atomic Force Microscope Beams with a Hertzian Contact Boundary Condition

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Recent nanoscale microscopy research has focused on dynamical methods in which an atomic force microscope (AFM) probe is vibrated while in contact with a specimen. The linear vibration response is often used to determine quantitatively the specimen stiffness. Surface stiffness variations may also be imaged simultaneously with a standard topography scan. If the vibration amplitude is large enough, nonlinear vibrations have been observed. The nonlinear interactions between the AFM tip and the specimen are thought to be the primary source of the nonlinearities that influence the dynamic response. Nonlinear responses observed experimentally include the static offset (or lift-off) and primary response softening as well as the development of subharmonics and superharmonics. Here, this problem is formulated in terms of a nonlinear boundary value problem, which is solved using the method of multiple scales. The main results of this analysis are the nonlinear normal modes of the vibration. These modes are comprised of terms representing the softening effect of the resonance, the static offset, and harmonics. The softening effect on the primary response is shown to be a function of the particular vibration mode as expected. In addition, the insensitivity of the static offset to surface modulus for high applied loads is seen explicitly. Although the focus here is on Hertzian contact mechanics, other contact models will be discussed in terms of their nonlinear effects. In particular, the influence of adhesion energy, neglected in the Hertz model, is examined. Implications for experimental work will also be presented.

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An Experimental Study of Thermal Buckling in Plates

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This work presents the results of a thermal buckling analysis for clamped, rectangular plates based on energy considerations. The analysis reveals that the two edge length to thickness ratios $(a/h, b/h)$ are independent parameters, i.e. fixing the aspect ratio (a/b) is not sufficient to ensure a unique problem. The results also show that predictable modal groupings and curve veering occur in the eigenvalue loci as the aspect ratio is varied. Accompanying this analysis are a series of experiments to determine the buckling temperature for plates with varying edge length. However,measurements of the critical temperature, T_{cr}^{F}, are complicated by the fact that initial geometric imperfections are inherent in any real structure. In this case, the pitchfork bifurcation associated with buckling is replaced by a saddle-node bifurcation at T_{cr}^{Im}, which is easily measured. An analysis is performed using von Karman plate theory to determine the ratio of T_{cr}^{F}/T_{cr}^{Im} as a function of the initial imperfection size, $\tilde{A}$. Knowing this functional relationship and the measured values of $\tilde{A}$ and T_{cr}^{Im}, the flat plate buckling temperature may be determined. Comparisons between the buckling analysis and the experimental results show good agreement.

Analysis of Interfacial Wedge Disclination Dipoles by the Image Dislocation Method

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Brittle polycrystalline solids and films often fracture along grain boundaries. In such intergranular fracture, a key parameter is the energy required to cleave a brittle material along a grain boundary plane, i.e., the fracture energy. A grain boundary can be modeled by a wall of wedge disclination dipoles separating grains of different orientations. The fracture energy of such a wall is given by the difference between the energy of free surfaces and the grain boundary energy. The latter is a sum of the elastic strain energy of the dipoles and the energy of the disclination cores.

In this presentation, the stress field and the elastic energy of an infinite wall of wedge disclination dipoles separating two transversely isotropic grains of zero and ninety degree orientations (respectively) are determined. The calculation technique for this bicrystal model is based on the image dislocation method, in which continuously distributed image dislocations are used to satisfy traction and displacement continuity conditions along the interface. The numerical results show that the elastic energy is a bell-shape function of the ratio of the dipole arm length to the dipole period, and that significant discrepancies exist between the solutions obtained using the bicrystal and the isotropic homogeneous assumptions [1].

Keywords: Disclination Dipoles, Elastic Energy, Bicrystal

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The Excess Energy of a Multiwalled Carbon Nanotube due to a Core Extrusion

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It has been observed that the van der Waals interaction can cause an extruded core of a multiwalled carbon nanotube (MWNT) to retract into the outer shells. The authors show that the restoring force resulted from the excess van der Waals interaction energy due to the core extrusion would drive the core to oscillate with respect to its fully retracted position because of the small intershell sliding resistance force and they predict that the oscillation frequency could be in the gigahertz range. The detailed theoretical calculations of the excess van der Waals energy due to the extrusion and the corresponding restoring force are presented. The authors have further derived an explicit expression of the oscillation frequency in terms of the physical and geometrical parameters of the MWNT, with the interatomic locking effect taken into account, and they have shown that the oscillation frequency can be significantly higher than one gigahertz.

CONTEMPORARY DEVELOPMENTS IN MECHANICS

In Honor of Professor Millard Beatty

SESSION W4B

Stability and Bifurcation of Inflation of Elastic Cylinders

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A method of obtaining a nonlinear stability analysis of inhomogeneous deformations of arbitrary, incompressible, hyperelastic materials is presented. The analysis that we develop replaces the second variation condition expressed as an integral involving two arbitrary perturbations, with an equivalent (third order) system of ordinary differential equations. The positive definiteness condition is thereby reduced to the simple numerical evaluation of zeros of a well behaved function. The general theory is illustrated by applying it to the problem of the inflation of axially stretched thick–walled tubes. The bifurcation theory of such deformations is well known and we compare the bifurcation results with the new stability analysis.

The Anatomy of Plasticity: A Case Study

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The anatomy of the theory of plasticity at large deformation is shown through the study of an example model and its associated response under shear, tension, and combined tension torsion. It is shown that a structure can be made to model plasticity that is consistent for one dimensional, infinitesimal, and large deformation plasticity. This structure clearly directs the development of more complex models. A description of how to include more complex response characteristics will be provided.

Two Versions of Fourier's Law for Heat Conducting, perfectly elastic, Isotropic Solids

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In a standard notation, the heat flux vector/unit area in the deformed configuration of an isotropic solid is

$$\mathbf{q} = \left(\phi_0 \mathbf{I} + \phi_1 \mathbf{B} - \phi_{-1} \mathbf{B}^{-1}\right) \nabla T. \qquad (1)$$

For a material conducting heat consistent with a nonclassical form of Fourier's law the coefficients ϕ_r (r =0, +1,-1) are functions of the invariants

$$I_1 = tr\mathbf{B}, I_2 = \frac{1}{2}\left(I_1^2 - tr\mathbf{B}^2\right), I_3 = det\mathbf{B}, \qquad (2)$$

and temperature T. Saccomandi [1] has demonstrated that of the known families of isothermal universal deformations possible in incompressible solids many are compatible with suitable non- uniform temperature fields if the heat flux has the *restricted Fourier* form

$$\mathbf{q} = \hat{\phi}_0(T)\nabla T. \qquad (3)$$

However, Dillon [2] assumed a different form of Fourier's law, namely the special case of

$$\mathbf{Q} = I_3^{\frac{1}{2}} \mathbf{F}^{-1}\mathbf{q} = I_3^{\frac{1}{2}} \phi_1 GRAD\, T,\ GRAD\, T = \mathbf{F}^T \nabla T,$$
$$\Leftrightarrow \mathbf{q} = \phi_1 \mathbf{B} \nabla T, \qquad (4)$$

obtained by setting $I_3^{\frac{1}{2}}\phi_1 = -K$, a constant. The form (2) is also compatible with the families of universal deformations and coupled temperature fields demonstrated possible in incompressible materials by Saccomandi [1]. For incompressible materials comparisons of the two laws are then readily made for these deformation-temperature classes. In addition, Dillon's [2] specialization of (2) is used to analyse the non-universal azimuthal shear of a hollow cylinder of an almost incompressible solid subject to a radial temperature gradient, and the results are compared with those obtained by Dunwoody [3] for the same problem using the classical form of Fourier's law.

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Analytical Solutions for Bending and Flexure of Helically-Reinforced Cylinders

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There has been a great deal of interest in the problems of modelling cables and ropes. A recent review by Cardou and Jolicoeur [1] considers the modelling of a cable which consists of a central core surrounded by one or several helically-wound wire layers and cites 107 papers. Other authors have adopted a continuum approach regarding each layer as a transversely isotropic material whose principal direction is along a helix surrounding the central axis of the cable. In each layer the helix angle is constant so that, when referred to cylindrical polar co-ordinates, the cylinder has a constant stiffness matrix in each layer. The intention in this paper is to use the continuum approach and describe the analytical solutions that govern the simple bending, flexure, or bending under a uniform load, of an anisotropic elastic cylinder consisting of a single material of this type. The extension of this work to a composite cylinder consisting of several concentric layers, surrounding a central core, which are either bonded together or make a frictionless contact, will be briefly described (see, Crossley [2]).

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Keywords: Elastic, Anisotropic, Bending, Cylinder

Representation Theorems for Isotropic Functions, with Application to Basis-free Representation of Kinematic Quantities

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Some representation theorems are presented for certain isotropic second-order tensor functions ($\phi(\mathbf{A}, \mathbf{H})$, where $\mathbf{A}$ and $\mathbf{H}$ are second-order symmetric tensors, and $\mathbf{\Phi}$ is linear in $\mathbf{H}$.

Since the paper of Rivilin and Erickson [1] in the fifties, it has been known that $\mathbf{\Phi}(\mathbf{A}, \mathbf{H})$ has a representation of the form

$$\mathbf{\Phi}(\mathbf{A}, \mathbf{H}) = \varphi_0\mathbf{I} + \varphi_1\mathbf{A} + \varphi_2\mathbf{A}^2 + \varphi_3\mathbf{H} + \varphi_4(\mathbf{AH} + \mathbf{HA}) + \varphi_5(\mathbf{A}^2\mathbf{H} + \mathbf{HA}^2)$$

The class of isotropic tensor functions described above has various mathematical and physical applications. For instance, the time derivative of an isotropic function $\mathbf{G}(\mathbf{A}(t))$ can be expressed as the isotropic function $\mathbf{\Phi}(\mathbf{A}, \dot{\mathbf{A}})$. Moreover, the solution of tensor equation $\mathbf{AX} + \mathbf{XA} = \mathbf{H}$ is also the isotropic function of $\mathbf{A}$ and $\mathbf{H}$.

Here we address the aforementioned problems for some new representation formulae, pertaining to the case where the value of $\mathbf{\Phi}$ is symmetric or skew-symmetric, and admits distinct and repeated eigenvalues. In this representation, the coefficients can be determined easily and only contain the invariants of tensor $\mathbf{A}$. As applications in continuum mechanics, basis-free formulae for some physical quantities in kinematics are derived by the representation theorems. Comparing with the previous results, the present formulae have the concise structure and simple coefficients.

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Effect of Inhomogeneous Inclusions on Anisotropic Elastic Fields of Dislocations

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Microstructural defects such as dislocations and second-phase particles play a central role in the fabrication, performance and reliability of materials and their structures. A numerical methodology for the three-dimensional stress field due to dislocation loops embedded in anisotropic elastic media is developed. Dislocation loops are discretized into segments, each of which is represented by a parametric space curve of specific shape functions and associated degree of freedom. Based on Eshelby's micromechanical equivalent inclusion method, the interaction between second-phase particles and dislocation loops is demonstrated. In particular, the effect of material anisotropy is discussed. Calculation of dislocation stress field and their interaction with inclusions would provide a way to show the size dependence of strength and plastic hardening of particle-reinforced metal-matrix composites.

Symposium on

General Mechanics

In Honor Of
Professor B. Boley

Organizer:
Professor G. Dasgupta
(Columbia University)

GENERAL MECHANICS SESSIONS

In Honor of Professor Bruno Boley

SESSION R2G
General Mechanics

Boley's Method for Solving Two-Dimensional Thermoelastic Problems Applied to Piezoelastic Structures

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In this paper an exact two-dimensional piezoelastic solution for the cylindrical bending of a two-layer piezoelastic plate is presented. We consider the plate to be built up by two identical piezoelastic layers, with electrodes at the interface of the layers and at the outer sides of the plate. The plate is studied in a plane state of strain, the mid-plane deforming into a cylindrical surface perpendicular to the (x,z)-plane. For the solution of this problem we utilize a method originally developed by Bruno Boley for two-dimensional thermoelastic problems, see Boley [1]. In this contribution, Boley presented an exact solution of the thermoelastic problem by introducing an expansion of the Airy stress function and a step-by-step solution for each term. Furthermore he discussed relations of the exact solution to strength-of-material theories. In the present piezoelastic problem we also consider a formulation by means of the Airy stress function. Due to the anisotropic material properties of piezoelastic materials, a differential operator similar to Hubers operator for bending of thin orthotropic plates is governing the Airy stress function in the present case. Furthermore, in the piezoelastic problem the z-component of the electric field vector takes the place of the temperature in the thermoelastic problem. Solving the piezoelastic problem by Boleys method thus is straightforward. In a first step, we solve the problem for an arbitrary distribution of the electric field. Afterwards, we consider the distribution of the z-component of the electric field vector in the form of a power series expansion with respect to the z-direction for each of the two layers. By taking into account the charge equation of electrostatics, a cascade of consistent strength-of-material theories of different approximation level is eventually extracted. It turns out that the level of approximation for the mechanical field and the electric field is not independent.

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Granular Flow; Dynamics from New Experiments

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Our ability to understand granular flow at high strains and strain rates is inhibited both by the theoretical complexity and the difficulty, historically, due to lack of reliable experimental evidence. Recent work using a positron camera has given a fund of useful information. The systems reported here are horizontal cylindrical vessels, all having an agitator with a sequence of blades set upon it. Such equipment is widespread in the process industries being used for mixing, drying and agglomeration amongst many other operations. In the cross-sectional plane, three distinct regions can be found a wall region, a region where there is a section affected directly by the blades and a core having a slowly moving interior and rapid flow on the surface, Axially, a set of convection cells is always found, whatever the blade design. Scaling laws for the speed and number or rotations can be deduced easily and a possible means of allowing for the effect of vessel diameter, the most important and least understood variable, will be considered.

Elastodynamic Solutions by Application of the Reciprocity Theorem

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Reciprocity theorems in elasticity theory provide a relation between displacements, traction components and body forces for two different loading states of a single body or two bodies of the same geometry. The purpose of the present work is to give direct applications to the computation of time-harmonic elastodynamic displacement fields. As discussed in this paper, it is possible to obtain a complete solution for certain configurations and concentrated loading cases by the use of elastodynamic

reciprocity. The known auxiliary solution for these cases we call a ívirtualî wave. This is a wave motion that satisfies appropriate conditions on the boundaries, and is a solution of the elastodynamic equations. It is shown that combining the desired solution as State A with a virtual wave as State B provides explicit expressions for State A. As desired solutions we consider the Rayleigh surface-wave motion generated by a sub-surface force in a half-space, and Lamb-waves in a layer generated by a line load.

Elastic-Plastic Contact Analysis of a Sphere and a Rigid Flat

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An elastic-plastic finite element model for the frictionless contact of a deformable sphere pressed by a rigid flat is presented. The evolution of the elastic-plastic contact with increasing interference is analyzed revealing three distinct stages that range from fully elastic through elastic-plastic to fully plastic contact interface. The model provides dimensionless expressions for the contact load, contact area, and mean contact pressure, covering a large range of interference values from yielding inception to fully plastic regime of the spherical contact zone. Comparison with previous elastic-plastic models that were based on some arbitrary assumptions is made showing large differences.

Keywords: sphere, contact, elastic-plastic

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Stationary Damage: An Analytical-Computational Approach for Examining Poroelastic Media Suceptible to Damage

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The theory of poroelasticity deals with the mechanics of porous elastic media that are saturated with fluids. The study of the coupling that ensues constitutes an important aspect of the developments in geomechanics and has laid the foundation for the application of the theory to a wide range of engineering applications covering, geomechanics, seismology, materials science and biomechanics. In the classical treatment of poroelasticity, it is invariably assumed that the porous skeleton remains intact during the time-dependent interactive processes between the porous skeleton and the pore fluid. Experimental evidence from testing of geological materials indicate that substantial alterations in the fluid transport characteristics can occur in a material even at stress levels well below those required to cause failure or collapse of the porous medium. This alteration in the fluid transport characteristics can lead to substantial changes in the times required for the pore pressure dissipation processes. One way of examining these alterations would be to structure an incremental stress analysis procedure where the stiffness and hydraulic conductivity characteristics are updated with time to reflect the changes. The approach proposed in this paper is to consider that the development of damage in the poroelastic medium that occurs at the instant of application of a loading is stationary, and experiences no change with time. This enables the use of a large body of analytical solutions for elastostatic problems to assess the initially damaged configuration. The resulting analysis is one that deals with the poroelastic behaviour of an inhomogeneous region where the inhomogeneity in the fluid transport characteristics and/or the elasticity characteristics is produced at the application of the initial loading. The paper presents the analysis of certain contact problems for a damageable poroelastic solid where the stationary damage concept is invoked. This approach is particularly suited for situations where the loading is time-independent and the laws describing the evolution of fluid transport and elasticity changes are known functions of the stress or strain state. The problems examined include the mechanics of pressure decay in a spherical cavity and the indentation of a damageable poroelastic half-space by a spherical indentor.

GENERAL MECHANICS SESSIONS

In Honor of Professor Bruno Boley

SESSION R3J
Granular Mechanics

Dynamic Behavior of an Intruder in Boundary-Driven Granular Flows

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In the industrial sector involved with the handling and processing of granular solids, the occurrence of segrega-

tion is a ubiquitous problem that ultimately leads to adverse economic consequences. The critical issue in this regard is the ability to create and maintain homogeneous blends of particulates that have diverse physical properties. Among the particle properties that can promote segregation, particle size is recognized as one of the principal factors.

This investigation is focused on the behavior of a large particle within a bed of smaller uniform particulates that experiences a shear flow induced through the motion of the boundaries. A three-dimensional discrete element code is used for this purpose, in which particles are modeled as "soft" inelastic, frictional spheres that are governed by well-known collision models. Numerical integration of the equations of motion of the system then yields the evolution of the particle positions and velocities.

The computational simulation cell consists of a cube in which parallel upper and lower bumpy surfaces move at constant velocity in opposite directions, while the remaining boundaries are periodic. The mean flow field is characterized by a granular temperature (normalized kinetic energy of the translational, fluctuating velocity) profile, which is maximum near the wall where the shear rate is highest, and which decreases inwards toward the center. We monitor the motion of a single large particle of diameter D, (called the *intruder*), that is placed within a bed of smaller uniform spheres (d). For all case studies investigated (size ratio $D/d = 1,\ 1.5,\ 2, 3$), the mean solids fraction was maintained at 0.40. Analysis of the results showed that for $D/d = 1$, the particle tended to sample the entire region between the moving walls. However, as the size ratio increased, the intruder migrated towards the center of the flow field, away from the region of high shear near the walls. Extended simulation runs of 1000 seconds showed that the large particle would remain near the flow center once there. Computations revealed that when intruder was below the approximate center of the velocity field, the number of contacts from surrounding smaller spheres on its lower half was greater than on its upper half. In addition, the trend was reversed when the intruder was initially placed above the center. Thus we interpret this as an indicator of a position-dependent net force responsible for moving large intruders towards the flow center.

Currently, our efforts are directed towards viewing this system as a complex dynamical system. We intend to apply methods commonly used in the field of chaos in order to obtain a better understanding of the phenomenon. Other studies underway include the study of systems composed of distributions of particle sizes, for which we have obtained some preliminary results.

Direct Simulation of Pressure Driven Flows of Dense Powders

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A code based on the distributed Lagrange Multiplier/Fictitious Domain (DLM) method is used to numerically simulate gas-solid pressure driven flows in two- and three-dimensional channels. The DLM method allows us to solve the exact initial value problem for the gas-solid systems containing thousands of particles. The diameter of powder particles is assumed to be between 100-100μm. The method is used to study the dense phase pneumatic transport processes under the absence of or reduction in gravity. More specifically, the simulation data is analyzed to study the roles of applied pressure gradient and gravity in the formation of plugs and the transport efficiency.

Micromechanics of High-Rate Compression Failure of Ceramics

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Ceramics' failure modes range from brittle to ductile depending on the deformation conditions. The micromechanisms of their compression failure are examined over a broad range of deformation rates, from quasi-static to ballistic strain rates. Recent advances in experimental techniques to study these phenomena are presented. Data on damage initiation and evolution in ceramic armor materials are used to decipher the essential feature of failure phenomena. Under moderate confining pressures and at moderate deformation rates, brittle failure involves initiation of micro-cracks at dominant micro-flaws and pre-existing micro-cracks, and their subsequent interactive growth, leading to axial splitting, faulting or a mixture of brittle-ductile failure. Under great confining pressures, common in ballistic impact on the other hand, classical crack-growth models seem inadequate for representing the actual failure initiation and evolution. Computational simulations of the early stages of impact response of ceramics show development of extremely high shear stresses within the target ahead of the projectile, a state conducive to pulverization. Transmission electron microscopy of recovered Al2O3 powder of impact-penetrated ceramics shows extensive twinning with submicron spacing. Dynamic compression of ceramics has also shown extensive dislocation activities. These observations are used to identify potential mechanisms of pulverization under high compressions.

Keywords: Ceramics, Compression Failure, High-Strain-Rate

A Constitutive Theory of Electromagnetic Microcontinuum

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A microcontinuum may be envisioned as a continuous collection of deformable point particles, each possesses finite size and directions representing its microstructure. This work is concerned with the determination of both macroscopic and microscopic deformations, motions, stresses, as well as electromagnetic fields developed in the material body due to external loads of thermal, mechanical, and electromagnetic origins. The balance laws of mass, microinertia, linear momentum, moment of momentum, energy, and entropy for microcontinuum are integrated with the Maxwell's equations. In the construction of the constitutive theory for microcontinuum physics, (1) the electric field, magnetic flux, generalized strains, temperature and its gradient are considered as the independent constitutive variables, (2) the polarization, magnetization, current, generalized stresses, heat flux, entropy, and generalized Helmholtz free energy are treated as the dependent constitutive variables, (3) axioms of objectivity, equipresence, thermodynamic restrictions, microscopic time reversal, and material invariance are strictly followed. Based on the linear constitutive relations, many physical phenomena, such as the electromagnetostrictive, piezowryness, magnetowryness, pyroelectromagnetic, Peltier, and Seebeck effects, can be systematically explained The nonlinear constitutive theory can predict higher order effects such as the Hall (Nernst) effect, i.e., current flows perpendicular to the magnetic flux and electric field (temperature gradient) The resulting energy equation clearly indicates the dissipative effect due to the second law of thermodynamics. The finite element formulation of microcontinuum physics is also presented.

Applicability Analysis of Continuum Theories from the Viewpoint of Phonon Dispersion Realtions

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The dynamics of atoms in crystals - lattice dynamics - are basic to many fields of study in the solid state, and has been characterized by phonon dispersion relations, which is an essential feature representing the atomic structure and atomic motions in crystal. Phonon dispersion relations can be calculated from atomic force by the discrete atomic model. The analog of atomic force is the constitutive relations in the continuum theory, which serve to distinguish one material from another. It follows that the phonon dispersion relations can be also calculated through the constitutive relations of a material by a continuum model if the model can manifest the dynamics of atoms in crystals, and hence provide a bridge to link the interatomic force to the constitutive relations. This also provides a chance for the continuum field theories to be examined on the region of applicability and validity from the viewpoint of phonon dispersion relations.

The phonon dispersion relations based on the classical continuum theory, Eringen's micromorphic continuum theory and micropolar theory, Mindlin's microstructure elastic theory, Mindilin and Toupin's couple stress theory, Cosserat's theory, strain gradient theories and nonlocal theories have been presented. The results have been compared and analyzed. The applicability of each continnu field theory has been discussed. It is seen that (1) the classical continuum theory is only valid for very long wave-length problems, (2) the couple stress theory, strain gradient theories and nonlocal theories do not stem from the consideration of microstructure and micromotion. On the other hand, both the atomic structure and the dynamics of atoms have been manifested in micromorphic theory and micropolar theory, which therefore dramatically extend the application region of continuum theories to the microscopic length and time scales.

GENERAL MECHANICS SESSIONS

In Honor of Professor Bruno Boley

SESSION R4J
Finite and Boundary Element Method

An Extended Finite Element Method for Solidification

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An extended finite element method [1, 2] for the solution of multi-dimensional solidification problems is presented. In this method the standard finite element basis is enriched with a discontinuity in the derivative of the temperature normal to the interface as described in [3, 4]. The

enriched part of the temperature field θ is

$$\theta(x,t)^{enriched} = \sum_{I}^{ne} N_I(x)\phi(x,t)a_I(t) \qquad (1)$$

where ne are the number of enriched nodes, N_I are the standard finite element shape functions, ϕ is the distance to the interface and a_I are additional dofs that are related to the measure of the disconintiuity in the temperature gradient. This enrichment enables the approximation to represent the discontinuity in the heat flux at the interface within an element interior. As a result the phase interface can evolve without re-meshing or the use of artificial heat capacity techniques. An example is shown in below.



Figure 1: Solidification of a metal casting

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Non-Singular Hybrid Boundary Element Method for Elastomechanics

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On the basis of the hybrid displacement boundary element met= hod (HDBEM), a non-singular formulation is presented. In contrary to standard boundary element formulations, the HDBEM is not based on a boundary integral equation but derived from a three-field principle based on Hamilton's principle. In the domain, a superposition of fundamental solutions is used for the approximation of field variables. By locating the load points outside of the domain, singular boundary integrals are avoided. The influence of the load point placement is examined and a preferred region is found leading to good results and a low sensitivity on the actual load point location. Time- and space-dependency are separated yielding time-independent symmetric system matrices that can be used for the calculation of forced vibrations as well as for eigen-analysis and transient solutions. The domain integral describing inertia forces is mapped on the boundary by means of an analytical higher order fundamental solution. The non-singular formulation of the HDBEM is applied to 3D elastostatics and elastodynamics. The accuracy of the method is demonstrated by the example of a plate containing a circular hole under tensile load. This example is chosen because it gives a high stress concentration on the notch. The comparison of numerical results to the analytical solution shows the outstanding performance of the non-singular HDBEM. For elastodynamics the method is demonstrated by wave propagation problems in a slender beam. The transient solution calculated with a standard Newmark integration scheme again coincides excellently to analytical solutions.

Interpolation Constraints and Thermal Distributions

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An approximation to a distribution governed by temperature readings taken at the edge of a polygonal domain can be constructed using interpolation functions which satisfy first order, constancy and linearity, conditions. The values prescribed by the normed interpolation function should be bounded between zero and one. This restriction is especially necessary when representing temperature, since negative values for temperature in Kelvin are physically unacceptable. Compliant interpolation functions can be constructed on all convex polygonal domains including those bounded by vertex and mid-side nodes. Using constructed interpolation path-lines concave domains can also be represented. Within non-concave domains these path-lines are linear. In concave domains they are necessarily non-linear. These formulations allow for smooth representation of data collected at discrete points.

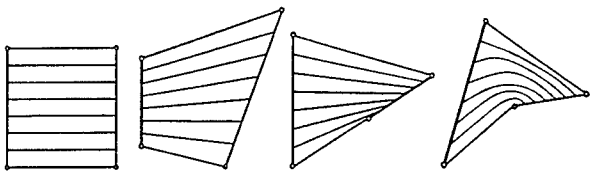


Figure 1: Interpolation paths within quadrilateral domains

Keywords: Temperature distribution, mid-side node, concave finite element

FEM Prediction of Steam Generator Tube Failures in Nuclear Power Plants

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Prediction of crack failure in steam generator tubes of nuclear power plants is an important ingredient in scheduling inspection and repair of tubes. Prediction is usually based on nondestructive testing of cracks. Nondestructive testing often reveals two neighboring cracks. If the cracks interact, the tube pressure under which the ligament between the two cracks fails could be much lower than the critical burst pressure of the individual crack. Predicting the pressure causing failure of the ligament, called coalescence pressure, is important. The failure criterion was not well established until nonlinear finite element studies of crack coalescence of two in-line cracks demonstrated that FEM nonlinear models are capable of predicting coalescence criteria fairly accurately for 100% through-wall cracks. The ligament rupture starts when local instability of the ligament occurs under plane strain conditions. As a result of this local instability, the ligament thickness in the radial direction reduces drastically. The thickness/pressure gradient becomes very high and the ligament is no longer capable of resisting the applied tube pressure. Good correlation of FEM results with experimental data has been observed at Argonne National Laboratory's ET Division. This failure criterion and FEM work has been extended to axial cracks of varying ligament width, notch length, number of notches, and cases where cracks are offset axially or circumferentially.

Keywords: steam generator tubes, coalescence pressure, nuclear power plant, ligament rupture

GENERAL MECHANICS SESSIONS

In Honor of Professor Bruno Boley

SESSION F2G
Analytical Methods

Dynamics of Two van der Pol Oscillators Coupled via a Bath

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In this work we study a system of two van der Pol oscillators, x and y, coupled via a "bath" z:

$$x'' - e(1-x^2)x' + x = k(z-x)$$
$$y'' - e(1-y^2)y' + y = k(z-y)$$
$$z' = k(x-z) + k(y-z)$$

Our motivation for studying this system comes from the chemistry of the eyes. There is experimental evidence that there exist circadian rhythms in each of our two eyes. These are periodic motions, limit cycles, with periods of approximately 24 hours. E.g. melatonin levels have been observed to vary periodically in this way. It has been conjectured that the visual system, which must operate over some 10 orders of magnitude in the course of night and day, has its sensitivity controlled through these oscillations by anticipating the changes in light intensity which occur at dusk and dawn.

It is naturally desirable that both eyes operate in phase. However, there is no direct connection between the two eyes. Instead, the eyes can influence each other by affecting the concentration of melatonin in the bloodstream. Alternatively, the eyes may be coupled via neural pathways in the brain. In this work we have chosen to model the former method of coupling between the eyes. x and y represent the concentrations of melatonin in each of the eyes, and z represents the concentration of melatonin in the bloodstream (here referred to as a bath.) We investigate the existence and stability of the in-phase and out-of-phase modes for parameters $e > 0$ and $k > 0$. To this end we use Floquet theory and numerical integration. Surprisingly, our results show that the out-of-phase mode exists and is stable for a wider range of parameters than is the in-phase mode. We also investigate the occurrence of other periodic motions by using the method of averaging for small values of e and k.

Green's Functions for Anisotropic Media

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The spatial description in the governing field equations of mathematical physics is invariably self-adjoint. The homogeneous canonical form for a linear system is:

$$[\mathcal{L}_{2n}\{u\}] = [\mathcal{L}_n][\mathcal{L}_n]\{u\}] = \{f\} \tag{1}$$

where:

$\mathcal{L}_n$: partial differential operator of order n (2-a)

u : spatial solution (2-b)

f : forcing function (2-c)

In general the Green 's function G_n:

$$[\mathcal{L}_n]\{\mathcal{G}_n\} = \delta \tag{3}$$

is easier to obtain than $\mathcal{G}_{2n}$:

$$[\mathcal{L}_{2n}]\{\mathcal{G}_{2n}\} = \delta \tag{4}$$

Starting from the *lower order Green's function* $\mathcal{G}_n$ the *higher order Green's function* $\mathcal{G}_{2n}$ will be obtained by the convolution process that is indicated by the *operator in the following equations.

From equation (1),the anisotropic material property $k(x,y,z) > 0$,is incorporated preserving the self-adjoint form:

$$[\mathcal{L}_n]\left(\frac{k(x,y,z)[\mathcal{L}_n\{u\}]}{k_0}\right) = \{f\};\ k_0 : \text{maximum of } k(x,y,z) \tag{5}$$

Define:

$$[\mathcal{L}_u]\{v\} = \{f\};\ \{v\} = \left(\frac{k(x,y,z)[\mathcal{L}_n\{u\}]}{k_0}\right) = \mathcal{G}_n * f; \tag{6}$$

Now

$$\{u\} = k_o\mathcal{G}_n * \left(\frac{\{v\}}{k(x,y,z)}\right) \tag{7}$$

These anisotropic Green 's functions improve the quality of discrete solutions including those of the boundary element method for anisotropic media.

Snap-through of Layered Shallow Shells under Thermal Load

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The present investigation considers the stability of shallow shells subjected to a temperature distribution that is assumed to be an arbitrarily prescribed function of the space coordinates. The governing boundary value problem is derived under the approximating conditions of the von Kármán-Tsien theory, modified by the generalized Berger-approximation. The shell edges are assumed to be prevented from in-plane motions and are simply supported. Moderately thick shallow shells above a polygonal planform are composed of multiple perfectly bonded layers. In the special case of laminated shells made of transversely isotropic layers with physical properties symmetrically distributed about the middle surface, a correspondence to effective moderately thick homogeneous shells is established. Shear deformation is approximately considered according to the Reissner-Mindlin theory.

Application of a multi-mode expansion in the Galerkin procedure to the boundary value problem, where the eigenfunctions of the corresponding linear plate problem are used as Ritz-approximations, renders a coupled set of algebraic equations for the generalized coordinates with cubic as well as quadratic nonlinearities. The phenomena of thermal snap-through, snap buckling and the corresponding post-buckling behavior within the elastic range are studied. In a single-term approximation, the corresponding solution turns out independent of the special polygonal planform of the shallow shell. Furthermore, in order to investigate mode-jumping, i.e. snap-through in higher modes, also the double-mode approximation is analyzed in detail. For this case of thermal snap-buckling it is assumed that the geometry of the shell is affin to the first eigenmode of the corresponding flat plate.

In numerical studies the influence of the shell's curvature parameter and the temperature distribution on the various types of loss of stability are investigated.

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A Unified Formalism for Elastostatics or Steady State Motion of Compressible or Incompressible Anisotropic Elastic Materials

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For a two-dimensional deformation of an anisotropic elastic material, the Lekhnitski formalism applies to elastostatics only. It does not apply to steady state motion such as surface waves or a moving line dislocation. The Stroh formalism applies to elastostatics as well as steady state motion. However, it does not apply to an incompressible material because some of the elastic stiffnesses become unbounded in the incompressible limit. Modifying a new formalism studied recently, a more explicit and remarkably simple expression of the matrices in the new formalism is given, and a unified formalism that is applicable to elastostatics as well as steady state motion of a compressible or incompressible anisotropic elastic material is obtained. As an application, the secular equation is presented for surface waves propagating in a monoclinic material with the symmetry plane at $3_x = 0$ that has a more explicit expression than what is available in the literature. Specialized to the case of orthotropic or incompressible materials is trivial. Also presented is an explicit sextic equation for the eigenvalues p that is valid for any steady state wave speed. We show that the inplane and antiplane deformations (elastostatics or steady state motion) of an incompressible monoclinic material with the symmetry plane at $3_x = 0$ is identical to that of an incompressible orthotropic material.

Effect of Thermal Residual Stresses on Elastoplastic Behavior of Metal Matrix Composites

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During the fabrication and subsequent heat treatment processes, particle-reinforced metal matrix composites may develop large internal residual stresses due to the difference of coefficients of thermal expansion between the matrix and reinforcement. The purpose of this presentation is to study the effect of thermal residual stresses on the effective elastoplastic behavior of composites.

We consider the thermal residual stresses as a part of the prescribed eigenstrain in terms of micromechanics treatment. Local stress and strain fields in the composites can be disturbed by taking the residual stresses into consideration. Homogenization procedure is utilized to derive the governing ensemble-volume averaged elastic constitutive field equations and the overall yield function for the composites based on the probabilistic spatial distribution of particles. This micromechanics-based effective constitutive model can characterize the macroscopic plastic yield behavior of the composites under three-dimensional loading/unloading histories. Comparisons between the computational results and experimental data for the composites are shown to illustrate the capability of the proposed method.

Generalized Plane Strain Thermopiezoelectric Analysis of Multilayered Plates

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The generalized plane strain thermopiezoelectric deformations of laminated thick plates are analyzed by using the Eshelby-Stroh formalism. The laminated plate consists of homogeneous laminae of arbitrary thicknesses. The three-dimensional equations of linear anisotropic thermopiezoelectricity simplified to the case of generalized plane strain deformations are exactly satisfied at every point in the body. The analytical solution is in terms

of an infinite series. The continuity conditions at the interfaces and boundary conditions at the top and bottom surfaces and edges are used to determine coefficients in the series. The formulation admits different thermal, electrical and mechanical boundary conditions at the edges of each lamina, and is applicable to thick and thin laminated plates. Laminated plates containing piezoelectric laminae poled either in the thickness direction or in the axial direction are analyzed and results are presented for plates with edges either rigidly clamped, simply supported or traction-free.

GENERAL MECHANICS SESSIONS

In Honor of Professor Bruno Boley

SESSION F3G
Mechanics of Materials

Probability-Based Analysis of Size Effect in Porous Materials

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The probability-based analysis of size effect in porous materials is considered in this paper. The porosity is modeled as a series of identical, small, sharp cracks with crack length (void size) characterized by a known probability distribution function. The distance between two cracks is also treated as random variable with a given probability density. The strength of the materials is considered in proportion to the fracture toughness. The size effect is the result of the postulation that the material strength is governed by the shortest distance between two adjacent voids. The larger the material volume the more likely a shorter mean distance between two voids is found. As a result, the increase in the stress intensity factor leads to a weaker material strength.

In this paper, the mean distance between voids is considered inversely proportional to the material volume. Both lognormal and Weibull probability density functions are used to model the random variations of the void size and of the distance between two adjacent voids. The first-order second-moment method is used to obtain the probability distributions of material strength as a function of volume. It is found that the mean strength decreases but the coefficient of variation increases with increasing volume. The results confirm the importance of size effect in reliability design of porous materials.

Keywords: Probability distributions, size effect, porous materials, fracture mechanics

Solar Energy by Fiber Reinforced Composite Material

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There are different solutions to obtain solar energy. The solutions can be grouped as mechanical, heat, electrical energy, etc. One of them is the direct method to gain mainly mechanical, but also heat energy through a special construction based on fiber reinforced composite material. If the reinforcment is metal with high thermal expansion, it is possible to manufacture the so called bimaterial that is similar to the bimetal.

By the bimaterial, using in special construction, it is possible to produce mechanical and heat energy (stored in water) utilizing sun- shine and cold water.

The paper deals with the mechanical theory and construction of bimaterial and with its application in "Sun-Water-Engine" (SWE) to produce solar energy. Some of the details of SWE will be shown and examples on practical application will be mentioned.

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Bifurcation Phenomena in the Rigid Inclusion Power Law Matrix Composite Sphere

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This paper contains an analysis of bifurcation of interface separation related to cavity nucleation in a radially loaded composite sphere consisting of a rigid inclusion separated from a power law matrix by a uniform, nonlinear cohesive zone of vanishing thickness. Governing equations for the spherically symmetric and non-symmetric problems are obtained from results of the analogous hyperelastic finite strain theory by a limiting process that preserves nonlinear matrix and interface response at infinitesimal strain. A complete solution to the spherically symmetric problem is presented including formulae for the bifurcation load, the evolution of elasto-plastic boundary and interface separation, and the stresses in the elastic and plastic regions of the matrix. An analysis of the problem of non-symmetric bifurcation, under spherically symmetric conditions of geometry and loading, yields formulae for the bifurcation load and first non-symmetric mode shape associated with rigid body inclusion displacement.

For both the symmetric and non-symmetric problems, detailed results are provided for an interface force law that captures interface failure in normal mode and linear response in shear mode. We show that for the spherically symmetric problem (i) there are threshold values of parameters above which bifurcation will not occur, (ii) threshold values of parameters below which there do not exist equilibrium solutions in the post bifurcation regime, (iii) bifurcation occurs after the maximum interface strength has been attained. For the non-symmetric bifurcation problem, (i) bifurcation will always occur, although it can be delayed by interfacial shear, (ii) for the smooth interface, non-symmetric bifurcation occurs after the maximum interface strength has been attained and always precedes spherically symmetric bifurcation.

Keywords Bifurcation, nucleation, debonding, inclusions.

Line Forces in Uniform Supersonic Motion in Anisotropic Linear Elastic Solids: Radiating and Non-Radiating Solutions

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In 1949 the late J. D. Eshelby [1] showed that a straight edge dislocation moving at the uniform supersonic speed $v = \sqrt{2}c_s$, where c_s is the shear wave speed, in an infinite isotropic linear elastic solid would not radiate energy in its far field, provided that the dislocation Burgers vector was parallel to the direction of uniform motion. This is the only supersonic radiation-free solution possible in elastically isotropic solids. Recently Barnett and Zimmerman [2] have elucidated, in a rather simple fashion, the exact conditions under which radiation-free uniform supersonic motion of straight dislocations in generally anisotropic elastic solids can occur. Such results are of interest following the experimental observations by Rosakis, Samudrala, and Coker [3] of shear cracks propagating at the "magic" Eshelby speed and the one-to-one correspondence of radiation-free supersonic dislocation solutions and radiation-free supersonic crack solutions noted by Gao and his co-workers [4].

In the present work we show that, with only minor modifications, the determination of conditions allowing for non-radiating line forces in uniform supersonic motion in solids of general anisotropy may be obtained using the analysis of Barnett and Zimmerman for dislocations. For non-radiating supersonic dislocation motion, Barnett and Zimmerman showed it was necessary and sufficient for the dislocation Burgers vector to be orthogonal to all real Stroh **l** eigenvectors associated with all real Stroh eigenvalues at the supersonic speed in question. When two and only two Stroh eigenvalues are real, either one or an infinite number of Burgers vector choices is possible. When four and only four Stroh eigenvalues are real, the four corresponding real Stroh **l** eigenvectors must be co-planar, with the dislocation Burgers vector taken normal to the plane of coplanarity (this is exactly the condition occurring for Eshelby's solution, and it is met in media of cubic symmetry for common media such as iron over a continuous range of supersonic speeds). The condition for non-radiating line forces in uniform supersonic motion is simply obtained from the above statements by replacing the real Stroh **l** eigenvectors by the real Stroh a eigenvectors, and by replacing the dislocation Burgers vector b by the line force strength **f**, i. e., **f** must be chosen normal to all real Stroh **a** vectors corresponding to real Stroh eigenvalues.

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Short Crack Fracture Mechanic s and the Fatigue Limit

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Macroscopic hardness and tensile properties of metals have been used extensively to predict the fatigue limit of metals. These approaches have been based solely on empirical modesl (curve fits) with numerous correction factors to account for the effects of variables such as surface finish and size to name a few. Murakami has established a method of predicted the variation of ΔK_{th} for short cracks. His approach has been combined with the Hall-Petch relationship to predict the effects of hardness, microstructure size, and flaw size on the fatigue limit of metals. This method, termed the Hall-Petch-Murakami model (HPM), is based on the concept that the fatigue resistance, i.e. the threshold condition of a non-propagating crack, is determined by two parameters: non-propagating defect or crack size and the streength of the barrier to crack propagation. The concept of three defect types associated with three different flaw dominated fatigue regimes has been derived. The HPM model has been successfully applied to low, medium, and high strength steels, synergistic effects of surface finish and intergranular cracks, competition between surface and subsurface fatigue nucleation, and optimization tempering of steels. Statistical variation of hardness, inclusions, and surface finish flaws is investigated for their effects on the fatigue limit.

Keywords: short cracks, fatigue limit, HPM model, probability

Symposium on

Time Dependent Failure Phenomenon

In Honor Of
Professor H. Brinson
Professor A. Cardon

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TIME DEPENDENT FAILURE PHENOMENON

In Honor of
Professor H. Brinson and Professor A. Cardon

Session T4G
Analysis and Durability of Adhesive Bonds

Durability of Adhesively Bonded Composite Joints: A Review

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Joining composite parts with adhesive joints is increasingly used and studied, due to its instant mechanical efficiency compared to other joining techniques. Limiting to thermoset matrix composites in both parts of the joints, we reviewed research work on durability of such assembly under mechanical and environmental loads, including fatigue, temperature and moisture. Discussion, resulting conclusions and trends will be presented.

Thermal Fracture in Functionally Graded Thermal Barrier Coatings due to Time-Dependent Behavior

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Functionally graded materials can be used as durable thermal barrier coatings (TBCs) to protect metallic materials from high temperature environments. The thermal

fracture behavior in functionally graded yttria stabilized zirconia (YSZ)-NiCoCrAlY bond coat (BC) alloy TBCs is studied using analytical models. These graded TBCs are comprised of layers of YSZ-BC alloy composites of varying YSZ volume fractions. The response of three TBC architectures of similar thermal resistance to transient thermal loading simulating a laser thermal shock test is considered.

The effective time-dependent (viscoplastic) response and thermo-elastic properties of the individual layers are estimated using mean field micromechanics models such as the self-consistent and Mori-Tanaka methods. These effective properties are utilized in fracture mechanics analyses to study the role of coating architecture on the formation of cracks at the surface of the TBC. The effect of the morphology of these surface cracks on the propensity for growth of delamination cracks at the TBC-BC interface is then assessed. Possible strategies to inhibit the growth of these delamination cracks that govern the final failure of these coatings are discussed. The results of these analyses are correlated with experimental observations from thermal shock tests on these TBC architectures performed using a high power laser.

Deformation of a Double Bonded Beam under Three-point Bending

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Moussiaux, Cardon and Brinson [1] developed a test method to determine adhesive properties by using bending of a bonded beam. Compared with other methods, this method has the advantages of requiring simple experimental devices and test specimens. It can be used for either static or dynamic test, and therefore can be used to determine time dependent properties of adhesive materials.

Of central importance to this method is a solution, derived from the elementary beam theory, that relates the adhesive properties to the load and deflection of the beam. Much study has been conducted to assess the accuracy of this solution.

This problem is reformulated by using variational principle. The total energy of the system consists of the strain energy due to bending and axial strain in the beams, the strain energy in the adhesive layer due to shear, bending, and normal strain, and the potential energy of the load. The variation condition of minimizing the total energy leads to the equilibrium equations and the natural boundary conditions. These equations are compared with those in [1]. The solution and the comparison with experimental data are presented.

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Combined Load Testing of PSAs for Joint Design

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Semi-structural pressure sensitive adhesives (PSAs) are commonly used in some industries and have been so for many years, yet appropriate design methodologies are not well known by most mechanical designers. By generating a design methodology that is based upon material properties that are familiar to engineers, the understanding of and confidence in PSA joint design will be enhanced. This work has involved an extensive series of tests on commercially available PSA tapes in order to identify and measure relevant material properties to develop an appropriate design approach for these material systems. Because these materials are extremely tough, a fracture-based approach is difficult to develop and employ, especially at ambient conditions. A strength-based approach seems appropriate for these material systems, especially for short-term loading events.

Using an Arcan test fixture, tests were conducted over a range of orientations and loading rates. Specimens consisted of extruded aluminum adherends bonded with the semi-structural tapes. Using the peak load obtained from each test, the average shear (τ) and normal (σ) stresses were calculated using simple sine and cosine relationships. These values were then cross-plotted, resulting in rate-dependent failure envelopes, which can be used in strength-based designs.

In addition to varying the crosshead rate, tests were also conducted at various temperatures and relative humilities. Using this data, shift/correction factors were generated, which allow the failure curves to be used outside of the original test conditions.

The complete set of curves provides the engineer with strength data required to complete typical designs, within the design space. By knowing the working environment,

loading rate, and stress state, one can determine the allowable design stresses for a range of loading conditions. A subsequent paper will address durability issues for long term loading that is beyond the scope of these results.

Failures for all tests were observed to occur within the adhesive layer, but often near one of the interfaces. Adhesive ghosting was seen on all specimens, indicating that failures were cohesive rather than adhesive in nature. Although the results were all collected on aluminum, the design data may be useful for other substrates if the bonds are sufficient to always induce cohesive failures. Concerns about long term durability, especially with other adherends, however, should first be addressed.

A Study of Durability of Pressure Sensitive Adhesive Tapes

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Semi-structural pressure sensitive adhesives have found growing applications in many engineering designs because of their ease of use and resistance to damage from fatigue and dynamic loading. The effects of long term loading may be of more concern for these viscoelastic polymeric materials. This study of the durability of semi-structural pressure sensitive adhesives explores the viscoelastic behavior of commercially available tapes using two different techniques: creep rupture and subcritical debond testing.

Subcritical debond rates of the pressure sensitive adhesive tapes were measured as a function of applied strain energy release rate, G, using a curvature mismatch technique developed earlier. Flat aluminum strips (beams) were bonded to curved aluminum mandrels using the tapes. By varying the beam widths and thicknesses, a range of applied strain energy release rates could be achieved. The debond rates, da/dt, were measured as a function G at several temperatures and relative humidity levels. The debond rates were determined by measuring the debond length of the beams over time throughout the tests. Log-log plots of da/dt versus G were generated for different temperature and relative humidity conditions. Shift factors for both temperature and relative humidity were developed to predict behavior at conditions not explicitly tested.

In addition, durability was also characterized using both creep rupture and instrumented creep rupture tests extending up to several months. Creep strains were measured in the instrumented tests, in addition to time to failure obtained for all specimens. Cylindrical aluminum adherends were bonded to produce either normal loading (butt joints), shear loading (lap joints) or mixed loading (45° angles). These tests were conducted at various environmental temperatures in a custom-built stepper motor creep frame. Plots of Stress vs. Time to Failure, Strain vs. Time, and Creep Compliance vs. Time give insights into the durability and viscoelastic behavior of the adhesive tape.

TIME DEPENDENT FAILURE PHENOMENON

In Honor of
Professor H. Brinson and Professor A. Cardon

SESSION W3F
Time Dependence in Polymers

Time Dependent Failure of Polymers – Energy Related Methods –

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Failure of polymers does not mean only fracture or rupture. Phenomena such as transition from linear to nonlinear viscoelasticity, crazing and yield are also signs of failure. While yield and fracture can easily be observed in short term tests (for instance constant strain rate or constant stress rate experiments), crazing can be observed rather under long term loading, such as creep or stress relaxation tests. The transition from linear to nonlinear viscoelasticity can be detected only by more sophisticated procedures.

If in addition one remembers the strong dependence of the behavior of mechanically loaded polymers upon temperature, environmental conditions and, of course, upon time, one can understand that prediction of failure of polymers is a very difficult problem. An attempt to explain the different forms of polymer failure is based on energy related methods.

During loading, the work done by external forces on a viscoelastic material is converted into a stored part (potential energy) and a dissipated part (lost energy); each of those parts may be divided into two other parts: the isotropic one, connected with volume changes and the deviatoric one, associated with shape changes. According to the Reiner-Weissenberg theory of strength, failure occurs when the stored energy reaches a certain value, which is assumed to be a material constant. Results obtained

on the basis of this theory are in good agreement with those obtained for the transition from linear to nonlinear viscoelasticity. On the other hand, crazing of polymers under stress relaxation , where after the loading step no more energy is supplied to the specimen, but crazes become visible after some time, can not been explained by the Reiner-Weissenberg theory.

Generally, failure depends upon the loading history and on must asses the effect of history on the nature of a deformation process. Thus, one must consider the relative participation of the two primary mechanisms, viscous flow and elastic deformation. The participation of these two processes varies with the rate of deformation and since the viscous processes require appreciable time whereas the elastic ones are quasi-instantaneous, the higher the rate, the greater the elastic part For that reason, attempts made for predicting failure must take into consideration the whole loading history of the material.

With polymers, the application of an energy related theory of strength renders possible the determination of the limit of various forms of failure, allowing also predictions. It is obvious, that the obtained limits are no more strain limits or stress limits, but energy limits, depending upon both, strain and stress.

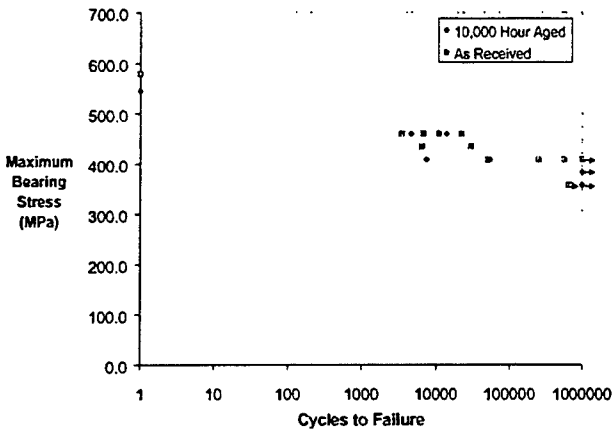
Keywords: viscoelasticity, failure, loading history, strain energy

High Temperature Time Dependent Modeling of PMCs - Forget About It! IM7/PETI-5 is Here!

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Polymer matrix composites (PMC) are being considered for a number of elevated temperature aerospace applications, 177°C (350°F). Mechanical fasteners may be required to join these PMC, making the elevated fatigue behavior of these highly loaded joints a possible design concern. A modified test set-up was used to simulate the stress state of bolted composite joint. Using this modified set-up, IM7/PETI-5 composites in a 64 ply, quasi-isotropic lay-up showed a 20% improvement over IM7/K3B in elevated temperature bearing fatigue tests. Further, the bearing fatigue life of IM7/PETI-5 showed no dependence on frequency or 10,000 hour aging at 177°C (350oF) as shown in the Figure below. Upon completion of the fatigue testing, failure analysis revealed that the bearing failure mechanisms were delamination, ply buckling, and 0o ply fracture. 10,000 hours of bolts bearing creep loading at elevated temperatures also showed on time dependent elongation. Overall, IM7/PETI-5 composites was found to be very durable with no significant time dependant behavior at 177°C (350°F).



Perspectives on the Durability of Polymeric Materials

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The lifetime of polymers is influenced by conventional frature considerations, but in some ways is more complex than conventional materials. Here we survey work performed by the author to examine the lifetime and durability of plastics and rubber with emphasis on the macroscopic response of the materials rather than on the microstructural mechanisms that are ultimately responsible for the failure. We will examine the behavior of PMMA and a series of filled rubbers within the context of time and cycle dependent cumulative damage rules. In addition, one aspect of glassy polymer failure that is unique is the formation of crazes prior to failure. We will examine the impact of the so-called physical aging process on both craze initiation and craze growth of polymer glasses under static loading conditions.

Measurement of the Creep/Creep Recovery Response in a Thin Polymeric Film at Finite Strain Levels

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The time dependent mechanical response of a thin polymeric film (polyethylene terephthalate or "PET") was

studied experimentally and analytically. Uniaxial tensile loading was assumed. The load levels involved induced stress levels well above the yield point of the polymer, resulting in large finite strain levels. A combination of Schapery's nonlinear viscoelastic model and Lai's nonlinear viscoplastic model was used to characterize time dependent behavior. Since finite strain levels were involved, true stress and true strain were used to describe the stress-strain response. Since the applied stress was allowed to exceed the yield point, plastic behavior was added to the constitutive model after separating the irrecoverable strain into instantaneous plastic strain and viscoplastic strain. The material properties associated with Schapery's and Lai's model were determined by conducting a series of creep/creep recovery tests at several stress levels, including stress levels well above the yield point. The validity of the constitutive model was evaluated by comparing predicted and measured response during two-step loading tests. In some cases the second step in stress was lower than the first step in stress, whereas in other cases the second step in stress was higher than the first step in stress. Reasonable agreement between predicted and measured response was achieved.

Sorption of Water in High Tg Polymers: Analysis of Transport and Interactional Issues

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Molecular interactions of absorbed water molecules with two different high performance polymer matrices, polyimide and epoxy resins, have been investigated by means of classical gravimetric analysis coupled with time-resolved FTIR spectroscopy. Various species of absorbed water molecules have been identified spectroscopically, depending on the molecular structure of the two matrices. Sorption and desorption kinetics at several activities of water vapor and equilibrium sorption isotherms evaluated by both experimental techniques will be presented along with useful information gathered by comparing the results of the two experimental approaches. These results will be discussed with reference to the molecular interactions and state of aggregation of the penetrant molecules in the two systems.

TIME DEPENDENT FAILURE PHENOMENON

In Honor of
Professor H. Brinson and Professor A. Cardon

SESSION W4F
Analysis and Durability of Composites

Long-Term Reliability Analysis of Fiber Composite Structures with Applications to Deepwater Offshore Engineering

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Advanced fiber composite materials are currently being considered for a wide range of primary load-bearing structural applications in deepwater offshore energy exploration and production (E & P) engineering systems, including both subsea and topside structures. Long-term reliability of the composite structures is of critical concern in the risk assessment of offshore E & P systems as they are normally designed for service lives of twenty-five to thirty years under 100-year extreme environmental loading. Besides the stochastic environmental loads, inherent uncertainties associated with long-term failure strengths of constituent materials (i.e., high-strength fibers and brittle resin matrices) introduce additional complexities in the long-term reliability evaluation of the composite structures. In this paper, a probability-based reliability analysis methodology is developed for proper risk assessment and management of large composite structural systems in deepwater offshore engineering operations. Basic probabilistic failure models and associated degradation schemes, based on physical modes of individual ply composite failure and long-term damage progression, are introduced first. With the aid of advanced composite laminate shell mechanics and a proper progressive ply failure scheme, probability-based limit state functions are constructed for tubular offshore composite structural elements. An efficient and accurate computational structural mechanics algorithm is also developed for large offshore composite structural systems. For illustration, the reliability analysis method developed here is then applied to

a composite production riser (CPR) string in a 3,000 ft tension-leg platform (TLP) under an environmental loading typical of Gulf of Mexico. Numerical results are obtained for the case study to elucidate some of the interesting and important, fundamental offshore composite structural reliability problems. Comparisons are also made against the data obtained from long-term failure tests of full-size (i.e., diameter) composite riser joints.

Prediction of the Strength Evolution of Polymer Based Composite Material Systems

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Polymers are viscoelastic, exhibit time dependent properties and are very sensitive to environmental conditions such as temperature and moisture. At the design moment it is necessary not only to have informations on the classical instantaneous properties of the material but also some prediction of the changes of those properties over an imposed time period, 10-20-50 years, after a complex stress history related to mechanical loading and environmental variations is needed if structural integrity has to be guaranteed.

For polymers and polymer matrix composites the prediction of the stiffness evolution is possible on the basis of the Schapery nonlinear viscoelastic constitutive equations as proposed by H.F. Brinson, [1]. Based on the observation of the residual strain after recovery, this model has to be completed by some viscoplastic component as shown by M. Tuttle, [2], X. Xiao, [3] and Y. Qin, [4]. This combined nonlinear viscoelastic-viscoplastic model gives predictions in good agreement with experimental results for single creep and creep recovery, and cycles of temperature and moisture changes.

Discrepancies between the model predictions and real time experimental results appear if some dynamic cyclic loading is superimposed on the single creep and creep recovery conditions. Those discrepancies can be reduced by the introduction of a damage component in the model and a good choice of the damage potential. Strength and stiffness are not related in general except for some living tissues and out of the fact that a complete stiffness decrease result in a failure situation.

The time dependent strength evolution can be modelled in a similar way as the stiffness evolution, but this is a rather empirical approach. Failure is the results of the change of an homogeneous stress-strain behaviour by some localisation phenomena to a heterogeneous stiffness distribution. A model for the strength evolution can be based on the experimental observation of the heterogenisation of the stress-strain behaviour. The initiation of the heterogenisation development is a safe prediction tool for the analysis of the strength evolution of a time dependent material system. The experimental follow-up has to be performed by a non contact measuring device. A fullfield optical method such as the ESPI-analysis is a good candidate.

Some examples obtained on carbon-epoxy systems will be presented and the possible prediction of the strength evolution will be discussed.

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The Effects of Loading History on the Fracture Behavior of Rubber-Toughened Epoxy

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Most of the toughening mechanisms in rubber-modified epoxies are viscoelastic. As a result, their failure behavior depends on temperature and loading history. This has been studied for model systems by varying the temperature and loading rate in constant cross-head speed experiments. If the toughening in viscoelastic, however, the fracture energy should depend not just on loading rate but on the complete load history. Constant cross-heads tests are only one very specific kind of history. To examine this problem in a more general way, tests were performed here using four different types of loading. First, slow and fast constant cross-head speed tests were conducted to establish a baseline. Second, a series of samples were loaded

at a slow cross-head speed, but prior to failure, the cross-head speed was shifted to high. By varying the point at which the speed change occurred, the influence of various parts of the loading curve could be judged. The third set of tests was similar to the second except that the samples were loaded at slow speed to a particular point, and then the cross-head displacement was stopped. After a given hold time, the sample was loaded to failure at high speed. By varying the hold point and hold time, the effects of load level and time can be separated. In the fourth set of experiments, the initial part of the loading history was similar. The samples were loaded to a given level, and then the displacement was held fixed for a 1h.

Rather than loading the samples to failure, however, the samples were unloaded and allowed to recover before being loaded rapidly to failure. This made it possible to examined consequences of unloading. The results from all four types of experiments could be qualitatively explained with a simple crack blunting model involving viscoelastic response of the material.

Keywords: toughening, fracture, viscoelasticity, epoxy

Viscoelastic and Nanogeometry Effects in Carbon Nanotube-Reinforced Polymers

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We investigate the effects of nanotube curvature on the modulus of carbon nanotube-reinforced polymers. Recent experimental results suggest that substantial increases in the modulus of such materials can be attained through the addition of very small amounts (1carbon nanotubes as a reinforcing phase. In addition, microscopic images of nanotubes dispersed within a polymer show that they tend to exhibit significant curvature. Here we develop a preliminary model that incorporates curvature effects into micromechanical analyses of carbon nanotube-reinforced polymers. An analytical model describing the decrease in effective reinforcement as a function of nanotube curvature will be presented. This model will be compared to the results of a finite element analysis and to experimental data.

Because there is significantly more surface area per unit volume fraction of inclusion in the case of CNRPs (in comparison to traditional carbon fiber composites), the presence of nanotube reinforcement may drastically impact the viscoelastic response by influencing molecular mobility on the atomic scale. To study the impact of nanotube-polymer interaction on the viscoelastic behavior of CNRPs, we will present results of both DMA and in-house creep experiments of blank and nanotube-reinforced polymer materials. These experimental results will then be used to identify those aspects of current viscoelastic models that will need to be adapted for use with CNRPs. Preliminary modeling of these results will also be presented and the implications of incorporating nanotube-polymer interactions into mechanical/viscoelastic models, will also be discussed.

TIME DEPENDENT FAILURE PHENOMENON

In Honor of
Professor H. Brinson and Professor A. Cardon

SESSION R3G
Design and Structural Issues

Design for Durability: Three Examples of Practical Design Approaches for Composite Structures

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This paper reviews three examples, providing practical design and manufacturing ideas for durable composite structures. The examples illustrate the transition process from applied research to commercial products. The NSF-powerpole example illustrates the ability to form tubular structures with varying cross-section, on the basis of straight pultruded sections. The wind turbine blade example illustrates the power of thermoplastic composites in forming and joining complex surfaces. Finally the GIFT housing example illustrates the quick assembly of rugged structures, which have been designed to have substantially more staying power when subject to earthquakes and natural disasters.

Keywords: Design, Durability, pultrusion, commercial products

Fatigue Performance of Glass-Reinforced Composite Springs for Automotive Applications

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Composite materials in leaf springs applications offer many advantages: weight reduction, tailored properties,

low dynamic stiffness. As well weight reduction(200-250 kg on a semi-trailer), composites springs are suitable for "road-friendly" suspensions design. There are important issues which have to be addressed, especially in relation to fatigue performance and long-term durability. Maximum working bending stresses of the order of 500 MPa represent about 40materials and springs must survive about 300,000 full-load cycles. They are very thick components, with a number of implications on design, manufacturing and fatigue performance. Interlaminar shear stresses are quite significant and manufacturing techniques need to be optimised to achieve consistent high-quality components. Defects such as porosity, poor fibre wet-out and resin-rich areas will have an effect on interlaminar shear strength and hence on long-term fatigue properties. Additional complications arise from the curved shape of the leaf springs, which introduces through-the thickness normal tensile stresses, and from the current mechanism for clamping the spring to the axle. This is essentially due to the fact that manufacturers of suspension systems wish to keep the current clamping arrangement to allow metal and composite springs to be interchangeable. However, clamping introduces additional interlaminar shear stresses which, added to those arising from bending, do present a challenge in terms of durability and fatigue.

The presentation will illustrate how the design, materials and time-dependent performance issues have been addressed and solved, providing minimum strength levels in bending, tranverse tension and shear to ensure an acceptable component life.

Keywords: leaf springs, fatigue, automotive, shear stresses

The author wishes to thank Eureka and DTI for financial support to the project.

"Rubber-Band" Behavior of PA Materials

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It is well known that rubbers shrink when they are exposed to an elevated temperature, and elongate when they are cooled back to the reference temperature. This, so called, "rubber-band" behavior is typical for all cross-linked polymers. It results from the thermally induced oscillations of molecular segments around the cross-links. The thermoplastic polymers do not show this kind of behavior. When heated they elongate, and when cooled they shrink, similarly as all common materials. In this paper we show that the "rubber-band" behavior may be also observed in oriented PA materials, and may be used as a measure of the level of the mechanically induced higher-order structure, typically observed in fibers.

Rate Dependent Behavior of Plastic Materials in Crash Simulation

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To shorten the vehicle development cycle and yet to meet stringent safety regulations, auto designers increasingly rely on crash simulations via nonlinear finite element analysis. In a modern vehicle, the parts in direct contact with occupants, such as the door trim, instrument panel and knee bolster, are often made of plastics. To accurately predict the injury level of passengers in crash scenarios, these parts need to be modeled into details and a constitutive relation capable of describing both small and large deformation up to rupture is preferred.

In crash simulation, a serious concern for plastics is the viscoelastic effect. Plastics generally demonstrate stronger strain rate effect than metals and their rate effect demonstrates not only in the yield strength, flow curve but also in the modulus of elasticity and the failure strain. Additional difficulties presented by plastics include the pressure effect on yield, the softening exhibited in tensile stress-strain curves and adiabatic heating at intermediate strain rates.

This paper investigated the material modeling capability of LS-DYNA and its application in Federal Motor Vehicle Safety Standard (FMVSS) 201 simulation. It was found that the simulation results were sensitive to the rate dependence of the yield stress, the Young's modulus and failure strain. Modeling the rate dependence of these properties was essential to capture the timing and extent of failure. The yield criterion had relatively small effect on the response. This may be due to the fact that the part was modeled by shell elements where the state of stress is bi-axial.

Keywords: plastics, strain rate, constitutive modeling, crash simulation

Symposium on Turbulence in Chemical Processing

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TURBULENCE IN CHEMICAL PROCESSING

In Honor of Professor Robert S. Brodkey

SESSION W3D

Some Important New Experimental Observations on Surfactant Drag Reduction

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Starting in the 1950's, research and development studies on turbulent drag reducing additives focused on high polymers which are now widely utilized in pipeline transport of hydrocarbon liquids such as crude oil. However, high polymer drag reducing additives degrade irreversibly when subjected to shear, such as in passing through a pump, and therefore they are only suitable for "once-through" systems. In the past fifteen years, drag reduction research emphasis has shifted to surfactant drag reducing additives because of the "repairable" self-assembly nature of these systems after mechanical degradation which permits them to be used in recirculation systems such as district heating and district cooling systems.

Some unexpected behaviors of surfactant drag reducing systems will be presented such as a new lower limiting friction factor asymptote and a new steeper limiting mean velocity profile asymptote compared to the well known high polymer asymptotes, zero turbulent Reynolds stress profiles in highly drag reducing systems, the influence of counterion chemical structure on drag reduction, rheology and microstructures of cationic surfactants and the effect of shear on surfactant microstructure. The questions of whether viscoelasticity, high extensional viscosity and threadlike microstructure are necessary requirements for a surfactant solution to be drag reducing are also addressed.

Keywords: turbulent surfactant drag reduction, mean velocity profile, drag reduction asymptote, rheology, microstructure

The Turbulent Velocity Field in a High Speed, In-Line Rotor-Stator Mixer

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Rotor-stator mixers are broadly employed in chemical processes to produce emulsions, dispersions, multiphase gel networks, etc., and to control particle size. Despite their widespread use, there is almost no fundamental basis by which to theoretically predict or experimentally assess their performance. As a result, process development, scale-up and operation are often by trial and error, leading to increased processing costs, start-up problems and lost time to market. Our goal is to develop a fundamental understanding, at least on a mechanistic basis, of the controlling fluid dynamics for single and multiphase processes We will present our approach to this broad and ill-defined problem, and will emphasize the strong interaction among theory, simulation, experiment and intuition that is needed to make progress.

We will present our work to understand the turbulent flow field within a continuous, in-line, slotted rotor-stator device. Sliding mesh computations have been performed with FLUENT, over a full 360 degrees of rotation, in order to determine the effect of both rotor-stator and volute geometry. Both two dimensional RANS and three dimensional LES simulations have been performed. To test model performance, a flow loop has been constructed in which two color LDA measurements were obtained, in water, in the stator slots and volute. Furthermore, when possible, data were acquired in the rotor-stator gap. Both fixed and rotating frame data were acquired. The latter required synchronization of the LDA output with that of a shaft mounted optical encoder. The LDA data and CFD model predictions will be compared and the effect of the controlling fluid dynamics on process performance will be discussed.

Keywords: LDA, CFD, rotor-stator mixer, RANS, LES

3-D Laser Anemometer Measurements in a Labyrinth Seal

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The flow field inside a seven-cavity labyrinth seal with a 0.00127m clearance was measured using a 3-D laser-Doppler anemometer system. Through the use of this system, the mean velocity vector and the entire Reynolds stress tensor distributions were measured for the first, third, fifth and seventh cavities of the seal. There was one large recirculation region present in the cavity for the flow conditions tested, Re = 28,000 and Ta = 7000. The axial and radial mean velocities as well as all of the Reynolds stress terms became cavity independent by the third cavity. The azimuthal mean velocity varied from cavity to cavity with its magnitude increasing as the flow progressed downstream.

Keywords: LDA, labyrinth seal, Reynolds stresses, velocity patterns

Motion of Bubbles in Turbulent Tubulent Flows: Size, Shape and Directional Distribution

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Bubble column reactors are widely used in the chemical industry and in majorityof the cases, the flow is turbulent. The complexity of fluid motion is responsible for the present relatively poor status of knowledge about the mixing in bubble columns. In order to understand the hydrodynamics of mixing in systems, where the gas-liquid interface is of most importance and contributes significantly to the overall performance of the reactor, it is desirable to understand the motion of the gas bubbles in turbulent flows. In these studies, an attempt has been made to discern the possible relationships between the distribution of bubble rise velocity vectors, sizes and their directional distribution in turbulent flows in detail.

LDA, being a non-intrusive velocity measurement technique was used for the characterization of two-phase bubbly flow in a cylindrical bubble column of 150mm i.d containing tap water. A 150mW Argon-ion laser was the source. Simultaneous 2D measurements of instantaneous axial and radial velocity components (u and v, respectively) were made in forward scatter mode at 100 different axial and radial positions in the column for sufficiently longer time at superficial gas velocity of 20mm/s.

The data was systematically preprocessed for denoising through multiresolution analysis of the local flow field (Kulkarni, et al., 2001) and the bubble events were identified by the method of cross-correlation (Deshpande et al. 2000). The level of local turbulence was confirmed by estimating the local flatness factor (FF>3). The data was then processed for the estimation local hydrodynamics parameters. The motion of a bubble in dispersed phase flows is governed by a multitude of factors associated with the viscous and turbulent effects that will render it fully three dimensional and hence multidirectional. The 2D velocities measured simultaneously for all identified bubble were used for the estimation of the magnitude as well as the direction of resultant vector and the bubble slip velocity vectors (u_s and v_s). The magnitude of resultant velocity vector was used for the estimation of equivalent bubble diameters for tap water (Nguyen, 1998) and the bubble shapes could be calculated on the basis of dimensionless numbers (Re, We, Eo, and Ta). Similar procedure was repeated for the 2D 'v' and 'w' data to realize the bubble motion in 3D on the assumption that the flow is statistically frozen.

The results yielded radial variation in the local bubble number distribution. Since the actual bubble rise velocity (i.e. slip velocity) is a function of the bubble size, the probability distribution of rise velocity represented the size distribution as well as the shape distribution, which varied spatially. In the central region of the column the observed directional distribution of bubbles was close to Gaussian distribution with some distorted features towards the wall. On a gross scale, the results showed that the velocity vectors corresponding to larger bubbles always followed a trajectory close to vertical, while smaller bubbles followed the flow field. The estimated local Reynolds normal and shear stresses were further related to the local bubble dynamics.

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Keywords: turbulent bubbly flows, LDA, size distribution, directional distribution, bubble shapes

LES/PIV of Flow in a Stirred Tank with Rushton Turbine

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Here we report on the detailed stereoscopic PIV measurements of the flow inside a stirred tank stirred with a Rushton turbine and corresponding computational results from large eddy simulations performed using a spectral multi-domain technique. The computations were driven by specifying the impeller-induced flow at the blade tip radius, which was obtained from the stereoscopic PIV measurements made in the immediate neighborhood of the impeller. A theoretical model of the impeller-induced flow has been developed in defining the mean impeller-induced flow as a superposition of circumferential, jet and tip-vortex pair components. Time dependent perturbation of the impeller induced flow away from the mean are represented in terms of POD modes. The improved impeller-induced inflow as boundary condition allows for the development of tip-vortex pairs in the interior of the tank. Both dynamic Smagorinki and dynamic mixed models are considered. It is observed that the jet component of the impeller-induced flow becomes unstable and shows signs of both sinuous and varicose behavior. The vortex pairs are well anchored near the blades, but as they extend outward into the tank their backbones exhibit time-dependent fluctuation. The instability of the jet is intimately connected with the fluctuation of the tip-vortex system. Detailed comparison with the experimental measurements in the interior of the tank is provided. The detailed experimental results from tanks of two different size, over a range of Re, are also used to obtain the scaling behavior of the mean flow (the circumferential, jet and tip vortex components) and the fluctuation (the POD modes).

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TURBULENCE IN CHEMICAL PROCESSING

In Honor Of Professor Robert S. Brodkey

SESSION W4D

An Investigation of Hydrodynamic Interactions within Glove Line Leaching Tank

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Computational Fluid Dynamic (CFD) models were employed to study the hydrodynamics interactions of the glove forms in typical glove leach tanks. Leaching tank hydrodynamics are believed to be a key factor in relating product defects with the process operating conditions, such as the line speed, glove orientation and water flow rate. The problem was divided into several smaller domains. First, the water inlet jets were simulated to understand the effect of these jets on the flow in the tank straight section. Second, the flow around a single submerged glove was modeled. Third, the transport of ions around a glove was simulated. Fourth, the surface waves around the glove cuff were simulated using a Volume-of-Fluid (VOF) technique. Finally, flow interactions around ten glove forms were studied in a leach tank straight section. Various glove orientations were considered. Leaching efficiency is dependent on local surface shear, turbulence level, and local ion concentration. The simulation predicts downward pressure on the cuffs of the gloves as a result of the surface wave. The resultant downward shear force increases with glove line speed and could contribute to cuffs sliding down at higher line speeds. Suggestions based on modeling results have been proposed to solve the production defects and improve leaching efficiency and uniformity

Keywords: CFD, leaching, mass transport

Turbulent Micromixing in Systems with Complex Chemistry

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The work described here is motivated by the need for micromixing models to describe the interaction between turbulence and chemistry in systems where pollutants and undesirable by-products are formed. Models of turbulent mixing in systems with complex chemistry are reviewed, and some that are used to predict turbulent micromixing rates are examined using direct numerical simulation of the turbulence at R_λ of 30 for non-premixed constant density flows. Among the models examined is that proposed in the pioneering work of Brodkey and Lewalle.[1] Unfortunately it is found that moment-closures of reaction rate terms in the Reynolds-averaged transport equations behave poorly for multi-step reactions.

Stochastic models of probability-density-function based theories are more promising. A comparison of the IEM (interaction by exchange with the mean) model with the Beta Mapping Closure[2] shows that both are satisfactory under conditions of equal-volume mixing when the time scale of the mixture fraction variance matches the DNS data. Additional DNS studies are needed to examine the case of non-equal volumes of initially segregated reactants.

Keywords: turbulence, mixing, stochastic models, reacting flows

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[2] K. Tsai & R.O. Fox, *Phys. Fluids* 7, 2820 (1995) and IEC Res. 37, 2131 (1998)

The Application of the Spalart-Allmaras Turbulence Closure Model and GLS Finite Element Method for Predicting Stirred Tank Flows

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The computational fluid dynamics (CFD) package, ORCA, uses a Galerkin least-squares (GLS) finite element technology and the Spalart-Allamaras closure model for solving the RANS equations. The numerical technique used within ORCA has been proven accurate in the context of stirred tank reactors (Zalc et al. 2001) and is tested and discussed in turbulent stirred tank reactors.

The basis of the CFD solver, imbedded within the ORCA CFD package, is a Galerkin finite element formulation. This formulation is insufficient to yield a stable solution for the incompressible Navier-Stokes equations because of the inherent instabilities arising from the continuity equation and the convective term in the momentum equations. However, least-squares operators are added providing rigorous mathematical stability and convergence without sacrificing accuracy. This formulation minimizes the error of the approximating functions, while satisfying the all conservation equations locally on the elements and globally on the entire system, while maintaining system stability. Conservation principles are specifically formulated and solved. The GLS formulation provides the basis of the confidence, robustness, accuracy, convergence, and stability of ORCA, providing 4^{th} order accuracy with respect to the spatial discretization, and 2^{nd} accuracy order in time.

The Spalart-Allmaras turbulence closure model is used to solve the RANS equations. This model has been widely used in the aerospace and automotive industries. In many cases involving boundary layers and jet flows, the Spalart-Allmaras model has been shown to be more accurate than the k-ε models (Bardina et al. 1997). The Spalart-Allmaras is a one equation turbulence model that solves directly for the eddy viscosity ($\square_t$ transport within the turbulent Reynolds stress (ε_{tij}) equation (Turbulent Reynolds Stress: $\tau_{tij} \propto \mu_t$ Eddy viscosity model: $\mu_t = \rho\tilde{\nu}f_{\nu 1}$). Here $\tilde{\nu}$ is an eddy kinimatic viscosity variable and $f_{\square 1}$ is function of the Spalart-Allmaras model (Bardina et al. 1997). Spalart-Allmaras model is different because it only solves for one closure compared to the k-ε and k-ε that require solving for two closures. Also, different characteristic transport functions are applied for different flow characteristics.

Due to the recent application of the Spalart-Allmaras Closure model and the GLS Finite element CFD for simulating stirred tank flows, a base validation is presented for an axial impeller in a turbulent flow. The three dimensional wall jet created along the baffle of the tank, as shown in Bittorf and Kresta 2001, is used as an initial basis for numerical validation. Since the wall jet acts ideally in both expansion and decay, this provides an ideal test case.

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Zalc J.M., M.M. Alvarez, F.J. Muzzio, and B.E. Arik, 2001, Extensive Validation of Computed Laminar Flow in a Stirred Tank with Three Rushton Turbines, AIChE J., 47, 2144-2154.

Keywords: CFD, turbulence closure, finite element, mixing tank flows

Numerical Simulation of a Turbulent Mixing Tank Using an Embedded Boundary Approach Within a Structured Cartesian Grid

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Mixing tanks have a fundamental importance in the Chemical Process Industry. Most attempts to model these have been using multiple moving unstructured meshes (as in Fluent). We present an embedded boundary method for the modeling of the fluid-continuous solid interaction present in a stirred tank. This approach has the advantage that the CFD calculation can be performed in a purely Cartesian frame of reference, leading to efficiencies both in mesh generation and in the solution of the resulting equations. The complex shape of the impeller and its interaction with the fluid are captured by using a CAD package to accurately model the geometry of the impeller, and then projecting that geometric information on to a Cartesian mesh with cut cells. Accurate subgrid models are used to realistically calculate the momentum and energy fluxes between the impeller and the fluid.

We will present calculations for a Rushton blade, with both laminar and turbulent flows. For turbulent flows, large-eddy simulation (LES) is used. We are currently working on improved sub-filter models for momentum exchange between the blade and the fluid using accurate geometry information for the cut cells, such as area fractions, volume fractions, and surface normals.

Keywords: CFD, mixing tanks, embedded boundary method, subgrid models

Being Well Over Seventy, This Is What I Still Would Like to Do

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We still lack an unequivocal validation of computer fluid dynamics (CFD) for full-field, time-resolved, velocity vector measurements. We need to ask some questions:

1) What is really needed to demonstrate a full validation for the velocity vector field?
2) Can we assume that codes are valid if they can reproduce averages of velocity for one or more dimensions in time and space?
3) If the answer to question 2 is in the negative, what else should we be looking at?
4) Can we assume that instantaneous flow fields are reproduced, as required by complex kinetics, if we just validate using averages?
5) Can we even expect to calculate meaningful instantaneous flow fields, let alone validate them?

The answer to the first question remains open. To date, no one has *fully* validated any turbulent computational effort. This is a result of the inadequacy of both the modeling and the completeness of the experimental data. Even the best direct numerical simulations (DNS) for the simplest of geometries (channel flow) at modest Reynolds numbers have not been fully validated. We don't have experimental data that exactly correspond to the computations.

The answer to the second question is negative. The simplest numerical approach is the Reynolds average Navier-Stokes simulations (RANS) and for this, the answer is certainly no. Even for the most elaborate DNS, we can come close for the distributions of one or more components of the average velocity and rms values. When the rms distribution is added, rarely is more than one component found to check well. Higher-moments validations (skewness, and flatness measures) are almost nonexistent because of the lack of experimental data. Only when we can begin to check higher order moments, that are far more sensitive to modeling assumptions, will we gain a better degree of confidence that our codes are valid (question three).

Most phenomena of interest to us are not fundamentaliy based on the average. For example, selectivity in chemical reactions depends more on when molecular interactions occur. In operations of this nature, dynamics are more important than long-time averages. It has been long known that the average flow field in a mixing vessel is never observed on an instantaneous basis. Should

one be surprised that selectivity in such vessels is difficult to compute? Clearly, validations using averages is no guarantee that we can reproduce dynamics (question four). The dynamics of flow can be averaged, but there are many scenarios in the time domain that can result in the same average.

It is suspected that the Navier-Stokes equations are chaotic and one should not expect computations to track experiments in the time domain, except for very short times. What is meant by very short is not clear. Does this mean that even highly resolved DNS calculations have no counterpart in reality? I don't think so! Such calculations are one of an infinite number of possible realizations that can be obtained from an infinite set of initial conditions. The question is really one of how chaotic is the flow. The question remains: is this time short when compared to the residence or turnover time of the flow?

Keywords: CFD, turbulence structure, validation, chaotic flow

Symposium on

Research and Education in Experimental Mechanics

In Honor Of
Professor J. Dally

Organizer:
Professor W. Fourney
(University of Maryland)

Research and Education
in Experimental Mechanics

In Honor of Professor J. W. Dally

SESSION M3M
Optical Methods I

Real-Time Full-Field Optical Measurement Methods for Experimental Mechanics

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It is important to measure distributions of height, displacement, stress or strain of structures in real-time. Optical methods such as moiré, moiré interferometry and photoelasticity can measure full-field distributions of the above values. In order to obtain accurate results from the grating or fringe patterns obtained by these methods, phase shifting methods are useful. In this paper, some new phase shifting methods proposed by the authors are introduced to measure full-field distributions of the values in real-time.

Firstly, shape measurements by moiré topography using a Ronchi grating or an interferometric fringe pattern with a cosinusoidal brightness distribution are introduced. By using the integrated phase shifting method proposed by the authors, shape measurements of various objects such as an electronic bulb and a human face are performed in real-time, as shown in Fig. 1.



Fig. 1 Shape analysis of face including inside of mouth

Secondly, flatness distribution analysis by the integrated phase shifting method using Twyman-Green interferometer is introduced. An analysis of nano-scale displacement distributions produced by thermal deformation of a micro-accelerometer fabricated by micro-machining is demonstrated.

Thirdly, a new method for simultaneous real-time measurement of two-dimensional displacement components obtained by four-beam moiré interferometry is proposed. Two moiré fringe patterns for both of two displacement components are recorded in a single image. The phase distributions representing both displacements are separated and obtained from a series of 12 images by adopting simultaneous phase-shifting for both directions.

Lastly, the integrated phase-shifting method for photoelasticity is developed. By rotating an analyzer at a constant rate and an output quarter-wave plate at a double rate of the analyzer and recording images by a CCD camera continuously, sequential six phase-shifted images are obtained. The separation and phase analysis of isochromatics and isoclinics of photoelastic fringe patterns are performed from the six images.

Keywords: Real-time, shape analysis, moir interferometry, photoelasticity

Observations on Crack Growth From from Frozen Stress Models of Complex Shapes

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Around 1965, it appeared to the writer that a need existed for a laboratory based experimental method for providing a cost effective code verification method for the many numerical solutions being developed for 3D crack problems within the scope of LEFM. By creating a marriage between the frozen stress photoelastic method and the Griffith-Irwin Equations of LEFM [l] already applied to two dimensional cracked photoelastic models [2], the writer and his colleagues were able to measure stress intensity factor (SIF) distributions for a variety of 3D cracked body geometries [3]. Many improvements have been added from both the numerical and experimental sides since that time. It is the intent of this discussion to focus upon some general observations resulting from these studies which appear to be consistent for cracks growing stably in homogeneous, isotropic materials in 3D problems. Unless otherwise noted, the crack growth appears to follow high cycle fatigue crack growth. Since most of the experimental details are documented in [4], we shall proceed to a discussion of the observations mentioned above.

It was well know that, when a fatigue crack grew in a finite plate under Mode I loading, the aspect ratio varied during growth. By studying SIF distributions before and after growth photoelastically, it may be concluded that the first growth will occur at greatest SIF, after which the SIF at the point of growth is relatively reduced but may be relatively increased at nearby locations along the crack border with increased load resulting in a change in crack shape.

When a mixed mode load is applied to a planar, part-through crack, the crack will reorient itself to try to eliminate Mode II. In ideally brittle materials, a sharp kink results in order to restore Mode I. For most materials however, the change in direction is more gradual during which the shear mode is reduced, resulting in a Mode I dominated growth in a new direction. If a part-through planar crack is loaded in Mode I along part of its border, and with a mixed mode along another part of it's border, the part loaded in pure Mode I grows in the same plane as the original crack plane but the mixed Mode part traverses a curved path after reorientation. However, all of the growth is Mode I dominated. During growth, the point on the crack border where the planar part joins the part of the crack representing a curved surface is at first a local discontinuity along the flaw border, with SIF values along the flaw border peaking here. However, as the crack grows, a rather rapid reshaping of the crack border occurs, eliminating the discontinuity in the crack front, and moving the maximum SIF to the intersection of the curved part of the crack with a free boundary.

Whenever a part through crack reorients itself to reduce the shear mode, the reorienting process begins at the point of highest combined SIF and spreads over the entire crack front as growth occurs in the new direction. The shear mode diminishes towards zero as the new growth direction is found.

The above observations will be illustrated in the paper after which certain conclusions can be drawn;

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Keywords: fracture mechanics, photoelasticity, fatigue, mixed mode

Measurement on the Acoustoelastic Effect of Lamb Waves Using Laser Ultrasound Technique

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In this research a laser ultrasonic technique (LUT) is used to investigate the acoustoelastic effect on the dispersion relation of Lamb waves propagating in stainless steel plates. Acoustoelastic effect is the stress or strain induced change in the wave propagation speed in an elastic body.

Lamb waves are guided acoustic waves propagating in flat plates. The LUT technique uses a Q-switched Nd:YAG pulse laser for thermoelastic generation of acoustic waves. While propagation along the plate, the acoustic modes are detected with another set of laser system. With the generation laser scanning along the propagation direction of the Lamb modes, a B-scan data can be obtained. Using a two-dimensional fast-Fourier transform signal-processing scheme, the dispersion relations of Lamb waves propagating in the plates are determined. A loading frame with load-cell is used to apply axial tensile stress on stainless plate samples of 0.95 mm. Dispersion relations for Lamb modes propagating parallel and perpendicular to the loading directions are both measured. For both these two directions, very small reduction of Lamb wave speeds is observed due to the acoustoelastic effect. Finally, the acoustoelastic coefficients are measured with the LUT.

Thermoelastically-Measured Isopachics and BEM for Inverse Stress Analysis on and Adjacent to Loaded and Traction-Free Boundaries

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Thermoelastic stress analysis (TSA), partly because of its ease of application and availability of point-by-point, line-scan and full-field output, is an effective, noncontacting method for stress analyzing actual components. However, measured TSA information can exhibit appreciable scatter, and recorded temperature data on and adjacent to the edge of a component is typically unreliable. This hampers ability to even adequately evaluate stress concentration factors. Moreover, most available techniques for acquiring reliable TSA data on an edge, say from distant TSA information, either involve mapping techniques, can be numerically unstable, or are restricted to a traction-free edge[1-4]. Predicting reliable edge temperatures from measurements away from the boundary constitutes an inverse problem. The quality of the results of inverse analyses are often quite susceptible to fairly small variations (e.g., scatter) in the input values. The boundary element method (BEM) enjoys advantages relative to the situation, among these being that it is the boundary values that are sought by this approach. In particular, by commingling input temperature information away from the edge with BEM concepts, the ability to determine stresses reliably on, and in the neighborhood of, loaded or traction-free edges of cutouts is demonstrated here. This capability is greatly aided by the present development of a regional boundary element which consists of three quadratic boundary elements and six nodes. Mapping techniques are not used. Experimentally, two-minute, 320 by 256 pixels TSA scans are employed.

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Keywords: Thermoelastic Stress Analysis, Hybrid Stress Analysis, Inverse Problems, Boundary Element Methods

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Experimental Verification of Moiré Hole Drilling to Obtain Material Elastic Constants and Residual Stresses

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The use of the **moiré hole drilling method** in a homogeneous, isotropic infinite plate with a through hole allows, using a single optical image, the solution of two inverse problems. One is the hole drilling or residual stress inverse problem, while the other is the pre-existing hole inverse problem which allows obtaining material elastic constants, i.e., the modulus of elasticity and Poisson's ratio, simultaneously. Up to the present time no experimental verification of the moir hole drilling method has been presented. Thus, the purpose of this paper is to present

results that experimentally verify the solution to the moir hole-drilling problem in all its possible manifestations.

The approach taken to solve this problem uses an over-deterministic method, using large amounts of fringe-order information from anywhere in the displacement field, away from the edge of the hole and the axes of symmetry, to solve both of these inverse problems. Three approaches with an incrementally increasing level of difficulty are addressed: The **first** considers the case where the alignment of the principal stresses coincides with the coordinate axes and the moiré gratings used to measure horizontal and vertical displacements; the **second** concerns itself with misalignment of the principal stresses relative to the aligned coordinate axes and the moiré gratings; while the **third** deals with misalignment of both principal stresses and moiré gratings with respect to the coordinate axes.

Research and Education
in Experimental Mechanics

In Honor of Professor J. W. Dally

SESSION M4M
Optical Methods II

A Mathematical Model for Random Bundle Illumination in Electronic Holography

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The practical use of electronic holography requires the use of optical fibers as components of the illumination system. The use of monomode polarization preserving fibers presents a restriction in the efficient use of the light energy. To overcome this obstacle multimode fibers have been used. There are a large number of papers written on this subject. The use of random fiber bundles to record patterns is a step further in the efficiency of light intensity use and simplicity in the optical set up. The use of fiber bundles provides an efficient use of the light since it is very easy to input the laser power to a fiber bundle. Although there are losses, the packing efficiency of the fibers is very high, 92%, and losses due to reflection and scattering are similar to the losses of other fiber systems. Furthermore bundles can be used to split and reshape the input configuration. Fiber bundles can be bifurcated and trifurcated simplifying beam splitting.

The question to be answered is: can fiber bundles be used to record electronic holograms? The answer is yes. Of course there are some limitations that must be mentioned.

To understand the image formation process of holograms recorded with fiber optics illumination a simple mathematical model has been developed. The basic assumption in this model is that the fibers are randomly distributed. We have a large number of partially coherent point sources. It is also assumed that the laser energy is launched with a small angular aperture and that most of the energy is concentrated in the fundamental mode of the fibers making up the bundle. It is also assumed that the distance between the fiber bundle end and the illuminated surface is very large when compared to the size of the bundle. Each fiber produces a wave-front and since the distance between the source and the surface is very large, the plane wave-front approximation can be used. The images of these random sources are received in the sensor through reflection and diffusion on a rough surface. A statistical analysis of the random illumination leads to an expression of the correlation size of the speckle collected on a pixel, assuming that one speckle occupies one pixel,

$$_{c} \quad A_c/A\sqrt{4A_s/}$$

In this equation A_c is an integral of the mutual coherence function between the two interference wave fronts averaged on the area A of the sensor. A_s defines the area of a speckle. This equation reduces to the ordinary definition of a speckle radius for coherent sources. The consequence of this derivation is very important, the deterioration of the fringe visibility with respect to the correlation is far more pronounced than in the case of conventional type of illumination. This is what is experimentally observed. High visibility fringes can be obtained but deterioration of visibility occurs with displacements, which are far smaller than in the case of conventional illumination. Two examples of the fiber bundle illumination are shown. In plane displacement interferometer arrangement is used for static loads, and out of plane displacement measurement is done for vibrating turbine blades. The quality of the fringe patterns observed is very good in both cases.

Keywords: electronic holographic interferometry, speckle interferometry, random fiber bundle illumination.

Photoelastic Analysis of Reinforcements of Plates with Superficial Defects

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Dally and co-authors modeled the effect of patch reinforcements applied to the skin of pressurized fuselages that were cracked in service. The patches are bonded to

the cracked skin with adhesive and bridge the crack to effect the repair. In that study a low birefringent material was used to simulate the patches which were bonded over the cracked regions of polycarbonate plates. Neglecting the photoelastic response of the acrylic reinforcements, the stress distribution at the cracked regions of the polycarbonate plates were studied using transmission photoelasticity. In the present paper a similar investigation is carried out using reflection photoelasticity. This technique was applied to the study of reinforcement of plates with stress concentrations caused by holes and notches. The reinforcements consisted of rectangular plane patches bonded over polycarbonate plates that were machined to introduce different geometries of defects such as holes and notches. This type or repair reinforcement is used in the heavy machine industry to repair cracks and is also common in the pipeline oil transportation industry to repair corrosion defects which are not through wall defects. To avoid Young modulus mismatch and better simulate steel reinforcement patches on steel structural components, the patches were also made from polycarbonate plates. A reflective adhesive was used to bond the patches to the notched plates. This experimental procedure allowed that a 2-D reflection photoelastic analysis could be applied to the optical responses generated by the illumination of both sides of the photoelastic models. Using this approach it was possible to take in account the birefringent response of the reinforcement and to determine the stress distributions actuating in both superimposed bonded plates, separating the stress distribution occurring in the patch material and in the reinforced region of the notched plates.

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Keywords: Stress concentration, Holes, Notches, Reinforcements, Refection Photoelasticity

Obtaining Full Field Subsurface Rayleigh Wave Displacements from Surface Measurements

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It is often possible to detect surface displacements occurring in a semi-infinite half-space due to propagation of a Rayleigh wave, by means of accelerometers, holographic interferometry or even moiré interferometry. However, these techniques reveal little or nothing about the subsurface behavior of the material. The current work addresses the problem of obtaining full field subsurface Rayleigh wave displacements from such surface displacement measurements. The point of departure is the work by Thau and Dally that examines similar Rayleigh wave behavior from the analysis of the surface isochromatics in a dynamic photoelastic sequence of images of a propagating Rayleigh wave. It is straightforward to show, given this starting point, that the same thing may be accomplished through analysis of surface displacement measurements. The full field vertical and horizontal isothetics are shown to be obtainable from such measurements.

Recent Advances in Computer Vision for Surface Deformation

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Digital image correlation is being used as a tool for the measurement of surface deformations in many fields and over a broad range of length scales. In most cases, the method measures the displacement field on a subset-by-subset basis with sub-pixel accuracy that depends on factors such as the spatial content of the image intensity data, image noise and the correlation algorithm used to obtain the displacement field.

In this work, recent data from two separate studies will be presented. First, results from an extensive investigation regarding the systematic errors caused by the method of intensity interpolation in the digital image correlation

method will be described. Using an iterative spatial domain cross-correlation algorithm for optimization, it is shown that lower order intensity interpolation functions (e.g., linear) can introduce displacement shifts and, hence, local errors in the measured strain may approach 40% of the actual values. These errors can be minimized by a combination of higher order intensity interpolating function and, in some cases, low pass filtering of the images.

Second, very recent results outlining a new method for obtaining the complete surface strain field in two-dimensional digital image correlation is described. A single B-Spline function is used to represent the object deformation field throughout the entire region of interest, with position and continuity constraints imposed directly in the solution process. Results will be presented that clearly show the proposed method is computationally efficient, accurate and robust for those cases studied.

Keywords: Digital image correlation, interpolation errors, B-splines

Electron-Beam Moiré: The Technique and Its Application to Advanced Packaging

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Electron-beam moiré is a technique designed to measure small displacements on a local scale. It was first developed at NIST in 1991 and described in a series of articles by Dally and Read (1-4). The resolution of the technique and the size of the area over which measurements are made render the technique particularly appropriate for the study of thermomechanical deformations in electronic packaging. As such, the technique has been used to quantify displacements in a variety of packages including flip-chip solder bumps, microvias in a high-density interconnect circuit board, embedded passive components, and, most recently, solder columns in a column grid array (CGA).

The technique operates on the same premise as video moiré. The raster of the electron beam in the scanning electron microscope (SEM) interferes with a crossed-line grating instrumented onto the cross-sectioned surface of the specimen, generating moir fringes (Figure 1). With a crossed-line grating, it is possible to obtain both normal and shear displacements. Changes in the fringe field due to thermal loading of the specimen are recorded and strains are calculated. Strain concentrations due to the mismatch in the coefficients of thermal expansion (CTE) of the contained materials are observed during the course of thermal cycling in order to detect when and how failures occur.

For the specific application to the CGA, electron-beam moiré was used to look for shear strain in the outermost, corner solder columns. In the package, the solder columns connect the low-expansion, ceramic-encased die to printed circuit board (PCB) without any underfill to mechanically bond the two disparate materials. The manufacturer was interested in the behavior of the materials over a temperature range from $-5°C$ to $130°C$; therefore, gratings were patterned onto the cross section at the top and bottom of those solder columns. The package was thermally cycled four times and images were collected at the temperature extremes and at room temperature for each cycle so that plastic deformation could be detected and measured if it occurred. The extreme values for normal strains were $e_{y,\,130°C} = 0.7\%$ and $e_{y,\,-5°C} = -0.2\%$ in the PCB during the first thermal cycle. Neither plastic deformation, nor shear strains were apparent during the four thermal cycles.

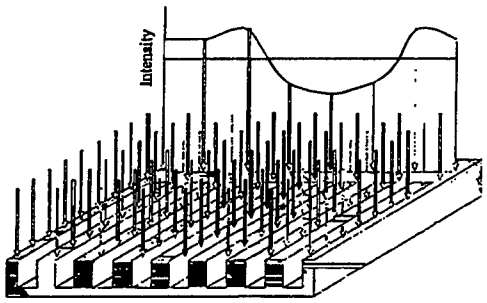


Figure 1. Illustration of how electron-beam moiré fringes are generated. The arrows represent the raster of the electron beam.

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Inverse Methods in Experimental Mechanics: Whole-Field Data

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This paper presents a method of reconstructing the complete stress analysis solution for problems using limited whole-field optical data. It is based on a wavelet (or

unit load) representation of the unknown applied loading in conjunction with a general finite element program. The incorporation of regularization terms provides a robust solution to these usually ill-conditioned problems.

One key to our approach is to take the applied loadings as the fundamental set of unknowns even if we are not specifically interested in them. This is a problem in force identification. That is, the problem of interest here is: Given some sparsely distributed measurements $u(x, y, t)$ perhaps imperfectly), and knowledge of the system function $G(x, y, t)$ (perhaps imperfectly), determine the loading $P(x, y, t)$. This problem is quite difficult for two reasons. The first is that it is ill-conditioned which means that small errors in the measurements or the modeling can cause very large variances in the identified forces. Second, most of the proposed solution methods need to know the system function in analytical form and this has meant that most of the structural systems analyzed were relatively simple. Both of these difficulties will be addressed in this paper.

It is the goal of this paper to develop a method of force identification for static and dynamic problems that is robust enough to be applied to complex structures. Furthermore, we wish to be able to determine multiple isolated forces as well as distributed pressures and tractions. The data used is to be in the form of digital images. After developing the main ingredients of the method, we illustrate its attributes using experimental data from holography, moir and photoelasticity. The sample experiments were chosen to present a range of difficulties and thus illustrate a range of attributes of the proposed method.

Keywords: force identification, inverse theory, optical methods, regularization.

Research and Education
in Experimental Mechanics

In Honor of Professor J. W. Dally

SESSION T3M
Dynamic Fracture I

Dynamic Failure of Brittle-Ductile Laminates

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The fracture behavior of a dynamically loaded edge crack in a brittle-ductile layered material, as a function of applied loading rate, was experimentally investigated. Layered specimens were prepared by sandwiching a thin layer of ductile aluminum between two thick layers of brittle Homalite-100. The layers were bonded using Loctite Depend 330 adhesive, and a naturally sharp edge crack was introduced in one of the Homalite-100 layers. These single-edge notched specimens were loaded in dynamic three point bending using a modified Hopkinson bar. The fracture process was imaged in real time using dynamic photoelasticity in conjunction with digital high-speed photography, and the applied load and load-point displacement histories were determined from the strain signals recorded at two locations on the Hopkinson bar.

The results of this study indicated two distinct mechanisms of dynamic failure, depending on the applied loading rate. At lower loading rates, the starter crack arrested on reaching the aluminum layer and then caused delamination along the aluminum-Homalite interface. On the contrary, as the loading rate was increased, interfacial delamination was followed by crack re-initiation in the Homalite layer opposite to the initial starter crack. It was determined that the times required for crack initiation, delamination and crack re-initiation decreased, as the loading rate was increased. However, it was also observed that the applied load values associated with each event increased with increasing loading rate. These observations indicate that both the dynamic failure process and plausibly the failure mode transition are affected by the rate-dependent properties of Homalite, aluminum and the interfacial bond. Finally, based on the measured peak loads and the observed failure mechanisms it was concluded that the incorporation of a thin ductile reinforcement layer can increase both the overall fracture toughness and strength of a nominally brittle material.

Keywords: brittle-ductile multilayered materials, dynamic failure, split Hopkinson pressure bar, high speed imaging.

Dynamic Behavior of Composite Materials

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Experimental methods were developed and applied for characterization of dynamic response of composite materials at strain rates up to 1800 s−1. The dynamic stress-strain behavior was determined for unidirectional and crossply laminates under compression and shear. Strain rates below 10 s^{-1} were generated using a servohydraulic testing machine; strain rates between 10 s^{-1} and 300 s^{-1} were obtained using a drop tower apparatus; strain rates

above 300 s^{-1} were produced using a Split Hopkinson Pressure Bar (SHPB). Unidirectional carbon/epoxy laminates (IM6G/3501-6) loaded in the longitudinal and transverse directions were characterized. Off-axis (15°, 30°, 45° and 60°) compression tests of the same unidirectional laminates were also conducted to obtain the in-plane shear stress-strain behavior. Crossply laminates were tested under axial compression.

In the longitudinal direction, where the fibers dominate the behavior, the modulus increases only slightly whereas the strength and ultimate strain increase noticeably with strain rate. The transverse (90°) properties, which are governed by the matrix, show an appreciable increase in modulus and strength over the corresponding static values but no significant change in ultimate strain. The shear stress-strain behavior, which is also matrix-dominated, shows high nonlinearity with a plateau region at a stress level that increases significantly with strain rate. The behavior of crossply laminates reflects that of its 0°plies and is similar to the longitudinal behavior of the unidirectional material. Failure mechanisms under dynamic longitudinal compression were studied by using a modified Hopkinson bar with a dynamic recovery apparatus. The final failure mode was fiber kinking as in the case of static loading.

Keywords: Dynamic response of composites; strain rate effects; Hopkinson bar technique; dynamic stress-strain behavior.

Failure of Unidirectional Composites Under Dynamic Transverse Loading

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Composite material structures fail in complex ways. Failure is often caused by events such as foreign object impact, which involves the dynamic loading of composite structure in a direction transverse to fibers. Therefore, the fundamental mechanisms leading to damage, and eventually to failure, need to be understood to develop analytical models, set up failure criteria and perform reliable computational analyses for structures made of composite materials. The present paper presents the results of an experimental investigation towards the better understanding of composite material response under transverse loading conditions.

Compressive response and failure mode of transversely loaded unidirectional E-Glass/Vinylester composites are investigated and reported for a wide range of strain rates from 10^{-3} to 10^{4} s^{-1}. Specimens are loaded perpendicular to fiber direction using a screw-driven materials testing system for low strain rates and a Kolsky (split Hopkinson) pressure bar for high strain rates. The results indicate that the mechanical response and the strength of composite in transverse direction is a strong function of strain rate and mainly governed by the properties of matrix material. Post-test scanning electron microscopy (SEM) is used to identify the transverse failure modes. The SEM observations suggest that macroscopic transverse failure is dominated by shear stresses and occurs within localized bands through multiple fiber-matrix interface failure at microscale. These shear dominated failure bands are found to be inclined in a direction approximately 35 degrees to the direction of loading. This deviation in the orientation of failure bands from maximum shear trajectories at 45 degrees suggests that the failure tends to occur in favored directions along which an optimum combination of frictional and shear forces acts.

Keywords: E-glass/vinylester; compressive failure; transverse loading, high-strain-rate.

Mechanisms of Deformation and Fracture of NACRE

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Natural organisms started to use biomineralization for structural purposes 550 millions years ago. Since then, through evolution, constant mechanical evaluation and selection has occurred: the resulting products (bone, ivory, tooth enamel, seashells) have remarkable mechanical properties and are starting to inspire new designs for synthetic materials.

Recently nacre has attracted much attention. Found in certain seashells, it is mostly composed of aragonite tablets (95bonded with thin organic networks (5poor structurally (aragonite is brittle, the organic phase is soft), but the micro- and nano-structure of nacre is such that its macroscopic mechanical behavior is remarkable. In tension, the sliding of the tablets along each other creates a ductile like behavior, which greatly increases the toughness of nacre and the impact resistance of the seashell. A key feature of this mechanism is the hardening of the sliding areas, so that nacre develops new sliding sites to

accommodate for the deformation. However, the hardening mechanisms are poorly understood. The ductility also increases the toughness of nacre, and as a crack advances it is bridged by the tablets, whose mechanism is similar to pull-out phenomena for fiber reinforced materials.

This work presents results of in-situ mechanical tests on nacre specimens. Quasi-static and dynamic tensile tests will be presented. Speckle correlation techniques are used to determine both longitudinal and transverse deformations. Fracture tests are also performed in both quasi-static and dynamic modes. Using the displacement field in the vicinity of the crack tip, given by speckle correlation and the tensile behavior of nacre, its local toughness is determined. In light of these results, a better understanding of deformation and fracture mechanism opens the way to tough, impact resistant, synthetic nano-structured materials.

Dynamic Crack Growth in Homogeneous and Functionally Graded Syntactic Epoxy Foams

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Syntactic foams can be distinguished from conventional foams in the way they are manufactured. They are processed by mechanically blending thin walled microballoons in different polymeric or metallic matrix materials. Porosity in syntactic foams is typically microscopic in nature and can be relatively easily controlled. They offer very attractive multifunctional characteristics such as high specific strength, energy dissipation, thermal, dielectric and acoustic insulation, to name a few. In this work, dynamic crack initiation and growth in homogeneous and functionally graded syntactic epoxy foams are studied under low-velocity impact loading conditions. First, the influence of volume fraction of the microballoons in the matrix on crack initiation and crack growth behaviors are examined in a series of homogeneous compositions. The optical method of Coherent Gradient Sensing in conjunction with high-speed photography is used for measuring transient crack tip deformations syntactic foam slabs subjected to low-velocity impact loading. The optical measurements are also used to obtain dynamic fracture toughness and crack velocity histories. Next, the influence of compositional grading of microballoons in the matrix is examined. Syntactic epoxy slabs with approximately linear variation in elastic modulus are prepared and crack initiation and growth in situations when cracks are located on the compliant and stiff sides of these graded foam slabs is studied separately. The fracture parameter as well as crack velocity histories are studied relative to the homogeneous counterparts in order to study the benefits of different types of compositional grading.

Keywords: syntactic foam, dynamic fracture, functionally graded material, optical interferometry

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Research and Education
in Experimental Mechanics

In Honor of Professor J. W. Dally

SESSION T4M
Dynamic Fracture II

High Speed, Two Dimensional, Infrared Observations of Transient Temperature Vortical Microstructures in Solids during Adiabatic Shear Banding

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The structure of adiabatic shear bands in solids has been a subject of much interest and modeling, with very little "real time" experimental evidence at hand. By using a unique infrared high-speed camera especially constructed for recording highly transient temperature fields at the microscale, we are able, for the first time, to reveal the spatial and temporal microstructure within dynamically growing shear bands in metals. It is found that the temperature distribution along the band is highly non-uniform and possesses a transient, short range periodicity in the direction of shear band growth in the form of an array of intense "hot spots", reminiscent of well known shear-induced hydrodynamic instabilities in fluids. This is contrary to the prevailing classical view which describes the deformations and the temperatures within shear bands as being essentially one-dimensional fields. The high-speed infrared imaging system used in this investigation is designed and developed to record two-dimensional thermal images at repetition rates up to one million frames per second. This system is designed to measure fast varying temperature fields of small objects (1mm × 1mm) undergoing highly transient (often adiabatic) deformations, where

heating may occur in a time scale of microseconds. Typical examples include the heating of materials subjected to high-speed impact and materials undergoing dynamic fracture or dynamic strain localization.

Keywords: high speed thermal imaging, dynamic shear banding, vorticity, dynamic fracture

Direct Observation of High Velocity Impact and Penetration in Ceramic Targets

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Ceramics such as Al2O3, SiC, TiB2 and B4C have been used in integrated armor for over a decade and are excellent prospect for the next generation multi-functional armor systems. It is necessary to understand the dynamic events involved when a high-velocity projectile impacts ceramic targets. At UCSD, we have used high-speed photography and flash X-ray radiography to document the interaction events at the front-face, back-face, and within the target when a high-velocity projectile impacts a ceramic tile. This has led to some basic understanding of the physics of high-rate failure of brittle materials. In particular, our research has demonstrated that the defeat capability of ceramic armor tiles could be considerably improved by tightly wrapping them in a thin membrane of suitable tensile strength. In this lecture we present some of our experimental results relating to the effect of thin membranes attached to the front face of Al2O3 armor tiles, on their ballistic performance. The experiments were conducted to study the comparative effect of several front-face materials, such as glass-fiber tape, E-glass/epoxy pre-preg, carbon-fiber/epoxy pre-preg, and Ti-3%Al-2.5%V alloy. Tungsten heavy alloy (WHA) was used as the projectile material. It was observed that front-face constraint imposed by a thin layer of E-glass/epoxy pre-preg resulted in a nearly 20% improvement in the ballistic efficiency for a mere 2.5% increase in areal density. The presence of the front-face thin membrane alters the failure mechanism, leading to the observed improvement. Computational simulations and micro-mechanical modeling have been used to explain these results.

Keywords: Ceramics, Impact, Failure Mechanism, Hybrid Composites

CTOA as a Dynamic Fracture Criterion

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The CTOA of a propagating crack in a pressurized 2-in-diameter, Schedule 10, carbon steel pipe was recorded with a high-speed framing camera. The CTOA was also computed using a split-ring model of the pipe, one dimensional thermal hydraulic depressurization code and the measured crack propagation history. The excellent agreement between the measured and the computed CTOA versus crack velocity relations demonstrated that the CTOA is an effective static and dynamic fracture parameter for pipe rupture. The CTOA criterion was then used in the ring model of the rupturing pipe and a thermal hydraulic depressurization code to simulate the large-scale burst tests of 48-inch diameter x 0.720-inch thick, X70 line pipes. The predicted and measured crack velocity histories were in excellent agreement.

Dynamic moiré interferometry was used to determine the CTOA of running cracks in 2024-T3 and 7075-T6 aluminum alloy SEN specimens. The SEN specimen was either fatigue pre-cracked (first series) or blunt notched (second series) for low and high crack velocity tests, respectively. Four frames of the moiré fringe patterns were recorded by an IMACON 790 camera. The framing rate was also fixed to either 10,000 or 100,000 frames per second. Multiple recordings of identically loaded SEN specimens at different delay timings were necessary to capture the entire fracture event that lasted about 1.2 milliseconds. Despite all efforts to generate reproducible tests, no two dynamic fracture tests are identical and thus the final composite fracture event was constructed with due consideration of the load-time histories and the varying crack opening profiles of each fracture test. The successive crack opening profiles associated with different tests showed the remnant of blunting of the fatigued crack tip prior to rapid crack propagation. This initial crack tip blunting resulted in the CTOA dropping from an initial high value to a constant angle of 6° and 4° for the 2024-T3 and 7075-T6 (first series) specimens, respectively, with crack extension. Identical results were observed in the static tests of these specimens. Elastic-plastic, dynamic FEA simulations of the dynamic fracture events were in excellent agreements with the experimental results. The steady state CTOA in the second series of 7075-T6 specimens was a higher 7.5°. When the CTOA is plotted in terms of the crack velocity, it passed through a minimum value at

an intermediate crack velocity of about 100 m/s. Unlike the popular gamma shape of the dynamic fracture toughness versus crack velocity relation, the CTOA of 7075-T6 specimens reached a constant value at the terminal crack velocity.

Keywords: CTOA; dynamic crack growth; moir inteferometry, dynamic elastic-plastic FEA.

Multiple Impact Penetration and the Effect of Induced Damage on the Constitutive Behavior of Concrete and Granite

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An experimental study was conducted at the University of Rhode Island to investigate the penetration process of multiple impacts into concrete targets. The concrete targets were subjected to repeated constant velocity impacts with ogive nose projectiles. The penetration and crater formation data were consistent with single impact penetration data from previous studies conducted at Sandia National Laboratories. In order to predict the depth of the multiple impact penetration, a single impact penetration model, developed by M. Forrestal at Sandia National Laboratories, was extended to account for the degradation of the target strength with each subsequent impact. The degradation of the target was determined empirically and included in the model as a strength-modifying factor. The model agreed favorably with the experimental data. However, to further understand the multiple impact penetration process and the degraded material properties of the target materials, a study was conducted to look at both the static and dynamic properties of concrete and granite as a function of induced damage.

Initially, both static and dynamic compression experiments were performed on concrete and granite specimens with various levels of induced damage. The static compressive strength of both materials decreased with increasing levels of damage due to the induced damage causing the activation and propagation of failure cracks in the specimens. In contrast, the dynamic compressive strength remained unchanged with increasing damage due to the inability of the inherent cracks to initiate and propagate to relieve the strain energy before complete specimen failure occurred. For the undamaged specimens, the dynamic compressive strength was approximately twice the static compressive strength for both the concrete and granite specimens.

A second series of dynamic and static tensile-splitting experiments were performed on concrete and granite specimens to investigate the effect of induced damage on their tensile strength. The experiments showed that the static splitting strength was highly dependent on the orientation of the induced damage with regard to the applied loading, however the dynamic tensile strength decreased with increasing damage with no apparent dependency on the random damage orientation. Photoelastic experiments have shown that the mechanism of failure changed for the dynamically tested damaged specimens, reducing their dependence on damage orientation. The photoelastic experiments also determined that the tensile splitting specimen was in equilibrium at the time of failure, and that the dynamic stress field closely resembles the static splitting stress field.

Keywords: Multiple Impact Penetration, Tensile Splitting Experiments, Dynamic Material Properties, Concrete and Granite

The Use of Fracture Mechanics and Wave Propagation in Precise Initiation Blasting

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Employing the method of Lagrange diagrams in conjunction with fracture mechanics and elastic wave propagation the author will show how to calculate the delay time for precise initiation blasting. Open pit mine blast design will be considered and the effect of short delay time initiation on fragmentation enhancement as well as vibration control will be discussed.

A very convenient and illustrative method to present the dynamic behavior associated with wave and crack propagation is to use the so-called Lagrange diagram. Longitudinal and shear waves/pulses are of importance in blasting and a full understanding is required for short time delay calculations as well as optimization of fragmentation. A stress wave is the propagation of a disturbance in space and travels in time and is characterized by finite length and duration and band width. The latter is the important parameters in the new Advanced Blasting Technology (ABT).

The paper studies wave/pulse interaction between the blastholes in the light of fragmentation improvement. Within the framework of ABT the role of superposition of various waves in causing the crushing of the material, the interaction between any type of stress waves and cracks that radiate from a blasthole and a crack which emerges

from an adjacent blasthole will be applied to fragmentation blasting. In ABT optimal fragmentation requires the formation of a uniform fragmentation pattern around and between the blastholes during sequential blasting. If the delay time between the blastholes in a row and between rows is selected appropriately, the result will be close to uniform with a narrow band distribution of fragments. Non-ideal delay timing will result in an increased number of large boulders left for secondary fragmentation. Optimization of fragmentation in a general blast pattern design is not a trivial matter and requires the study of the interaction of more than just two adjacent blastholes and leads to con-commutative evolution of fragmentation.

Further generalizations of the method of Lagrange diagrams to include the effect of jointing and faulting and the application to bench blasting will be explained and demonstrated in the presentation.

Keywords: fracture mechanics, blasting, wave propagation, Lagrange

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Research and Education
in Experimental Mechanics

In Honor of Professor J. W. Dally

SESSION W3M
Micromechanics

The Read-Dally Thin-Film Tensile Specimen

W.N. Sharpe, Jr.

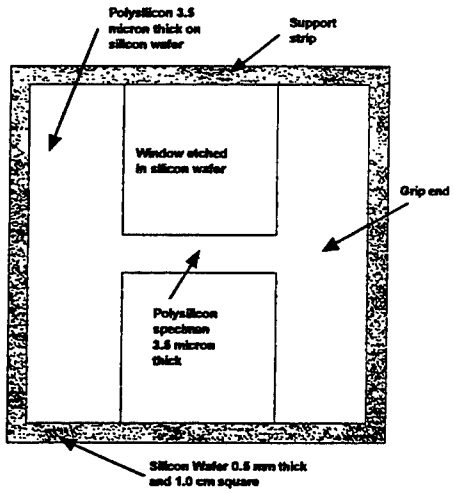
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Mechanical testing of thin metal and ceramic films is quite different than the testing of familiar structural materials. One cannot machine a specimen from the bulk material and put it into a set of grips. Most thin films are produced by deposition onto a substrate, and one must incorporate the specimen and the substrate to obtain a tensile specimen.

During a sabbatical at NIST-Boulder, Jim Dally worked with David Read to develop a new approach to preparing, handling, and testing thin films [Read and Dally, "A New Method for Measuring the Strength and Ductility of Thin Films", Journal of Materials Research, 1993].

The approach is to deposit, using photolithographic methods, the test material in the shape of a tensile specimen with a gage section and two large grip ends. A rectangular window is etched from the backside of the wafer to create a frame across which the tensile specimen extends. The frame is designed with two narrow support strips parallel to the specimen. The grip ends are glued into a small test machine (the Read-Dally device is a very clever one in its own right). Once the glue is cured, the two narrow support strips are cut to leave a single tensile specimen that is completely free.

This author and his colleagues have adopted their approach and used it extensively to test polysilicon, silicon nitride, and silicon carbide films that are 600 microns wide, and 4 millimeters long. These films range in thickness from 0.5 to 40 microns. The schematic at right shows the arrangement for polysilicon film testing. Biaxial strain is measured directly on these specimens by laser interferometry from two sets of reflective markers. This has led to accurate measurements of Young's modulus, fracture strength, and Poisson's ratio. The Read-Dally specimen has been a central feature of an extensive and long-running research program at Hopkins on the mechanical properties of MEMS materials.



Other researchers have also capitalized on this inaugural work, and the use of the Read-Dally tensile specimen will be reviewed in this presentation.

Keywords: thin film, tensile testing, polysilicon, silicon nitride, silicon carbide

Progress in Microtensile Testing

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Thin films are an essential component of all advanced electronic devices. Understanding and modeling of potential failure modes in these devices, especially interface de-

lamination, requires knowledge of the mechanical behavior of the films. Because the films are formed by physical vapor deposition, their microstructures, and hence, their mechanical properties, are quite different from those of bulk materials of the same chemical composition. While the general principles of conventional mechanical testing are applicable to thin films, special test equipment and techniques are required. This presentation will review developments in the field of microtensile testing over the past ten years, concentrating on the techniques developed at NIST Boulder and the contributions of Jim Dally. These include the silicon-frame tensile specimen, the piezo-actuated tensile test machine, and the new force-probe technique. Improved specimen geometries now allow microtensile test records to reflect the true nature and variability of different materials, and of alloying and composition effects in similar materials.

Microtensile testing has progressed to the point where standardization can be realistically discussed. Originally, specimens were so unique and delicate that they were designed, produced, and tested, all within the same laboratory. This research was part of the general development of the understanding of the physical nature of thin films. Now, specimens can be designed in one lab, produced in a separate fabrication facility, and tested in another lab in another organization. Round robin exercises have been reported on microtensile tests and results. Recent microtensile test results from our laboratory will be presented to demonstrate the variability of behavior among different materials. It will be argued that the standardization effort must be pushed forward, so that the real differences in material behaviors can be clearly separated from artifacts resulting from different specimen designs and test apparatus and procedures.

Keywords: ductility; mechanical; strength; thin film.

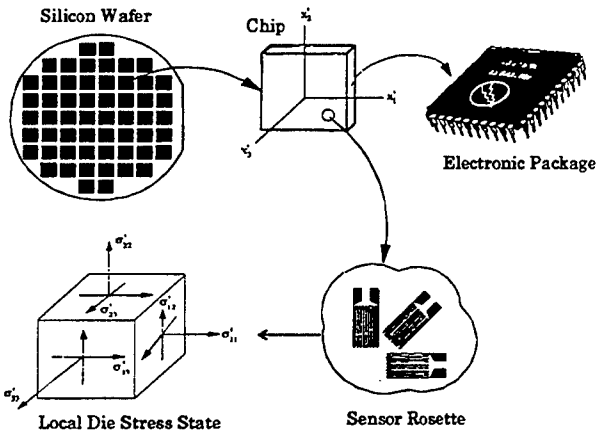
Silicon Piezoresistive Stress Sensors and Their Application in Electronic Packaging

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Structural reliability of integrated circuit chips in electronic packages continues to be a major concern due to ever-increasing die size, circuit densities, power dissipation, and operating temperatures. A powerful method for experimental evaluation of die stress distributions is the use of test chips incorporating integral piezoresistive sensors. In this presentation, a review will be made of both the state-of-the-art and in ongoing developments in the area of silicon piezoresistive stress sensor test chips. Developments in sensor theory, calibration methods, and packaging applications will be presented.

Sensor rosettes on (100) silicon can be used to measure as many as four components of the six-component stress state, whereas advanced test chips based upon (111) silicon can measure the complete stress state. However, not all of the measurements can be performed in a temperature compensated manner that is required for high accuracy results. Classic resistor rosettes suffer from reduced sensitivity due to high doping levels, and they measure values of the die surface stress averaged over a relatively large area. In current work, advanced stress sensors based upon the piezoresistive response of field-effect transistors and van der Pauw stress sensors have been demonstrated to provide improved sensitivity and highly localized measurement of stress.



Keywords: Piezoresistive Sensor, Stress Test Chip, Electronic Packaging

Applications of Nano-Micro Experimental Technique using Random Speckles

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Using random speckle for quantitative deformation measurement has its genesis in a 1968 paper by Dr. Jim Burch of England which shows that when two white light illuminated random patterns are shifted w.r.t. each other and Fourier processed, a correlation fringe pattern similar to Young's fringes are obtained representing the magnitude and direction of this shift. Since then this phenomenon has been exploited for various application and the corresponding techniques are called by different names such as (laser or white) speckle photography, speckle Interferometry, image correlation technique, etc.

The speckles are the information carriers whose size essentially determines the sensitivity and resolution of the technique. In this presentation, a nano/micro speckle technique is described whereby whole field deformation in a region as small as a few microns can be mapped. Applications of this technique to electronic packaging, composite interface, MEMS material characterization, etc. are presented.

Keywords: speckle, electronic, packaging, MEMS.

Extension of Moiré Interferometry into Micromechanics

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Today, moiré interferometry is used for many studies. They include studies of composite materials, piezoelectric materials, fracture mechanics, biomechanics, residual stress measurement etc. More recently, it has been practiced extensively in the microelectronics industry to measure thermally induced deformation of electronic packages. Moiré interferometry measures in-plane displacements with very high sensitivity. The data are received as interference fringe patterns, or contour maps, of the displacement fields. Because of the high sensitivity and abundance of data, reliable strain distributions-normal strains and shear strains-can be extracted from the patterns. The method differs from classical interferometry and holographic interferometry, which are most effective for measuring out-of-plane displacements.

Special considerations arise for deformation measurements of tiny specimens or tiny regions of larger specimens. The relative displacements within a small field of view will be small (even if the strains are not small), so the number of moiré fringes might not be enough for an accurate analysis. Perhaps the most important consideration, therefore, is the need for increased displacement sensitivity-enhanced sensitivity beyond the high sensitivity discussed above.

In a method called *microscopic moir interferometry*, sensitivity is increased progressively by two techniques. The first is an *immersion interferometer*, whereby the virtual reference grating is formed inside a medium of higher index of refraction; this strategy reduces the wavelength of the light and thus increases the upper limit of frequency for the virtual reference grating. Virtual reference gratings of 4800 lines/mm (122,000 lines/in.) are produced in practice, thus doubling the usual basic sensitivity. The second technique is optical/digital fringe multiplication (O/DFM), whereby fringe shifting and an efficient algorithm is used to generate an enhanced contour map of the displacement field; the map displays (times as many fringe contours as the original moiré pattern.

This paper reviews current practices of microscopic moiré interferometry. Diverse applications are presented to emphasize the wide scope of the method in engineering mechanics. They include thermal deformation analyses of microstructures in electronic packaging, deformations of polycrystalline metals, and experimental investigations of advanced composites.

Keywords: Microscopic moiré interferometry, Electronic packaging, Grain deformations, Advanced composites

A Novel Wafer-Level Test for Investigating Plasticity and Fracture of Freestanding Thin Films

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We have developed a membrane deflection experiment particularly suited for the investigation of sub-micron thin films that directly and independently measures actual load and strain elements of the test. The experiment consists of loading a fixed-fixed membrane with a line load that is applied to the middle of the span with a nano-indenter column. A Mirau microscope-interferometer is conveniently aligned with the nano-indenter to directly measure strains. This is accomplished through a specially manufactured wafer containing a window to expose the bottom surface of the membrane. The sample stage incorporates the interferometer to allow continuous monitoring of the membrane deflection during both loading and unloading. As the nanoindenter engages and deflects the sample downward, fringes are formed due to the motion of the bottom surface of the membrane and are acquired through the use of a CCD camera. Digital monochromatic images are obtained and stored at periodic intervals of time to map the strain field.

Through this method, loads and strains are measured directly and independently without the need for mathematical assumptions to obtain the parameters describing material response. Additionally, no restrictions on the material behavior are imposed in the derivation of the model. The test is well suited for identifying film residual stress, Young's modulus, onset of plasticity, and fracture stress.

We will present stress-strain signatures obtained on suspended thin gold membranes of different thickness includ-

ing membranes with nm thick passivation layers. Elastic modulus was consistently measured at 53-55 GPa. Several size effects on the mechanical properties were observed including yield stress variations with membrane width and film thickness. The presence of the passivation layer had the effect of reducing the membrane strength. Yield stress, as well as fracture strain and stress, were all found to be significantly lower for the passivated specimens.

Research and Education
in Experimental Mechanics

In Honor of Professor J. W. Dally

SESSION W4M
Education in Experimental Mechanics

Using LEGO Bricks and ROBOLAB to Teaching Engineering Students

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For the past several years LEGO bricks and ROBOLAB, a programming environment based on LabVIEW, have been used to teach design, creativity, and structured programming to freshmen mechanical engineering students at the University of Nevada, Reno. The class utilizes a project-based learning environment which consists of approximately 10 design projects. The class is unique in that a semi-self paced approached is used; the student's final grade is based on the number of "skill badges" he/she has acquired by the end of the semester. The order and rate at which the skill badges are acquired is up to the students themselves. The course culminates with a robot war and a presentation to local K-12 Schools at the end of the semester. Student enrollment has grown over 3 fold since the introduction of LEGO bricks.

This paper will present and overview of the evolution of the course and the assessment used to evaluate the course, student learning, and attitudes towards engineering as a profession.

Keywords: LEGO, project-based learning environment, outreach, self-paced

Learning by Doing : Hands-on Learning Pervades the Integrated Teaching and Learning Program

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The Integrated Teaching and Learning Program at CU-Boulder is committed to leading engineering education reform through enhancing hands-on, team-oriented opportunities for undergraduate engineering students and capitalizing on the effectiveness of learning by doing. The Program was named one of three finalists for Boeing's Outstanding Educator Award in 1996 and 1997. In 2000, it received the inaugural Recognition Award from the Corporate and Foundation Alliance, a group of 35 engineering and technology corporations and foundations working with the National Science Foundation to recognize the country's top undergraduate science, math, engineering and technology educational programs.

Using inter-disciplinary, hands-on approaches that make engineering come alive for students, and incorporating leading-edge technology, engineering students at CU-Boulder gain the understanding and confidence to succeed. The Program reflects the contemporary world of professional engineering by supporting students working in teams on real-world projects as they learn the open-ended problem-solving skills critical to their career paths.

The unique design and architecture of the ITL Laboratory (ITLL) was driven entirely by curricular reform objectives. It provides K-16 students with an interdisciplinary learning arena where the joys of engineering are experienced by K-12 learners in summer workshops; the principles of design are introduced during a student's first year in engineering; theoretical engineering science courses in the middle two years are augmented with hands-on, open-ended discovery opportunities; young inventors explore their potential for product invention and innovation through a hands-on entrepreneurship sequence; and interdisciplinary teams of seniors design, build and test real-world products.

The unique ITLL learning environment includes design studios; open experimental laboratory plazas equipped with pervasive data acquisition and analysis capability; student-centered, technology-rich electronics and manufacturing centers; team work areas; and a captivating array of interactive exhibits and kinetic sculptures capture the interest of budding engineers of all ages.

The ITL Laboratory itself is an integral part of the undergraduate engineering curriculum, allowing students to monitor the building's structural, electrical and mechanical systems through a network of 300+ embedded sensors, with the real-time data accessible via Internet.

Designated a *Program of Excellence* by the Colorado Commission on Higher Education, the ITL Program provides summer engineering outreach workshops and classes to extend hands-on learning to K-12 teachers and students, as part of its integrated K-16 engineering outreach initiative. More than 8,000 K-12 students and their teachers visit the ITL Laboratory annually, many to participate in hands-on, ears-on and minds-on K-12 engineering workshops. Supported through the National Science Foundation, 11 engineering students provide weekly hands-on engineering labs to 68 K-12 classrooms in seven public schools, instilling in budding engineers the understanding that *engineering is about creating things for the benefit of society.*

Keywords: Integrated teaching and learning, interdisciplinary, outreach, active learning

Engineering Design and Build Experience

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In 1997, through the inspiration of Dr. James Dally, Professor Emeritus, University of Maryland, the College of Engineering at the University of South Carolina embarked on an Engineering Design and Build Experience for first semester freshman students. Gathering inspiration from Dr. Dally's "Introduction to Engineering Design" Series, students designed and built seven utility tool sheds that were delivered to local Habitat for Humanity home sites. The focus of the experience was not so much on the end product, but yet on the process itself, as Dr. Dally stresses in his design series books. With this in mind, students were guided through the process of identifying customer needs, resource allocation and concept generation; all leading to producing a design with an accompanying prototype for Habitat for Humanity to evaluate for co nstruction on their home sites. This paper chronicles the activity of this experience from setting up a design and build facility in the College of Engineering, all the way to delivery the sheds for assembling at the home sites in a one hour time period-the one hour time limit being a design constraint. Through this experience, freshman not only gained knowledge of the design process, but perhaps more importantly, witnessed first hand how engineers can contribute and impact society in a very meaningful and positive manner.

Keywords: Introduction to engineering, Habitat for Humanity, design, freshman education

Development of an Integrated Statics and Strength of Materials Curriculum with an Emphasis on Design

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Traditionally, statics and strength of materials courses have been taught separately with the intent of emphasizing the mechanics of rigid bodies in statics and transitioning to the mechanics of deformable bodies in strength of materials. While this approach has proven to be effective in reinforcing students' understanding of basic principles in mechanics, it has been less than effective in providing students with an understanding of the relationship between the two subjects and their importance in designing structures. At the University of Maryland, the Mechanical and Civil Engineering departments are seamlessly integrating these two courses together, better preparing students to apply mechanics principles in the design of solutions to engineering problems. The new courses are centered around a simple, but well-developed, design project and efforts have been initiated to enhance the instruction with demonstration experiments and computer tools that are being delivered in new interactive, multimedia learning environment. Metrics for success concentrate on comparative evaluation of student performance in the traditional and integrated versions of the curriculum, as well as student feedback on the curriculum's satisfaction of ABET 2000 criteria.

Keywords: Integrated mechanics curriculum, ABET 2000, design, multimedia learning environment

The History of Experimental Mechanics Education - B.D. and A.D. (Before Dally and After Dally)

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During the last half of the 20th Century, typical beginning courses in experimental mechanics (for advanced undergraduate students or beginning graduate students) seemed to be stable and changes were almost imperceptible. Yet when one recalls the typical content of those courses for two time periods separated by fifty years, the changes are enormous.

For convenience, and in keeping with the theme of this session, I will call the1940s the B.D. Era (Before Dally

Era) and call the 1990s the A.D. Era (After Dally Era). By that designation, I do not intend to imply that Jim Dally was single-handedly responsible for ALL of the progress during that period. However, he and his textbooks did play a significant role.

In the B.D. Era, photoelasticity was the king, and appropriately occupied a significant portion of typical courses on experimental stress analysis (as they were called in those days). Then, photoelastic equipment and materials were primitive. Polarization was most commonly achieved by Nicol prisms and the material of choice was Bakelite BT 61-893. Both of those carried with them many severe limitations, mainly because only small sizes were available. Nevertheless, many important two-dimensional photoelastic studies were performed to solve problems then of current interest. Beautiful isochromatic fringe patterns were possible as illustrated in Max Frocht's classic book, *Photoelasticity, Vol. I.*

For A.D. Era photoelasticity, light sources had improved dramatically, large polaroid films and quarterwave plates were readily available, model materials were vastly improved and available in large sizes, intense light sources and high speed cameras had been introduced. Hence three-dimensional photoelasticity and dynamic photoelastic studies were numerous. Those topics were added to courses at many universities.

Strain gages in the B.D. Era were generally grids of fine wire mounted on a thin paper backing and strain indicators were operated manually. In the A.D. Era wire gages were replaced by foil gages of many sizes and configurations, and sophisticated measuring and recording systems were introduced which could process the data in real time. The brittle coating method remained a valuable tool, particularly for locating critical areas in complex structures. The method didn't change very much except that the A.D. Era lacquers smelled much better.

One dramatic change in experimental mechanics education resulted from the widespread use of personal computers. Many problems which used to be solved by experimental methods are now solved by numerical methods. Also, the invention of lasers in 1960 had far-reaching effects on experiment mechanics. In addition to their furnishing an extremely intense light source for photoelasticity, lasers also provided a source of coherent light. With that, the experimental methods called speckle interferometry, holographic interferometry, and moire interferometry were made possible, and became part of many university courses.

No history of experimental mechanics education would be complete without some comments about the educators. In the B.D Era, the two most distinguished educators apparently agreed to disagree with each other. They were replaced in the A.D. Era by Jim Dally and Bill Riley who were very compatible. After that the semiannual SESA/SEM meetings were not nearly as exciting . But the textbook, *Experimental Stress Analysis*, by Dally and Riley became a important milestone and had an enormous influence on the education in experimental mechanics.

Keywords: experimental mechanics, photoelasticity, strain gages, education

Symposium on

Recent Advances in Experimental Mechanics

In Honor Of
Professor I. M. Daniel

Organizer:
Professor E. E. Gdoutos
(Northwestern University)

RECENT ADVANCES IN EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION M2E
Optical Methods

Moiré Interferometry - Past, Present and Future

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Moiré interferometry is introduced as an outgrowth of moir fringe multiplication. Coherent laser light enabled the practical implementation of virtual reference gratings and high-frequency specimen gratings. Reliable analysis of shear depended upon the ideas in a little-known paper. These three facets are the essence of current techniques. Present-day applications are exemplified by work in electronic packaging and composite materials. Several significant advances are forecast to further broaden the usefulness and appeal of moir interferometry.

Optical Fibre Bragg Grating Sensors in Experimental Mechanics of Composite Laminated Plates

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Optical fibre Bragg grating sensors have proved in the past years to be extremely useful tools for internal strain

measurements in layered composite materials. Two applications of this type of technology are presented in this paper. Firstly, embedded Bragg grating sensors are used to study the through-the-thickness strain field of laminated plates in various quasi-static loading cases. It is shown how in three-point bending the onset of non-linearity in the strains can be detected for decreasing span/depth ratios in the specimens. The strain response of the embedded sensors is also investigated in the presence of a non-uniform strain field generated by a concentrated load. Finally, the use of fibre Bragg gratings is demonstrated in dynamic conditions, both in impulsive transient tests and using harmonic excitation.

Optoelectronic Displacement Measurement Method for Rotating Disks

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Radial displacements on an axial surface of a rotating disk can be measured with optoelectronic sensing devices consisting of infrared emitters and phototransistors. The aim of this investigation is to improve the stability and robustness of a previously described optoelectronic measurement system. Stability is improved by a computerized algorithm for the control of the emitter intensity based on feedback from a compensation portion of an optical pattern placed on the disk. Robustness is improved by using a laser emitter that allows for a larger standoff distance in comparison with the previously used light emitting diode. Radial displacements obtained with automatic intensity control of the laser emitter agreed with theoretical values in a glass/urethane composite disk to within ± 1 μm at rotational speeds up to 3300 rpm. With further development, the proposed displacement method has application in the noncontact measurement of radial and hoop strains through the radial thickness of high-speed axisymmetric rotating machinery such as energy storage flywheels.

Deformation Measurement of Sheet Metal Forming Using Photogrammetry

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A measuring machine based on a stereo device is developed for analyzing large sheet metal parts deformed by deep drawing. A cross grating on the surface is subdivided into meshes which are uniquely encoded by circular marks. This provides absolute indices for each grating point when taking segments of the surface by the stereo device. Hence overlapping areas can be used to fit together the segments with its spatial coordinates. By means of a theory of large deformation the principal strain and the principal directions are calculated.

Fracture Processes of Quasi-Brittle Materials Studied with Digital Image Correlation

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An understanding of the fracture process is necessary for design and utilization of quasi-brittle materials since cracking characterizes their failure. Subregion Scanning Computer Vision (SSCV) is an effective tool for observing these processes in an experimental setting. SSCV, based on Digital Image Correlation (DIC), is a full-field technique for quantitatively examining the development of cracks, with 0.5 micron resolution. DIC uses correlation matching to measure sub-pixel displacement in a sequence of digital images captured of a specimen undergoing failure. Using this technique, the complete behavior of specimens with multiple cracks at incremented levels of fracture can be investigated. SSCV improves on single-image DIC by dividing the specimen into 56 smaller subregions, each of which is imaged separately and so much improves measurement resolution. In this paper, examples of the results obtained in studies of crack growth in a model concrete under compressive loading and in a fiber-reinforced mortar under tensile loading are presented.

On the Use of Different Wavelengths to Digitally Determine the Isochromatic Fringe Order

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Four approaches, a novel, two modified and a previous developed approaches, are compared for the determination of the total fringe orders using different wavelengths. The results show that an error of 0.05 fringes

can be achieved by all methods. The MIN-MAX method gives the best result for fringe orders greater than 0.6, a better result can be given by the rest methods for fringe orders less than 0.5. The three-wavelength criterion could yield better result than that of the two-wavelength for determination of the total fringe order. Owing to various noises, both criteria cannot assure to obtain correct fringe order. Therefore two-wavelength method would be sufficient to determine the total fringe orders with a correctly determined total fringe order.

The Application of Speckle Metrology to Heart Mechanics

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Commonly used techniques for analysis of regional heart function include sonomicrometry, implanted markers, and surface markers. However, these techniques cannot offer the high spatial resolution needed to define regional abnormalities in the heart. We have recently applied a computer aided speckle interferometry technique (CASI) with high spatial resolution to measuring the deformation of heart muscle. We applied silicon carbide particles to the surface of the isolated heart and loaded the heart by increasing the intracavitary pressure. The movement of the speckle pattern was tracked with a CCD camera. This technique produces equivalent results to that of the gold standard in heart mechanics, sonomicrometry, but with three orders of magnitude higher spatial resolution. We have used this technique to determine changes in myocardial deformation of perfused, ischemic and reperfused rabbit hearts.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION M3H
Mechanical Behavior of Materials I

Hopkinson Techniques for Dynamic Triaxial Compression Tests

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A modified Hopkinson technique is developed to simultaneously load a sample in both the axial and radial directions. This is accomplished by using a composite incident-bar and a composite transmission-bar system. The incident-bar system consists of a large-diameter bar, followed by a small-diameter bar that fits inside a tube whose outside diameter is equal to that of the large bar. The transmission-bar system consists of a tube and a bar that fits inside the tube. The sample is placed inside a Teflon sleeve, and the Teflon sleeve is placed inside an aluminum sleeve. The Teflon sleeve is loaded during the test by the stress pulse traveling in the incident tube, producing a radial stress on the sample. The stress pulse traveling in the incident bar loads the sample that is sandwiched between the small-diameter incident and transmission bars. The radial stress is calculated from the hoop strain measured by a strain gauge placed on the outer surface of the aluminum sleeve. Mortar samples have been tested under a range of confining stresses and strain rates, and some of the results of these experiments are presented.

Asymptotic Scaling of Gradient Theory of Micro-Scale Plasticity of Metals

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The paper deals with the question of asymptotic behavior of Gao, Huang, Hutchinson and Nix's dislocation-based theory of strain-gradient plasticity on the micrometer scale, which is currently of keen interest for micromechanics. Certain peculiar features of the nano-scale extension of the existing theory are identified and possible remedies pointed out.

The Role of Pressure in the Behavior of Time-Dependent Materials

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We improved and upgraded the apparatus that Fillers, Moonan, and Tschoegl used several years ago to investigate the influence of pressure and temperature on the

mechanical properties of time dependent polymeric materials. The new apparatus can measure the volume and the shear relaxation moduli of solid polymer specimens, subjected to a combination of temperatures from $-60°C$ to $+110°C$, and pressures from atmospheric to 360 MPa. The paper demonstrates the capabilities of the new apparatus from the scientific as well as engineering stand point. Shear relaxation measurements on poly(vinyl acetate) (PVAc) and styrene-butadiene rubber (SBR) are also presented. For PVAc we present also the bulk creep compliance, coefficient of thermal expansion and the bulk modulus.

High Strain Rate Testing of Sandwich Core Materials

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Mechanical response of a cellular sandwich core material, balsa wood, is investigated over its entire density spectrum from 55 to 380 kg/m^3. Specimens were compression loaded along the grain direction in both quasi-static and dynamic strain rates from 10^{-3} to 10^3 s^{-1}. Results show that while the initial failure stress is very sensitive to the rate of loading, plateau (crushing) stress remains unaffected by the strain rate. Kinematics of deformation and micro inertial effects are suggested and discussed to explain this different behavior. Specific energy dissipation capacity of balsa wood was measured and determined to be comparable with those of fiber-reinforced polymers. As in quasi-static loading, buckling and kink band formation were identified to be two major failure modes in dynamic loading as well.

Development of a Shear Test for Low Modulus Foam Materials

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The shear properties of carbon (graphitic) foam, being brittle and highly porous, are not reliably measured with most of the standard test methods, such as, single rail, double rail, Iosipescu shear, etc. A new testing device is developed to accurately measure the shear stiffness and strength of carbon foam or other porous materials. Specimens of cylindrical cross-section are used to reduce high stress concentration that normally occurs in the vicinity of the grip section. Since strain gages could not be installed on the specimen surface (due to porosity), the shear strain is determined from the specimen end rotation. A high accuracy in the rotational measurement is achieved by using a stepper motor with multiple gear reduction. In view of testing low modulus material, the load cell of fixture was mounted on an axial roller to relieve axial constraint while twisting the specimens. The accuracy of the measurement and calibration of the test fixture was demonstrated by measuring shear modulus of PVC plastic.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION M4H
Mechanical Behavior of Materials II

Indentation of a PVC Cellular Foam

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An investigation of the indentation response of a PVC closed-cell cellular foam (Divinycell H80) by a cylindrical indenter was undertaken. The material has a density of 80 kg/m3 and shows a linear elastic almost perfectly plastic behavior in simple compression up to a critical strain at which densification takes place. The plastic Poisson's ratio of the material approaches zero. The load-indentation depth relation was monitored for a progressively increasing applied load. It consists of an initial linear part followed by a softening behavior. A simple model based on a rigid plastic behavior of the foam in compression and a maximum stress failure criterion was used to predict the load-indentation depth curve. Results for the indentation hardness indicate that it takes values close to one for small indentation depths, while it increases as the indentation depth increases.

Nanomanipulation and Characterization of Individual Carbon Nanotubes

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We describe the implementation of new tools for the measurement of the mechanics of nanostructures. These tools have been used to measured the stiffness, fracture strength, and various tribological properties, of carbon nanotubes.

Quasi-Static and Dynamic Torsion Testing of Ceramic Micro and Nano-Structured Coatings Using Speckle Photography

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An experimental methodology for the quasi-static and dynamic testing of Al_2O_3/TiO_2 and WC/Co coatings on aluminum substrates is presented. A stored energy Kolsky bar apparatus was used for both quasi-static and dynamic loading. Acquisition of speckle images at different loading stages allowed the determination of the shear strains in the gage region of the specimen and the identification of deformation mechanisms as a function of coating grain size. The interaction between coating and substrate is investigated by correlating damage to measured stress-strain curves. It was identified that as cracks develop in the coating, they are bridged by the underlying ductile substrate. Optical and SEM interrogation of the coating fracture surface also show a low percentage of porosity and severe damage created by residual stresses. These residual stresses arise during the coating manufacturing process. The pre-existing damage is believed to be the cause of the low shear moduli and strengths exhibited by the coatings. A comparison between quasi-static and dynamic response is carried out, to assess strain-rate effects, as well as micro versus nano grain size coatings of the same composition.

Grain Level Analysis of Fracture Initiation and Evolution in Brittle Materials

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A finite element analysis of crack initiation and fragmentation of brittle materials is presented. Intergranular cracking and dynamic fragmentation of ceramic microstructurres are modeled by interface cohesive laws motivated by the physics of breaking of atomic bonds or grain boundary sliding by atomic diffusion. The model incorporating cohesive laws captures microcrack initiation, propagation and coalescence, in addition to crack interaction and branching. A representative volume element (RVE) composed of a set of grains is analyzed with special consideration to micromechanical and stochastic effects. This model accounts for size distribution of grains, morphology, chemical phases, presence of initial defects as well as randomness of grain orientation, boundary strength and toughness. Microcracking and damage kinetics are examined by modeling of plate impact recovery experiments. Histories of normal velocity are utilized to identify model parameters and the effect of the material microstructure on failure kinetics. Simulated microcrack patterns and velocity histories are found in a good agreement with the experimental observation. The analyses show that grain morphology plays a major role in controlling the speed of crack propagation and as a result, the material damage rate.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION T2E
Non-Destructive Evaluation

Line Focus Acoustic Microscopy for Thin-Film Measurements

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A thin-film coating generally is a single or multiple layered thin film deposited on a component to extend its life and performance. As discussed in this paper the V(z) effect in line-focus acoustic microscopy is a very suitable technique for the quantitative nondestructive determination of thin-film elastic constants and the bond quality at interfaces. After a brief introduction to acoustic microscopy and a discussion of calibration for frequency dependence, the modeling of multilayered configurations is summarized. The modeling results are used in a measurement model for the V(z) effect which can be used to select a frequency range suitable for a particular configuration. In combination with measurements the model is subsequently employed to determine elastic constants and interface stiffnesses. Experimental results are presented for single, multilayered, isotropic and anisotropic films. The effect of imperfect interfaces on strength considierations is also discussed.

Recent Advances in Acoustography-Based NDE

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Acoustography is the ultrasonic analog of radiography and photography in that a 2D area detector is used to form full-field ultrasonic images. This unique detector, called the acousto-optic (AO) sensor, is capable of directly converting ultrasound into a visual image; much like a fluorescent screen is able to convert x-rays into visual image. It offers an exceptionally high pixel resolution since ultrasound field is detected by a continuous layer of liquid crystal material with molecules that are only 20 Angstroms in size. The AO sensor can be fabricated to have a large sensing area that allows image formation either through simple shadow casting (analogous to x-ray image formation) or with acoustic lenses (analogous to photographic or video camera). In this paper, we report on recent progress that is making acoustography a viable ultrasonic testing method both for through-transmission and reflection modes.

Experimental Limitations to Guided Wave Generation in Elastic Materials

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In generating small amplitude guided waves in elastic materials for diverse experimental investigations, one is faced with several limitations. This paper examines the limitations arising from the inherent nature of materials not to withstand, in some cases, the existence of guided waves either in certain finite frequency ranges or in the whole frequency spectrum. The material constants as well as the stress conditions in the materials play a key role in allowing the experimental generation of guided waves. The model examined in this paper incorporates a small layer either imbedded in a host material or a small surface layer overlying a host material, both materials in general being pre-stressed. The analysis defines limitation regimes where experimental generation of guided waves would not be possible. These regimes are given explicitly in terms of material constants and stress conditions.

Nondestructive Testing Using Shearography

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This article reviews shearography and its applications in nondestructive testing. Shearography is an interferometric technique for full-field and non-contacting measurement of surface deformation (displacement or displacement derivatives). It was invented to overcome some limitations of holographic interferometry by eliminating the reference beam, resulting in having much higher tolerance to environmental disturbances. Consequently, shearography can be practiced in a typical industrial setting, and it has already received considerable industrial acceptance, in particular, for nondestructive testing. One major difference of shearography from other NDT techniques is the mechanics of revealing flaws. Shearography reveals defects in an object by identifying defect-induced deformation anomalies which are more relevant to structural weakness. Other applications of shearography include strain measurement, material characterization, residual stress evaluation, leak detection, vibration studies and 3-D shape measurement.

Theoretical and Experimental Study of Laser-Ultrasonic Signal Characteristics Enhanced by Wetting the Surface

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This paper deals with a theoretical and experimental study to predict the characteristics of ultrasonic waves irradiated from a wet surface illuminated by a laser beam. The theoretical model is developed by assuming normal surface tractions distributed elliptically over the line-focused illumination source. The solutions for both longitudinal and shear waves are obtained using Fourier analysis, in which the transform integral is evaluated asymptotically. The theory is evidenced by the experimental study which allows for quantitative comparisons between the theoretical and experimental directivity patterns. The effects of beam width and frequency of the propagating wave, which are the most influential parameters on the characteristics of the generated wave, are investigated. The experimental results are in strong agreement with the theoretical predictions.

Defect Detection by the Scattering Analysis of Flexural Waves

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The propagation and scattering of flexural waves at obstacles in plates is studied experimentally and theoretically. When the guided wave hits a discontinuity like a hole, a typical scattered displacement field is obtained. Defects like a notch or a fatigue crack at the hole boundary change the scattered field significantly. The first antisymmetric Lamb wave mode A0 is excited selectively by means of a piezoelectric transducer. The scattered field around undamaged and damaged holes is measured on a grid around the hole using a heterodyne laser-interferometer. The out-of-plane displacement is measured with good spatial resolution, accuracy, and repeatability. Applying fast Fourier transform, the amplitude and phase values of the scattered field are extracted, overcoming the typical problems associated with the measurement of dispersive waves.

The experimental results are compared with theoretical calculations. The wave propagation is studied using classical plate theory and Mindlin's theory of plates. The scattered field around the circular hole is calculated analytically and good agreement is found for the range of validity of the used theories. The scattering at the hole with a defect is calculated numerically, using a finite difference scheme. The method can be applied for the detection of cracks at rivet holes in aircraft fuselage, an important nondestructive testing application. Guided waves allow a fast inspection of large areas, reducing the need for time-consuming scanning. The minimum detectable crack length and the sensitivity of the method are discussed.

Evaluation of Fiber Waviness in Thick composites by Ultrasonic Test

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An analytical model, based on the ray and plane wave theories, was proposed to understand the ultrasonic wave propagation in thick composites with uniform fiber waviness. In the analysis, the composites were assumed to have continuous fibers with sinusoidal fiber waviness in a matrix and were modeled as stacks of infinitesimally short off-axis subelements with varying fiber orientation along the lengthwise direction. From the analysis, it was found that the converted wave of the same mode as that of incident wave carried most energy and this tendency was sustained throughout the thick composites. The path and traveling time of ultrasonic wave in the subelement were obtained by computing the velocity and direction of group wave. The predicted results showed that the ray paths of quasi-longitudinal and quasi-transverse waves were highly affected by the degree of fiber waviness and had tendencies to trace toward the fiber direction and to converge to the adjacent peak of fiber waviness. Some parameters that showed strong effects on the wave propagation in the composites were identified for both insonified longitudinal and transverse waves. The experiments were also conducted on the specially fabricated thick composite specimens with various degrees of uniform fiber waviness using the conventional through-transmission method to verify the predicted results. Then, the analytically determined values were compared with the actual measurements obtained from the test specimens. Good agreements were observed among them.

Development of a Dry-Contact Ultrasonic Technique and its Application to NDE of IC Packages

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A dry-contact technique for transmitting higher frequency components of ultrasonic wave is proposed to accomplish an inspection which requires higher resolution without wetting the tested parts in water. In this technique, a plastic film is inserted between the water and the tested parts, and the interfacial continuity is improved by decreasing the pressure between the film and the tested parts. From both the experiment and the calculation used acrylic resin, we verified that the dry-contact technique achieves higher resolution similarly to the conventional immersion technique. The dry-contact technique was applied to the inspection of a delamination in IC package, and the delamination was imaged clearly without wetting the package.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION T3H
Composite Material I

Measured Response: State Variables for Composite Materials

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The present paper examines the concept of state variables for composite materials, and advances the premise that for irreversible processes in composite materials, the state variables are uniquely defined only for specific damage and failure modes, and that the popular "internal variables" typically used in the context of free energy concepts for the creation of constitutive equations can be replaced by a measurable engineering failure function. The paper will begin with a general discussion of the thermodynamic foundations that support the constructs of damage mechanics and continue with an outline of the manner in which strength can be cast as a state variable. Implications of the specific forms that result for evolution equations and rate processes will be discussed. Specific consequences for the case of temperature dependent material properties will be defined and compared to experimental data. The focus of the paper will be observables, i.e., physical quantities that are clearly defined and measurable.

On the Modeling of the Mechanical Properties of Composite Materials at High Strain Rates

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High strain rate compressive and tensile ultimate strength properties for a wide variety of composite materials as function of strain rate are modeled, using the Weeks - Sun equation. These include unidirectional, quasi-isotropic and woven composites, made of glass, graphite and aramid fibers in various thermoset and thermoplastic polymeric matrices. Through modeling, using the Weeks - Sun equation, dynamic composite material properties can be easily used in the design and analysis of composite material structures rather than static material properties. By doing so, excess weight or unexpected failure may be avoided.

Damage Quantification in Metal Matrix Composites

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An experimental procedure is presented to quantify damage in terms of microcrack density. This is accomplished by experimentally evaluating the components of a second-order damage tensor for a metal matrix composite material. The procedure involves the use of a scanning electron microscope and image analyzing software to quantify physical damage features found on a representative volume element. These features are quantified in terms of crack density, which is used in developing the second-order damage tensor. This procedure is applied to a titanium aluminide SiC-reinforced laminate. Laminates of the following staking sequences, $(0/90)_S$ and (± 45)S, are tested under uniaxial tensile loadings. Damage evolution is obtained by loading the specimens over a range of load intensities from rupture load down to 70% rupture load. A proposed formulation for a coupled anisotropic damage model for the inelastic response of composite materials is presented in this work.

Study of Damage in Particulate Composites

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The problem of damage in particulate composites with a soft matrix and rigid inclusions is experimentally studied. Two different approaches are used. In one approach the damage is evaluated though the increment of the material porosity. In the other approach a microscopic measurement of adherence between particle and matrix is used. The last approach provides a more realistic picture of the damage process and leads to simple models for numerical simulation.

Hygric Characterization of Composite Laminates

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A novel experimental method based on Fick's diffusion law is developed to determine the distribution of moisture concentration as well as the coefficients of moisture expansion of a composite laminate immersed in water. The technique is based on measuring the curvature of a $[0_n/90_n]$ antisymmetric crossply laminate introduced by the unbalanced in-plane interlaminar resultant forces, which can be related to the hygric expansion. The technique is verified experimentally for $[0_2/90_2]$ and $[0_5/90_5]$ graphite/epoxy specimens. The results show the enhanced measurement sensitivity of the new technique.

RECENT ADVANCES IN EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION T4H
Composite Materials II

Pneumatic Behavior of Composite Materials

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The dimensional change of some composite materials induced by ambient air pressure change was discovered and dubbed as pneumatic strain in 2000. This pneumatic behavior is similar to the hygric behavior. The pneumatic strain is proportional to the ambient air pressure change by the coefficients of pneumatic expansion. In this work, a technique termed suspending method was employed for characterizing pneumatic behaviors of different types of materials including fibers, plates and thin film specimens. Specimens including Kevlar 49 fiber, aluminum plate, aluminum foil, paper, celluloid sheet, pure epoxy plate, unidirectional T700 carbon/epoxy composite laminates were characterized. Results showed that Kevlar 49 fiber and aluminum have no pneumatic behavior. Paper, celluloid film, epoxy plate, and T700 carbon/epoxy composite laminate have pneumatic behavior.

The Effect of Specimen Size on the Compressive Strength of Carbon Fibre-Epoxy Laminates

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The effect of specimen gauge section (length x width) was investigated on the compressive behaviour of a $T300/924C\ [45/-45/0/90]_{3s}$ carbon fibre-epoxy laminate. A modified Imperial College compression test fixture was used together with an anti-buckling device to test 3 mm thick specimens with a 30×30, 50×50, 70×70, and $90mm \times 90mm$ gauge length by width section. In

all cases failure was sudden and occurred mainly within the gauge length. Post-failure examination suggests that 0 fibre microbuckling is the critical damage mechanism that causes final failure. This is a matrix dominated failure mode and its triggering depends very much on initial fibre waviness. It is suggested that manufacturing plays a significant role in determining the compressive strength and may be more important as the section thickness of the composite increases. Additionally, compressive tests on specimens with an open hole are performed. The local stress concentration arising from the hole dominates the strength of the laminate rather than the stresses in the bulk of the material. It is observed that the remote failure stress decreases with increasing hole size and specimen width but is generally well above the value one might predict from the elastic stress concentration factor. This suggests that the material is not ideally brittle and some stress relief occurs around the hole. X-ray radiography reveals that damage in the form of fibre microbuckling and delamination initiates at the edge of the hole at approximately 80% of the failure load and extends stably under increasing load before becoming unstable at a critical length of 2-3 mm (depends on specimen geometry). This damage growth and failure are analysed by a linear cohesive zone model. Using the independently measured laminate parameters of compressive unnotched strength and in-plane fracture toughness the model predicts successfully the notched strength as a function of hole size and width.

Interfacial Strength and Toughness Characterization Using a Novel Test Specimen

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In this study, a cruciform-shaped test specimen has been utilized to characterize the fiber-matrix interface under transverse loading. Initiation and growth of interface debonds are detected optically by observation of variations in the intensity of light reflected from the surface of the fiber during loading. Using the measured values of applied stress at debond initiation, and debond length and shape as a function of the applied loading, the tensile strength and the critical value of energy release rate of the interface, are estimated. Finally, an off-axis cruciform geometry, in which the wings of the cruciform sample are inclined at an angle with respect to the loading direction, is introduced to characterize the fiber-matrix interface under combined transverse and shear loading.

A Model for the Accurate Prediction of the Residual Strength after Damage due to Impact and Erosion of FRPs

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This paper discusses the prediction of the residual compressive strength after low velocity impact for different CFRP material systems. Several material systems were examined using each time different types of epoxy matrices and carbon fibers. Experimental results concerning residual compressive strength after impact for all the material systems are compared here to values predicted by the model developed by the CMG group. Predicted values agree very well with respective experimental results. In addition, in the present work, the influence of stacking sequence, existence and position of interleaves on the solid particle erosion in carbon fiber reinforced epoxy composites (CF/EP) are investigated. The erosive wear behavior was studied in a modified sandblasting apparatus at 90°-impact angle. The erosion behavior was considered as a repeated impact procedure (impact fatigue). Predictions made by the same model for the residual tensile strength after erosion give excellent results.

Experimental Characterization of Viscoelasticity and Damage in High Temperature Polymer Matrix Composites

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This paper describes the characterization of viscoelastic response of polymer matrix woven fabric composites subjected to high temperatures. The characterization is done by an experimental method aided by finite element modeling. The experimental characterization was based on creep data obtained under constant loads of different magnitudes and at different temperatures, and on recovery data collected after unloading. The carbon

fiber/polyamide resin woven composites with Tg around 380°C were used in the experimental program. An FEM model was developed to determine the non-linear viscoelastic response by implementing incremental constitutive relations into ABAQUS. The laminate properties were obtained by finite element micromechanis analysis using the neat resin data as input. Comparing its results with creep-recovery experiments performed at different stress levels and temperatures did the validation of the FEM model.

In many service conditions, polymer matrix composites are subjected to extreme environmental conditions, e.g., high temperatures, temperature gradients and moisture, in addition to the usual mechanical loads. The first step in durability analysis under such conditions consists of evaluating stress-strain-temperature-time-histories at selected critical locations using information concerning imposed loading and material constitutive behavior. The next step is to study damage mechanisms under simplified representative load histories. In extreme environmental conditions, the coupling between damage and viscoelasticity affects the overall material response and therefore must be characterized.

There are several factors affecting the viscoelastic behavior of polymer matrix composites such as temperature, moisture and stress level. Accordingly, a large number of tests need to be performed to characterize the viscoelastic response experimentally. Moreover, all experiments should be repeated for each fiber-matrix combination. In this work an efficient and systematic experimental procedure was followed to understand the effects of temperature and load level on viscoelastic response and to clarify the damage-viscoelasticity coupling. The first step in the procedure was to understand the origin of the nonlinear response. The coupling between damage in the form of matrix cracks and viscoelasticity was then studied by performing creep-recovery tests at different temperatures and load levels. Finally, tests were conducted to complete the characterization of viscoelastic behavior and to determine the viscoelastic properties of the material system.

Since there are several factors affecting the viscoelastic behavior, extensive amount of experiments would be required to complete the material characterization. To overcome this difficulty, a finite element structural macro model combined with finite element micromechanics was developed. The layer properties were obtained by micromechanics, which were then substituted into FEM model and the overall response was determined. Schapery's viscoelastic constitutive relations were represented in incremental form and implemented into ABAQUS finite element code. A user-defined subroutine was developed for this purpose to analyze orthotropic composite materials. The woven structure was idealized as a cross-ply laminate and damage was assumed to be in the form of matrix cracks. A cross-ply laminate with intra-laminar cracks in the 90° plies was considered in the FEM model.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION W2E
Composite Structures

Future Experimental Methods Needed to Verify Composite Life-Cycle Simulations

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The future experimental methods needed for composite life-cycle are identified by computationally simulating the fracture of an integrally stiffened composite structure. The simulation describes events occurring during the fracture progression at all composite structure scales, the fracture modes that contribute to those events and the respective local failure mechanisms. The fracture modes in their respective scales provide opportunities to suggest future testing techniques to measure them. For example, energies emitted can be calibrated to identify nondestructive techniques to measure corresponding energies such as acoustic, thermal and even optical. Successful testing methods can then be used to implement monitoring systems for in-service structural life-cycles.

Experimental Observations on the Delamination Behavior in Composite Structures

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The objective of the current paper is to present experimental data of interface cracks (delaminations) in layered Glass/Epoxy and Graphite/Epoxy composites under cyclic compressive (fatigue) and static (Mixed Mode Bending and Double Cantilever Beam) loads. The growth behavior ranges from self-similar growth along the interface in the unidirectional configuration to branching out

of the interface in 90 deg. and cross-ply configurations. In the case of cyclic compressive loading, the specimens undergo repeated buckling/unloading of the delaminated layer with a resulting reduction of the interlayer resistance. Also, for this case, equations describing the growth of the delaminations under cyclic loads are obtained on the basis of a combined delamination buckling/post-buckling and fracture mechanics model. The latter is based on a mode-dependent critical fracture energy concept and is expressed in terms of the spread in the energy release rate in the pre- and post- buckling state. The growth laws developed in this manner are integrated numerically, in order to produce the delamination growth vs. number of cycles curves. An important characteristic in all the configurations tested is that the state of stress near the delamination tip is of mixed mode, I and II. In the cases where branching (intra-layer cracking) occurs, there is some self-similar crack growth from the initial delamination (simulated as a Teflon sheet inserted in the plate) followed by branching of the crack through the thickness of the plate. Observed behavior ranges from sudden and catastrophic failure induced by the intra-layer crack in the 90 deg. specimen to the alternate successive initiation of intra-layer cracks and secondary interlayer cracks (delaminations) in the cross-ply specimens. Experiments and statistics show that there is a critical branching angle above which crack growth is greatly accelerated. The particular details of the experimental study, including the difficulties and challenges, are discussed.

Direct Identification of Elastic Properties of Composite Structures – A Wave-Controlled Impact Approach

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The determination of the four elastic constants for an orthotropic layer of composite materials usually requires that specimens be prepared and several tests be performed. This can be costly and time consuming and a number of investigators have sought to infer those properties from the free vibration characteristics of a single specimen. While this approach is successful tests are still performed on a specimen that must be assumed to be representative of the properties of the actual structure. In this paper, we investigate the possibility of generating impact that produce very localized bending deformations in the actual structure and monitoring the sound generated during the contact phase of the event. This approach could be used for in-situ determination of material properties, which is important with composite materials since the properties of a specimen can differ from those of an actual structure.

Static Behaviour of Pre-Stressed Polymer Composite Sandwich Beams

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The paper describes an experimental and numerical study of the effect of pre-stress on the progressive collapse of polymer composite sandwich panels subjected to a central line load. The beams were made from carbon pre-preg laid up in a quasi-isotropic form for the skins and Rohacell 51WF foam for the core. Prestress loads were 0kN, 5kN, 15kN - the latter load being 15of the in-plane failure load. Experimental results included force-deflection data and photos of the progression of skin and core damage. Experimental tests were simulated by the finite element code LS-DYNA. The focus for material modelling was the crush and failure behaviour of the polymeric foam core.

On Debond Failure of Foam Core Sandwich

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Face/core debond fracture toughness has sandwich beams with a foam core made from cross-linked PVC has been examined experimentally and analytically using a recently proposed test method called Tilted Sandwich Debond (TSD) test. In this paper we will present a brief summary of research accomplishments in this area.

Core Crush Mechanisms and Solutions in the Manufacturing of Sandwich Structures

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Core crush is a manufacturing defect occurred during the autoclave curing process of composite honeycomb

sandwich structures. It usually leads to costly part rejections since the defect is non-repairable. In addition, this problem has posted constraints on aircraft engineers by limiting the ranges of core density and core thickness that could be used when designing these types of structures. In commercial production, several techniques (e.g., ply tie-down, pre-cured adhesive over the core) have been applied to restrain the core from collapsing inward; however, these approaches require additional labor, time and material cost and thus may not be the best solutions. This paper discusses the recent understandings in core crush mechanisms and the subsequent developments in core crush resistant prepreg based on that foundation. It shows that the prepreg frictional resistance is the key factor in controlling core crush. While past research in the scientific community has mainly focused on resin effects in core crush, studies conducted in Hexcel show that the core crush can also be significantly reduced by controlling construction of the fiber tow shape and fabric architecture. Rounder fiber tow or more open fabric produces rougher prepreg surface and thus yields higher prepreg frictional resistance to reduce core crush. Experimental results show that, without changing the resin, the developed core crush resistant prepreg increases the prepreg frictional resistance and effectively reduces the core crush.

Displacement Fields Around a Circular Hole in Composite Laminates

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Moiré patterns representing in-plane displacement fields induced near a circular hole in graphite/epoxy composite laminates subjected to uniaxial tension are presented. The measured moiré patterns were obtained using an eight-mirror moiré interferometer. The moiré patterns are compared with predictions obtained using a combination of lamination theory and a reformulated version of the Savin elasticity solution. Predicted and measured displacement fields are in excellent agreement, although the magnitude of measured in-plane displacements transverse to the loading was slightly higher than predicted. It is speculated that this difference may occur because of the very different Poisson's ratio exhibite din tension and compression by polymeric composites.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION W3H
Hybrid Methods I

Reflections on the Importance of Experimental Results to all Mechanicists, Especially Theoreticians

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All too often, mechanicists divide themselves into two camps, theoreticians and experimentalists. This unfortunate state of affairs denies us the essential two-sided, realistic view of important physical problems. We must realize that theory cannot exist without suitable experiments, and that experiments cannot be properly designed or used in engineering practice without some form of theory. Thoughtful, penetrating interaction between theoretician and experimentalist is crucial. The truly effective experimentalist must have a strong theoretical background. The truly effective theoretician must have at least a rudimentary, if not a strong, experimental background. Of course, the ideal mechanicist would be neither a theoretician nor an experimentalist, but both *simultaneoulsly*! The important factor is cross-talk between the two points of view with the objective of achieving a *unified view* of a phenomenon and its model that can be used to treat behavior beyond that which was observed in experiments. This paper is about the elements that go into making up the unified viewpoint. Those elements include appreciation of the actual characteristics of the phenomenon studied as determined by experimental techniques and how those characteristics help develop and refine every theory. The point is that *experiment is the driving force behind theory.*

Mixed Numerical-Experimental Techniques: Past, Present and Future

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Direct methods in continuum mechanics start from the thermomechanical characteristics and by solving the equilibrium or motion equations, satisfying boundary and crit-

ical conditions, result in stress, strain and/or displacement fields. Inverse methods are starting from the obtained solutions in order to compute a priori unknown characteristics or parameters. Direct experimental measurements of some characteristics or parameters are sometimes very difficult, if not impossible, to perform. Special applications of inverse methods combining some experimental global results with computed results are known as mixed numerical-experimental techniques or hybrid methods. Those MNET can be applied in order to obtain thermomechanical characteristics of material systems with elastic, viscoelastic, elastoplastic or viscoplastic behaviour. They can also be applied for damage, interphase, damping and processing characterisation. The MNET-approach can also be used in many other fields out of mechanics if a good theoretical model exist and a sensitive "experimental" method is available.

A Moiré-Fe Method for Internal CTOA Determination

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A hybrid moiré-finite element analysis (FEA) method was used to determine the crack tip opening angle (*CTOA*) along a tunneling crack front in a three-point bend (SENB) specimen. The specimen was machined from a ductile 2024-T351 aluminum plate of 8.1 mm thickness and was pre-fatigued to an initial crack length to width ratio of $a_0/W \approx 0.45$. The specimen was then subjected to stable crack growth of varying $\Delta a = 0.5$ to 5.5 mm, after which the specimen was post fatigued to mark the final crack front and loaded to failure. A quarter segment of the SENB specimen was modeled with a truncated 3-D elastic-plastic FE model. Measured surface displacements, which were obtained by moiré analysis, and stable crack growth with increasing load were prescribed on the FE model. The *CTOA* was obtained from the computed crack opening displacement, approximately 1 mm behind, and normal to the crack front. The good agreement between the measured and computed surface *CTOA* are indicative of the accuracy of the procedure.

Patterns of Modern Experimental Mechanics

Principles of Modeling of Actual Responses of Materials. Machines and Structures

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The paper presents - in a very condensed form - origin, consequences, and a suggested resolution of the existing dichotomy in applied mechanics, which eventually causes unnecessary failures of machines and structures. The major contributing factor is the fuzzy distinction between the rigorously defined properties of hypothetical abstract mathematical constructs used in applied mechanics, and experimentally determined responses of simplified, approximate mathematical models of real engineering objects. Four figures illustrate this dichotomy. Only selected references are given. A reader is referred to the original publications.

Inverse Methods in Experimental Mechanics

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This paper provides a framework for the active use of experimental mechanics in solving partially specified (or inverse) problems. It is based on a wavelet (or unit load) representation of the unknown applied loading that allows the FEM analyses to be performed as an external process and thus utilize the power and versatility of commercial codes. As a demonstration of the method and its attributes, different structures are studied experimentally using strain gage and whole-field data.

RECENT ADVANCES IN EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION W4H
Hybrid Methods II

Complex Stiffness Identification by Inverse Methods

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The basic principle of an inverse method for material stiffness identification is to compare measured values of

a test specimen with computed values from a numerical model of the test specimen. The parameters in the numerical model are the unknown material stiffness properties and they are iteratively updated starting from an initial set of parameters until the computed output matches the measured values. This paper first outlines the general procedure used for material stiffness identification with inverse methods. The procedure is next illustrated with an example on the identification of complex engineering constants of composite materials. In this example the vibration behaviour of a freely suspended test plate is used as the information source. The measured quantities are the resonance frequencies of the test plates and the damping ratios of their associated mode shapes. The resonance frequencies are used to tune the real part of the complex moduli, while the damping ratios are used to identify the imaginary part.

Considerations of a Flutter Prediction Methodology using a Combined Analytical-Experimental Procedure

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A non-destructive procedure enabling one to predict the flutter instability boundary from the data acquired in the subcritical flight speed regime is presented. The proposed technique combines an analytical approach with the experimental tests carried out in flight or in a wind tunnel. The expected outcomes of this study are: a) to reduce the risks of flying in the proximity of the flutter critical boundary, and b) to reduce significantly the amount of flight tests required in any flight clearance test program, that are both time consuming and costly.

Displacement-Based Smoothing Hybrid Finite-Element Representation for Stress Anallllyzing Perforated Composites

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A reliable and effective displacement-based smoothing finite-element representation is demonstrated for determining stresses on, and near, the edge of a geometric discontinuity in finite, orthotropic composites. Relatively little measured displacement data are necessary and they originate away from the cutout. Data acquisition positions can be selected at the user's discretion and scatter in the measured input information is automatically filtered.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION R2E
Structural Testing and Analysis

Recent Advances in Long-Term Monitoring of Bridges

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The paper deals with the importance of long-term bridge maintenance to keep bridges safe along their service-life at a moderate price. The basis for a correct management policy is to know (via updating) the actual bridge resistance and applied loads. This is possible by regular inspections, but the final and best solution is to integrate permanent sensors to continuously monitor the structure. The final step in the process is to have a smart bridge. A new series of advanced sensors and techniques for long-term monitoring of bridges is becoming available thanks to the development of these techniques in other fields of engineering. The most suitable techniques are based on the use of optical fiber sensors and more specifically the use of Bragg grating sensors. The paper shows different experiences to show how this new technique can be successfully applied to the accurate long-term monitoring of bridges.

An Experimental Mechanics Approach to Structural Health Monitoring for Civil Aircraft

Nano Measurements on Biologically Inspired Structures

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The design philosophy for modern Civil Aircraft demands a structure that is free from propagating fatigue damage for at least the first half of its design fatigue life. Subsequently, well behaved growing fatigue damage is permitted providing that it can be detected by NDT

techniques and repaired within certain well defined inspection periods. This approach allows an economic airframe structure to be designed and maintained such that it 'grows old gracefully - but safely' and is not over designed to remain 'perfect' on its last day of operation. To achieve this design philosophy very strict NDT procedures are instigated on the aircraft structure at well defined check periods. This is time consuming - particularly in the case of an inspection where no detectable damage is present. The maintenance industry is expressing interest in the concept of 'condition monitoring' for cost reduction reasons - which is marvellous providing a way of determining true 'structural condition' could be found. Any such method must give higher confidence and be more economic than current NDT. This paper describes the development of a detection system that enables remote Structural Health Monitoring which has been developed from an Experimental Mechanics approach. By applying sensors to a component a 'biologically inspired' structure is produced effectively giving it a 'nervous system' that can detect the 'pain' of crack initiation and growth. Very precise laser measurements show that surface displacements of less than a 'nanometer' accompany the stress wave detected by piezo-electric sensors. This combination is used to produce what is in effect a remote 'Crack Growth Monitor' that benefits from an Experimental Mechanics approach. The development has produced a very advanced remote crack growth monitoring system for ground fatigue tests and opens up the possibility for application in flight. The issues that have to be address ed f or flight application are discussed.

Smart Structures Application to Airworthiness and Repair

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The present paper summarizes recent work, undertaken as part of a collaborative research program between DSTO and the DSTO Centre of Expertise in Structural Mechanics (CoE-SM), for development and assessment of new techniques for the in-situ health monitoring of structures and any associated repairs.

Experimental Investigation of Shrinkage Strains in Multilayered Stereolithography Parts

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The shrinkage characteristics of stereolithography built square laminate plates using an acrylic based photopolymer were studied after they have been post-cured under ultraviolet and thermal exposure. The specimen plates consisted of a resin plate laser cured on an identical plate of the same material that already had been cured and post-cured. The assembled laminate was then cured, and the resulting out-of-plane displacement (warpage) due to shrinkage was recorded by means of the shadow moir method. The exhibited warpage of the plates was related to the polymerization or cross-linking shrinkage strains through the elastic lamination theory, which was implemented to calculate the magnitude of the resulted shrinkage strains.

Suppression of Dimpling in Sheet Metal Parts Formed on Discrete Tooling

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Discrete-element reconfigurable tools are attractive for some low-volume metal forming processes. However, the use of these "pin" dies, where the ends of the pins are hemispherically shaped, can cause unacceptable dimpling of the finished parts. Thus, polymeric interpolators are used between the die and the part to suppress dimpling. This paper presents the results of experiments performed to characterize the dimpling process and to establish the requirements for useful interpolator materials.

Effect of Loading Rate and Geometry Variation on the Dynamic Shear Strength of Adhesive Lap Joints

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Dynamic and quasi-static experiments were performed using a novel lap joint specimen to evaluate the shear strength of adhesive bonded lap joints at different loading rates, length to width ratios and lap areas. Dynamic shear strength was determined by subjecting the lap joints to stress wave loading in a Split Hopkinson Pressure Bar (SHPB) apparatus. All joints were bonded by a general-purpose epoxy adhesive (Armstrong A-12®). The shear strength of the joint was determined using maximum transmitted load through the joint, assuming that the load was predominantly transferred through shear. A series of tensile and compressive experiments were performed to determine the shear strength of a lap joint, for loading rates varying from quasi-static to 2500 N/μsec. The results indicated that as the loading rates are increased to 1000 N/$^{\mu}$sec the shear strength of the particular adhesive bonded lap joint increases to three times its static value, after which it stabilizes. The effect of bonded length to width ratio on the shear strength of similar lap joints was also experimentally investigated for both quasi-static and dynamic loading conditions. Experimental results showed that maximum dynamic shear strength is achieved for a length to width ratio of 0.8. Experiments based on a 3×3 factorial design indicated a statistically significant effect of bonded length to width ratio on the dynamic shear strength of lap joints. A disordinal interaction was observed for bonded length to width ratio and bonded area, implying that the main effects of length to width ratio and bonded area on the dynamic shear strength of joints are not separable.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION R3H
Fracture and Fatigue I

The Origin and Inception of Fatigue in Steel - A Probabilistic Model

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This paper presents a simple model to simulate the fatigue behavior of materials. The model consists of a system of parallel springs, each with a non-linear stress-deformation behavior. The applied stress is modeled as a random variable. Using a probabilistic analysis, the system is subject to a series of stress applications. Upon each stress application, a certain number of springs fail. When a sufficiently large number of springs fail, the entire system is considered to have failed. The number of stress cycles corresponding to this condition is considered to represent the fatigue life. This system's behavior is similar to fatigue damage accumulation in materials and fatigue failure. The description of the model is presented in the paper along with a numerical illustration to demonstrate its applicability. The paper also discusses the areas where the model can be further developed to obtain a broader understanding of the fatigue behavior of materials.

Fatigue Damage Tolerant Analysis Using the Fatigue Damage Map

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Based on the principles of microstructural fracture mechanics the current work demonstrates the physical relationship between the size of crack plasticity and the five stages of crack growth from catastrophic crack initiation to failure. The relationship allows the continuous evaluation and distinction of the five stages of fatigue damage in the form of the Fatigue Damage Map (FDM). The FDM is used to determine the limits of damage tolerance by providing information regarding stress and the crack length for near-threshold and unstable propagation.

Crack Growth Behavior and SIF's as Observed by Optical Methods

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A laboratory based experimental method consisting of a marriage between frozen stress photoelasticity and the near tip equations of linear elastic fracture mechanics is applied to two three dimensional cracked body problems. Stress intensity factor distributions were determined for cracks in models of nuclear pressure vessels and rocket motor grain providing validation of numerical results.

A Model for Failure Initiation in Ductile Materials

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Initial results from a set of three-dimensional unit cell simulations clearly demonstrate the nature of the relationship between local constraint and local failure initiation

processes. The simulations show that the deformations are substantially different under high and low levels of stress constraint; the effective plastic strain at failure initiation is quite small under high triaxial stress constraint, increasing rapidly as constraint decreases. Through extensive parametric studies, the numerical results demonstrate that two-parameters – triaxial stress constraint and effective plastic strain – are sufficient for development of a three-dimensional ductile fracture criterion that is consistent with void growth concepts. Additional support for the proposed criterion is provided by experimental evidence that indicates the effective plastic strain at failure initiation is a monotonic function of stress constraint.

Crack Paths in Adhesive Bonds

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The reliability of a joint subjected to mechanical and thermal loads during processing and service constitutes a major technical problem. Joints contain flaws. The observed strength of a joint depends upon the location and size of the flaws, as well as the crack path through the joint. The aim of this investigation is to examine the path of a crack in an adhesive bond. Sandwich Brazilian disk specimens made of two aluminum adherends joined by a thin layer of epoxy are employed in the testing. This specimen allows for a wide range of mixed mode loading. A paraffin pre-crack is located within the adhesive layer. During testing, all cracks divert from within the layer and grow toward and into the interface. Comparison of crack path direction is made to two theories.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION R4H
Fracture and Fatigue II

Experimental Determination of Fracture Parameters for Predicting Crack Growth in Viscoelastic Polymers

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A micromechanical model for a viscoelastic cohesive zone has been previously formulated and based on a continuum mechanics model of the damage zone ahead of the crack tip in a polymer solid. The scale of the cohesive zone model is quite small, thus rendering it difficult to obtain the cohesive zone parameters experimentally. Presented herein is an experimental procedure for measuring the crack tip opening, damage zone profile ahead of the crack tip, crack tip opening rate, critical fibril breaking length and diameter. It is then shown that these parameters can be used to characterize the viscoelastic cohesive zone model.

Failure of Spot Weld: A Competition between Crack Mechanics and Plastic Collapse

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Spot weld made by resistance welding has been widely used in joining sheet metal of auto body since 1950's. Every modern car has over 2000 spot welds. Failure of the spot weld is therefore an important concern to auto body durability and safety design. Spot weld can fail in two completely distinct modes, namely, nugget pullout failure and interfacial failure. In this paper, we show that the nugget pullout failure is caused by plastic collapse and the interfacial failure is governed by crack or fracture mechanics. These two failure mechanisms compete each other and failure of a spot weld occurs as one of the failure criterions is first satisfied. Test data from General Motor Corporation, Daimler-Chrysler, The Welding Institute and the University of South Carolina are used to validate the theoretical prediction. Recommendation is made for minimum weld nugget size for a given sheet metal thickness so that nugget pullout failure, the acceptable mode of failure in industry, is ensured.

Investigating the Effects of Specimen Thickness and Pressure on the Crack Growth Behavior of a Particulate Composite Material

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In this study, the effects of specimen thickness and confined pressure on the crack growth behavior in a particulate composite material, containing hard particles embedded in a rubber matrix, were investigated. The experimental data were analyzed and the results are discussed.

Dynamic Fracture Experiments Using Point Impact

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This paper summarizes experimental results on dynamic crack initiation, using one- point impact technique. Two specific issues will be addressed here. The first concerns the determination of the mode I dynamic fracture toughness of small cracked beam specimens. Next, some basic results related to the testing of standard Charpy specimens at high impact velocities will be presented. All these tests have in common the fact that the impact is applied in one point to an unsupported specimen, so that fracture is triggered by inertial effects only.

Experimental and Numerical Investigation of Shear-Dominated Intersonic Crack Growth and Friction in Unidirectional Composites

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Dynamic crack growth in unidirectional graphite/epoxy composite materials subjected to in-plane impact loading is investigated experimentally and numerically. The experiments are conducted using CGS (Coherent Gradient Sensing) Interferometry in conjunction with high-speed photography to visualize the crack growth events. Cracks are found to propagate at subsonic speeds in the Mode-I case, whereas in both mixed mode and Mode-II the crack tip speed clearly exceeds the shear wave speed of the laminate. For these intersonically growing shear (Mode-II) cracks a shock wave emanating from the crack tip is observed. This provides direct evidence that the cracks propagate faster than the shear wave speed of the composite. The crack tip speed is initally observed to jump to a level close to the axial longitudinal wave speed along the fibers (7500 m/s) and then to stabilize to a lower level of approximately 6500 m/s. This speed corresponds to the speed at which the energy release rate required for shear crack growth is non-zero as determined from asymptotic analysis. The CGS interferograms also reveal the existence of large-scale frictional contact of the crack faces behind the moving shear cracks. In addition high speed thermographic measurements are conducted that show concentrated hot spots behind the crack tip indicating crack face frictional contact. These experiments are modeled by a detailed dynamic finite element calculation involving cohesive elements, adaptive remeshing using subdivision and edge collapse, composite elements, and penalty contact. The numerical calculations are calibrated on the basis of fundamental material properties measured in the laboratory. The computational results are found to be in excellent agreement with the optical experimental measurements (crack speed record and near tip deformation field structure). For shear crack growth, the numerics also confirm the optical observation of large-scale crack face contact.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION F2E
Neutron Diffraction and
Synchrotron Radiation Methods I

High-Resolution Neutron Diffraction Techniques for Strain Scanning

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Several high-resolution neutron diffraction techniques using Bragg diffraction optics based on cylindrically bent perfect crystals which have been tested with the aim of their efficient exploitation for strain/stress are summarized. Presented experimental results demostrate their experimental abilities for nondestructive testing and evaluation of a phase and deformation response of polycrystalline materials on residual stress or deformation loading. Due to the unique resolution and good luminosity achieved by focusing in real and momentum space, besides the macrostrain scanning, the presented techniques are also qualified for micro-strain/stress studies by an analysis of the diffraction profiles. At the medium flux reactor LVR-15 in NPI Řež there are operating two focusing

double axis strain/stress diffractometers. Good luminosity of the diffractometers and a sufficiently high-resolution (FWHM of the instrumental $\Delta d/d$ - profile can be less than 2^{-3} at $d_{hkl} = 0.2$ nm) permit investigations of both the macro- and microstrains in the sample gauge volumes of several cubic millimetres with a sensitivity in the relative peak shift of several 10^{-5} rad.

Draft Standard for the Measurement of Residual Stresses by Neutron Diffraction

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Residual stresses can have important consequences for the load carrying capacity and safety of engineering components. Neutron diffraction is a non-destructive method for determining residual stresses in crystalline materials. It is a relatively new technique and no standard is currently available for making these measurements. This paper gives the background to research that has been carried out to develop a standard. It outlines the main findings and indicates the precautions that are required to achieve accurate positioning and alignment of specimens (and components) in a neutron beam and the analysis required to obtain reliable results. It also shows that special attention is needed in dealing with near-surface measurements because of surface aberration. It is demonstrated that, provided the recommended procedures are followed, a positional tolerance of ± 0.1mm can be achieved with an accuracy in strain of $\pm 10^{-4}$ to give a resolution in residual stress of ± 7 to 20 MPa in most materials of practical interest.

Microstresses Determined by Neutron Diffraction and Self-Consistent Model

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Neutron diffraction was successfully applied to measure the lattice strain distribution in polycrystalline materials. The experimental data were studied with help of self-consistent model. Using a non-standard method of analysis the values of macro and microstresses in textured ferritic steel were estimated. The validity of self-consistent model for prediction of mismatch stresses in two phase materials was examined. The theoretical results were successfully compared with the diffraction data for "in situ" tensile test. The parameters characterising elastoplastic deformation of polycrystalline grain were determined.

Residual Stress Measurements at the Metal/Ceramic Interface Using Modelling of Neutron Diffraction Spectrometer

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The aim of this work is to improve some experimental techniques dedicated to the evaluation of residual stress

(RS). These methods have been applied to a sample consisting of a glassy ceramic coating moulded on a metallic substrate (palladium-silver alloy) used in dental applications. Knowing the residual stress distributions is very important to determine the lifetime of the sample. We will describe a new approach to evaluate the RS at interfaces and in the bulk of materials, using neutron diffraction techniques. The RS in a glassy ceramic coated on metallic substrate are generated by the manufacturing process. They are present in the two materials. The RS depend principally on the thermal treatments imposed to the sample and they could have a very strong influence to the lifetime of the sample and in particular for the existing bounding between the metal and the ceramic. Moreover, the mechanical proprieties of glassy ceramic are known to be affected by proprieties of particle dispersed throughout the glassy matrix. The difference in the coefficients of thermal expansion (CTE) that exists between a ceramic and a metallic material could also be at the origin of a stress field. The first part of this paper concerns a development of a numerical simulation [1], [2] of whole two-axis neutron spectrometers. This programme allows correcting systematic errors due to the great parasitic peak shifts which appear when the measurements are carried out at the interface between two different materials [3]. The second part of this paper leads on the experimental determination of RS by neutron diffraction in the ceramic and metallic materials. These measurements were performed using different European facilities: D1A spectrometer at ILL (Grenoble, F) and E3 at BENSC-HMI (Berlin, D) for the analysis of the palladium substrate, and G5.2 spectrometer at LLB (CEA- Saclay, F) for the characterisation of the glassy ceramic coating.

Elastoplastic Deformation of Two Phase Steels Studied by Neutron Diffraction and Self-Consistent Modelling

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In situ neutron diffraction experiments allow the measurement of phase specific strain, and thus stress, in a multi-phase system. Further, monitoring of multiple hkl lattice planes provides information as to the response of differently oriented grains within the polycrystal. These experimental results can be compared directly with predictions from a self-consistent Hill-Hutchinson model modified to take into account the presence of the second phase. The techniques and ideas are demonstrated with recent tests on two practical engineering steels (1) ferritic steel, with a small volume fraction of carbon in the form of cementite and (2) duplex steel, consisting of approximately equal amounts of austenitic and ferritic phases. Good qualitative agreement was obtained between model and experimental data in each case. Issues affecting the use of such a model for two phase systems are discussed. The interpretation of residual stress measurements, for both single peak and Rietveld multi-peak measurements is considered.

RECENT ADVANCES IN
EXPERIMENTAL MECHANICS

In Honor of Professor I. M. Daniel

SESSION F3E
Neutron Diffraction and
Synchrotron Radiation Methods II

Residual Stresses and Elastic Constants in Thermal Deposits

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In this study we investigate experimentally and theoretically the influence of various aspects of the pore structure on residual stress, coating adhesion to the substrate and elastic properties of the coating. For that purpose, feedstock powders of Inconel 625 were prepared with four different particle size distributions. The coatings were prepared by air-plasma spraying under nearly identical spray conditions on grit blasted steel substrates. Neutron diffraction was used to determine the average in-plane residual stresses in the coatings. The in-plane Young's modulus was determined using a four-point bending apparatus. The porosity and the pore distribution were characterized using small-angle neutron scattering as well as precision density measurements. It was found that both

the residual stresses and the elastic modulus of the coatings sprayed with coarse powder were considerably lower than the stresses in the coatings sprayed with the smaller particles. As the particle size decreases, a rising oxide content in the coating as well as a change in the pore distribution elevate the elastic modulus and, as a consequence of that, the residual stresses. The most pronounced effect on the pore distribution is a lower fraction of connected porosity which effectively decreases the pore aspect ratio. With no ductility left due to the embrittlement effect of the oxide particles, these coatings exhibit a low strain tolerance and the residual stresses are close to their maximum level.

Neutron Diffraction Assisted Residual Stress Analysis in Welded Structures

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Welding residual stresses in structural components can significantly compromise their performance and lifetime. Prediction of welding stresses based on numerical modeling has not yet proven to be reliable, while measurement of such stresses based on NDT remains a challenging task. It is shown in this paper that neutron diffraction is a reliable non-destructive method for residual stress analysis in structural weldments. The Large Component Neutron Diffraction Facility (LCNDF) at the High Flux Reactor (HFR), Petten has facilitated residual stress measurements in various weldments, including large steel piping welds. A key issue in applying neutron diffraction to welds is the reliable estimation of the stress-free lattice distance in the heat affected zone and weld pool and in all directions of interest. Results of numerous investigations at HFR show that this is achievable by testing small coupons, cut from a companion weld specimen, which are nearly free of macro-stresses and consequently it is reasonable to be used as reference specimens. In fact, the feasibility of this approach has been demonstrated in monolithic and bimetallic welds. In this paper residual strain/stress data in five welded specimens, based on neutron diffraction, are presented. The results presented in this paper consistently show that, by ignoring the spatial and directional variation of the reference lattice distance, which is exhibited throughout the weld pool and the heat affected zones, erroneous strain data can be derived leading to non self-equilibrating internal stress estimates.

Synchrotron Radiation In-Situ Analyses AA 6061 $+AL_2O_3$ During Tensile Deformation at Ambient and Elevated Temperature

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High energy synchrotron radiation enables the in-situ determination of the elastic strain developing during deformation of metals and especially of metal matrix composites. By using a white beam the strain response can be characterised simultaneous with texture development. The high photon flux of the synchrotron beam allows short data acquisition times and thus an in-situ combined stress and texture determination is possible at high temperature. Here results of investigations of the tensile load stress - elastic strain response of aluminium metal matrix composites are presented.

Symposium on

Mechanics of Liquid-Gas and Liquid-Solid Interfaces

In Honor Of
Professor S. Davis

Organizer:
Professor Paul Neitzel (Georgia Institute of Technology)

MECHANICS OF LIQUID-GAS AND LIQUID-SOLID INTERFACES I

In Honor of Professor S. Davis

SESSION T4E

Modeling of Solidification Microstructures

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The motion of the liquid-solid interface during solidification is subject to complex pattern formation due to the interaction of thermal and solutal fields, along with instabilities associated with capillarity. Prof. Davis and his coworkers have been instrumental in developing the underlying theory for the understanding of this process. After a brief discussion of the basic theory of morphological pattern selection, recent work on modeling dendritic microstructures will be presented. A phase-field method, coupled with adaptive 3D finite element analysis, is used to model the evolution of dendrites in the presence of fluid flow in the melt. Connections will be made between the fundamental theory, experiments, and large-scale numerical computations.

Modeling Mushy Layers During Ternary Alloy Solidification

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In the present work we formulate a model for the solidification of a ternary alloy from a cooled boundary. The model has much in common with models of mushy layers for binary alloys, however, the additional solute component present in ternary systems has important implications. In particular, we focus on growth conditions under which the solidification path through the ternary phase diagram gives rise to two distinct mushy layers. In the upper mushy layer, corresponding to higher temperatures, the primary solid phase solidifies. In the lower mushy layer, corresponding to lower temperatures, the evolution follows a cotectic line in the ternary phase diagram and a different solid phase forms. These two mushy layers are bounded above by a liquid layer and below by a eutectic solid layer. Our modeling has been motivated by recent experimental work on the solidification of a ternary alloy [1], where the double mushy layer structure was identified. We obtain a one-dimensional similarity solution for this ternary alloy system and investigate its dependence on the system control parameters. We also discuss possible convective states associated with the ternary mushy layer system.

[1] Aitta, Huppert and Worster, J. Fluid Mech. v. 432, 2001, pp. 201-217

Reactive Wetting and Spreading in Solder Systems

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The growing use of lead-free solders has generated a need for further fundamental investigation concerning the wetting and reaction of the new solder alloys on the most commonly used metallizations. Since the most popular

candidates for lead-free solders are tin-based, a combined experimental and theoretical investigation has been undertaken to better characterize the behavior of liquid tin spreading on gold, copper and bismuth substrates. Experimentally, a rapidly melted solid drop is used to study the wetting and spreading behavior of tin on a solid metal substrate in an environment which inhibits oxide formation. The behavior of liquid tin spreading on gold and bismuth is presented. High speed video imaging is used to obtain the temporal evolution of the contact line. Generally, a primary capillary spreading regime is followed by slower secondary spreading. For the metal/metal systems substrate solubility plays a key role in the secondary spreading behavior.

In order to better understand the behavior observed in the drop spreading experiments, two different computational models are employed. A drop spreading model which incorporates dissolution of the substrate by the advancing drop is used to investigate the secondary spreading regime. The model treats radial solute transport in an axisymmetric drop with evolving liquid/gas and solid/liquid interfaces. The Gibbs-Thomson condition is applied at the solid/liquid interface. The model yields results for the extent of spreading which are in very good agreement with experimental data. An evaluation is made of the role played by bulk flow compared to solute diffusion in the model. Additionally, the effect of Marangoni convection driven by solute gradients on non-reactive drop spreading is modeled using a two-dimensional flow model based on the full Navier-Stokes equations.

Long-scale Evolution of Thin Films of Molten Metal on a Substrate

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Pulsed laser interaction with thin metal films is important for many applications such as trimming of electronic components and fabrication of sensors. In experimental studies [1] several phenomena are observed when an initially isothermal film on a substrate is subjected to a laser pulse. The film quickly melts and then flows away from the center due to thermocapillary stresses, creating axisymmetric ridges and sometimes leading to the formation of small droplets. The area in the center dries out and remains dry after the melt solidifies. The purpose of our work is to develop mathematical models capable of describing the experimental observations

We show that due to the very small thickness of the metal film a standard thin-film analysis is appropriate. We derive and solve the long-scale evolution equations describing thermocapillary flow with evaporation. The effect of thermocapillary stresses enters the model through the linear dependence of surface tension on the interfacial temperature. In order to investigate possible film rupture one has to include the disjoining pressure terms. Several possible descriptions of such terms for liquid metals have been discussed in the literature [2,3], but their implications for the process of thin film rupture have received little attention. We investigate the dry-out in the framework of the simple power-law dependence of the disjoining pressure on the film thickness, although other possible mechanisms can also be considered in the framework of our thin-film model. The results of our numerical simulations are compared with the experimental data.

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A Dimpling Instability in Thin, Axisymmetric Liquid Droplets Heated From Below

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When a droplet is placed on a solid surface, it will spread to a finite equilibrium size if it only partially wets the solid. After this spreading process is over, there is no further fluid motion inside the drop. When the solid is uniformly heated, the droplet will spread to a finite size that is smaller than the case of the unheated drop (as shown by Ehrhard & Davis, 1991). However, there will always be a thermocapillary-driven flow inside the drop even after it has reached its equilibrium size. This flow is due to the variable thickness of the drop from its contact line to its center, which induces a temperature variation on the free surface and therefore a surface-tension-driven flow along the free surface from the hotter contact line to the cooler center. In this work, we shall show that this flow in unstable to axisymmetric disturbances if the uniform heating is large enough. We shall compare this instability to the rupture of a thin liquid film heated from below and show that the instability mechanisms are essentially the same in both cases.

MECHANICS OF LIQUID-GAS AND LIQUID-SOLID INTERFACES

In Honor of Professor S. Davis

SESSION W3E

Contact-Line Dynamics: Recent Developments

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Moving contact lines have been studied intensively for thirty years mainly for the simpliest case of viscous and surface tension interactions only. Here we shall discuss some generalizations to systems with thermocapillarity, phase transformation, viscoelasticity, and inertia.

Contact Line Flow in a Rotating Horizontal Tube[1]

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The application of lubrication theory is revisited for film flow inside a rotating cylinder. High-order solutions based on the dimensionless film thickness are provided with capillary effects included. The results show that surface tension and higher-order terms allow better comparison with experiments, but significant differences still exist. A much-improved prediction of the thin film at both high and low rotation speed is achieved by introducing the centrifugal force in the r-momentum equation, and the pressure gradient term in the theta-momentum equation. Film flow within a horizontal, axially rotating cylinder provides a simple framework for studying a viscous, free-surface flow. The contact line singularity is alleviated by introducing a thin wetting layer for the entire solid surface, maintained in a state of equilibrium by excess or disjoining pressure that is often divided into molecular, ionic-electrostatic, and structural components Rich phenomena are observed including the limiting cases: a symmetric liquid puddle on the bottom and solid-body rotation in a uniform thickness, corresponding to zero and infinite rotating velocity, respectively. Perturbation methods can find solutions of film flows in a large range of the rotation speed using either the ratio of the average film thickness to the cylinder radius or the ratio between gravity and the viscous force. Results show that lubrication solutions are only appropriate for intermediate flows even with high-order contributions included. To extend the validity range of the lubrication theory, we include disjoining pressure in the dynamic interfacial boundary condition, the centrifugal force and pressure gradient in the momentum equation. Our results show that much improved predictions for both fast and slow flows are achieved. Our numerical results show that the extended lubrication analysis can provide a much-improved model for thin films as compared to our and other's experiments.

[1] Supported by NASA Microgravity Physics

Interface Instability and Capillary Switches

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A liquid/liquid or liquid/gas interface whose shape is largely determined by the force of surface tension is called a capillary interface. Capillary interfaces are subject to instability, depending on their configuration. Liquid slugs, bridges and attached droplets are examples of capillary elements whose instability can be controlled via contact with solid boundaries and/or via communication with reservoirs. Combinations of capillary elements can exhibit bi-stable behavior, the defining characteristic of a capillary switch. We illustrate how capillary switches can be built from mono-stable components. Performance of the switch depends on the response of its capillary elements. Bistable behavior is captured in a force-deflection (e.g. pressure-volume) response diagram. We restrict to axisymmetric switches and compare predicted behavior with experimental observation. To be practical as microfluidic devices, one must be able to amplify the weak force of capillarity and to be able to reliably trigger the switches. Amplification can occur through parallel action while reliable triggering may be achieved in a variety of ways. The Palm Beetle provides an example from nature that focuses these issues.

Recent Results on Permanent Non-Coalescence and Non-Wetting

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It has been demonstrated (Dell'Aversana et al 1996, Dell'Aversana & Neitzel 1998, Neitzel & Dell'AVersana 2002) that the coalescence of two bodies of the same liquid or the wetting of a solid by a liquid may be suppressed indefinitely by imposing relative tangential motion between their interfaces, dragging surrounding (lubricating) gas into the space between them. This tangential motion may be provided by mechanical forcing or by bringing the two bodies to sufficiently different temperatures, employing the phenomenon of thermocapillarity. Recent experimental efforts have focused on understanding the effects of static electrical charge on the failure of the lubricating layer for both thermocapillary and sliding non-wetting cases and quantifying the vibratory environment of pinned droplets. In addition, recent efforts have been aimed at the numerical simulation of two-dimensional non-wetting cases. These will be discussed in this presentation.

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Symposium on

Advances in Composite Materials

In Honor Of
Professor G. Dvorak

Organizers:
Professor Z. Bazant
(Northwestern University)

Professor S. Torquato
(Princeton University)

Professor R. M. Christensen
(University of California)

ADVANCES IN COMPOSITE MATERIALS I

In Honor Of Professor George Dvorak

SESSION M3J

Failure Plane Orientations for Fiber Composites

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Abstract-Using a recently developed failure theory for transversely isotropic fiber composites, it is shown how the orientation of the failure surface can be determined for transverse tension and compression. It is also shown that failure surface orientations decompose into those of ductile type versus those of brittle type. Experimental data on failure surface orientations have been obtained for four carbon fiber composite systems based on both thermoplastic and thermosetting matrix materials. Average compression failure planes for the different composite materials were measured to range from 31° to 38° from the load axis. Reasonable agreement was obtained between these measured angles and those predicted from application of the new failure theory.

On the Spallation of Graded Coatings

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Graded Materials, also known as functionally graded materials, are generally multiphase composites with continuously varying volume fractions. Used as coatings and interfacial zones they tend to reduce the magnitude of stresses resulting from material property mismatch, increase the bonding strength, improve the surface properties and provide protection against adverse thermal and chemical environments. Thus, the concept of grading the thermomechanical properties of materials provides the material scientists and design engineers with an important tool to process and use new materials tailored for some specific applications. One such application of this new class of materials is as top coats or bond coats in thermal barrier systems. A widely observed failure mode in these layered materials is known to be interface cracking that leads to spallation fracture. In many cases it is the buckling instability of coating under mechanically or thermally induced large compressive loads that triggers spallation. In this lecture the interface crack problem for a graded coating is considered as an elastic stability problem. Under in-plane loading since the linear elastic deformation theory gives only a trivial solution, the interface crack problem is formulated by using a geometrically nonlinear continuum mechanics theory. A standard perturbation theory is used to reduce the problem to an eigenvalue problem and to determine buckling instability load. This solution provides a benchmark to assess the effectiveness of the results obtained from a plate theory and numerical postbuckling analysis

The primary objective of the study is the investigation of the effect of material nonhomogeneity and stiffness in graded coatings on the instability load, the postbuckling behavior and the fracture mechanics parameters such as the strain energy release rate and the stress intensity factors.

Computational and Analytical Approaches to Scaling in Solid Mechanics: From Nano to Mega

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In contrast to fluid mechanics, the deterministic problem of scaling in solid mechanics (i.e., the change of structural response caused by a change of size or scale) has long been neglected. One reason is that the classical theories, such as plasticity, elasticity with a strength limit, continuum damage mechanics and linear elastic fracture mechanics, possess no characteristics length. In that case the scaling is trivial – it is given by a power law. The problem becomes interesting in various modern theories that involve a characteristic length. In that case, the scaling law is generally a transition from one power law to another. Determination of the general properties of response in the transitional 'scale-bridging' range, typically the range of practical interest, is usually very difficult, which is why only particular cases are normally tackle d. Computational approaches, consisting of nonlocal and gradient models and cohesive crack model, serve this purpose, but not completely. In the case of scale bridging, the asymptotic properties on adjacent scales should be taken into account and the technique of asymptotic matching — a smooth 'interpolation' between the opposite asymptotic scaling laws (whose philosophy is borrowed from fluid mechanics) – should be exploited. Such asymptotic approximations began to be developed about a quarter century ago in connection with some special concrete structures, and recently they have been extended to many other materials.

Progressing from nano-scale to mega-scale, the lecture attempts a broad, albeit selective, review of recent results. First the discussion if briefly focussed on Gao, Huang, Hutchinson and Nix's dislocation-based theory of strain-gradient plasticity on the micrometer scale. Certain peculiar features of the nano-scale extension of the existing theory are pointed out, along with some possible remedies. Subsequently, the size effects on the milimeter scale, exhibited by kink-band propagation in fiber-polymer composites and by fracture of polymeric foam cores in sandwich shells, are examined, comparing computational results obtained by the cohesive crack or crack band model with asymptotic approximations based on J-integral and effective LEFM. Numerical solutions and asymptotic approximations of deterministic size effects on the scales from decimeter to 'mega-meter', which are encountered, e.g., in the fracture of sea ice, failure of concrete structures, and triggering of snow avalanches or mountain slides, are reviewed. Finally, interaction of the deterministic (energetic) and probabilistic size effects in concrete and fiber composites is described by nonlocal stochastic simulations as well as asymptotic approximations, and the inability of the existing stochastic finite element methods to capture Weibull-distributed far-off tails governing loads of extremely small failure probability is highli ghted. Numerical results and asymptotic approximations are compared to pertinent experimental data on scale effects in various materials. In closing, it is emphasized that the neglect of size effects must have been a significant con-

tributing factor in some famous catastrophic failures.

Reference:
Z.P. Bazant, Jour. of Mech. & Physics of Solids, in press.

Keywords: Fracture, Size Effect, Quasibrittle Materials, Plasiticity .

Constitutive Modelling of Composites and Laminates Based on Homogenization and Parameter Identification

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The study summarised herein concerns the following methodology, which may be useful in engineering analysis and design of composite structures.

To overall analysis purposes, a constitutive model in average stresses and strains (i.e. at the macro-scale) is chosen on the basis of qualitative essential features of the expected material behaviour, and of practical considerations on the pursued optimal compromise between the requirements of accuracy and computing economy.

Homogenization procedures based on the geometry of a representative volume and on the local (at the micro-scale) constitutive models adopted for the various phases (including interfaces) generate average stress responses to a number of suitably selected average strain paths.

The computed stress responses are employed as "pseudo-experimental data", as substitutes for or supplements to truly experimental data, for the quantitative identification of the parameters contained in the macroscopic constitutive model preliminarily chosen for the overall structural analysis.

The following features of the above methodology are discussed herein:

(a) the computationally efficient generation of the input paths in the space of average strains;

(b) the calibration of the chosen macro-scale model.

The former problem is solved with recourse to the geometrical theory and numerical techniques concerning regular polytopes, although an alternative approach is also envisaged.

For the latter (inverse) problem, both deterministic least-square techniques and sequential stochastic Kalman filter procedures are employed and comparatively discussed.

The presented numerical tests and practical applications concern: an epoxy-matrix E-glass-fiber periodic composite used for offshore structural components, the macroscopic model of which exhibits a transversally isotropic linear-elastic-brittle behaviour; a laminate composite with a rather ductile behaviour intended for insulators of high-voltage transmission lines. In the latter engineering situation, the proposed methodology is applied twice: first to the single ply, described in its plane by a viscoplastic model formulated in terms of average stresses and strains; then to the laminate, described by another viscoplastic model formulated in terms of generalised stresses and strains for plates in bending.

The Saint-Venant Torsion of a Circular Rod Consisting of a Composite Cylinder Assemblage

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We consider the Saint-Venant torsion of a cylindrical rod of a circular cross section which is completely filled by an assemblage of cylindrical circular rods. The constituent circular rods consist of a core and a coating both of which may be cylindrically orthotropic. The volume fraction of the core and coating is the same in all the constituent rods. The achieved microstructure is thus that of Hashin and Rosen's Composite Cylinder Assemblage which is now in torsion. We prove the following: a) The warping function on the lateral surface of the host rod is zero, b) Its torsional rigidity is independent on the positions of the constituent rods but is dependent on their size distribution, c) An exact expression for the torsional rigidity of the host rod is derived which depends on the size distribution, d) Under a certain combination of the properties of the constituent rods, the torsional rigidity becomes size-distribution independent, and is given by a very simple expression. If the coating disappears and the core is cylindrically orthotropic we get the configuration cf a polycrystalline rod. Simple bounds for the torsional rigidity of the constructed composite rod are obtained. It expected that the derived results may be of interest in bone mechanics and Carbon-Carbon composites.

ADVANCES IN COMPOSITE MATERIALS II

In Honor Of Professor George Dvorak

SESSION M4J

Actuated Composite Truss Plates

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Plates comprised of a solid face sheet backed by a truss structure with selected members that can be actuated are investigated for the purpose providing controlled displacements of the solid face sheet. The truss structure is a Kagome planar truss connected to the solid face sheet by tetragonal core members. The advantage of the Kagome planar truss, which appears to be unique to this geometry, is that its members can be actuated without internal resistance, apart from very small bending resistance due welded joints. Deformations of the composite truss plates that can be achieved with negligible stored elastic energy are detailed.

Maximally Random Jammed State of Particle Packings

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Bernal has remarked that "heaps (random close-packed arrangements of particles) were the first things that were ever measured in the form of basketfuls of grain for the purpose of trading or of collection of taxes." Random packings of identical spheres have been studied by biologists, materials scientists, engineers, chemists and physicists to understand the structure of living cells, liquids, composites, granular media, glasses and amorphous solids, to mention but a few examples. Despite its long history, there are many fundamental issues concerning random packings that remain elusive, including the nature of the venerable 50-year old notion of "random close packing" (RCP) state. We show that the RCP concept is not mathematically precise by introducing scalar metrics to characterize disorder and using molecular dynamics siumlations. To replace the old notion of the RCP state, we introduce the new concept of a maximally random jammed (MRJ) state, which can be made precise [1].

This lays the mathematical groundwork for studying randomness in dense packings of spheres and initiates the search for the MRJ state in a quantitative way not possible before. But what does one mean by a "jammed" state? We have devised several definitions [2], one of which is the "strictly jammed" state. This concerns whether the equivalent "contact" network is stable under deformations. The particle packing can be transformed to an equivalent "contact" network by joining the centers of contacting particles by lines. Once this equivalent network is determined, we are able to pose the stability question as a novel optimization problem. Specifically, overall deformations are imposed on the boundary of the network and the stability analysis is reduced to a linear programming problem [3]. If the network does not deform under these boundary conditions, then it is stable, or, equivalently, the packing is strictly jammed. If the network deforms, then the packing is not strictly jammed.

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3. A. Donev and S. Torquato, in preparation.

Elastically Optimal Microstructures in the High-Porosity Regime

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This talk unifies two themes that have up to now been investigated separately. The first is the analysis of high-porosity microstructures — where attention has mainly been devoted to special structures such as lattices. The second is the design of elastically-optimal microstructures — where a construction known as "sequential lamination" achieves optimality, but not manufacturability, at any value of porosity.

We unify these themes by examining a new class of high porosity structures, called "single scale laminates." These structures are simple enough to be easily described and manufactured, yet complex enough to include elastically optimal structures with any (possibly anisotropic) Hooke's law. In 2D, single-scale laminates are trusses, made using several families of parallel members; the square and triangular lattices are special cases. In 3D they

are closed-cell foams, made using several families of parallel thin walls.

Mathematically, single-scale laminates can be viewed as sequential laminates "without the separation of scales." Our main technical achievment is to show that in the high-porosity limit, the effective behavior of a single-scale laminate is the same to principal order as that of the associated sequential laminate.

Field Fluctuations and Macroscopic Properties in nonlinear composites

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This talk is concerned with a second-order homogenization method incorporating field fluctuations for nonlinear composite materials. The idea is to combine the desirable features of two different, earlier methods making use of "linear comparison composites," the properties of which are chosen optimally from suitably designed variational principles. The first method makes use of the "secant" moduli of the phases, evaluated at the second moments of the strain field over the phases, and delivers bounds, but these bounds are only exact to first order in the heterogeneity contrast. The second method makes use of the "tangent" moduli, evaluated at the phase averages (or first moments) of the strain field, and yields estimates that are exact to second-order in the contrast, but that can violate the bounds in some special cases. These special cases turn out to correspond to situations, such as percolation phenomena, where field fluctuations, which are captured less accurately by the second-order method than by the bounds, become important. The new method delivers estimates that are exact to second order in the contrast, making use of generalized secant moduli incorporating both first- and second-moment information, in such a way that the bounds are never violated. The new theory will be used to estimate the macroscopic behavior and field fluctuations in some model composite systems.

Inelastic Response of Random Fibrous Composites

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An accurate representation of time dependent inelastic response of polymeric composite systems with disordered microstructures is developed within the framework of classical homogenization method. A graphite fiber tow impregnated by an epoxy resin is selected as an example of such systems. While the deformation of fibers is generally assumed to remain within the elastic regime, the matrix phase may undergo an inelastic deformation conveniently described by the generalized Leonov model. Two different approaches are examined. In the first approach the complicated real microstructure is replaced by a material representative volume element with a small number of particles, which statistically resembles the real microstructure. Periodic distribution of such unit cells is considred and the numerical computation is carried out via the finite element method. The second approach exploits the Hashin-Shtrikman variational principles. The random character of the fiber distribution is incorporated directly into the variational principles employing certain statistical descriptors. It should be mentioned that the present medium is sufficiently described by the two-point probability function. Applicability of both approaches to the description of inelastic response of the present material systems will be further tested in conjunction with large multiscale analysis of vowen composite tubes.

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ADVANCES IN COMPOSITE MATERIALS III

In Honor Of Professor George Dvorak

SESSION T3J

Scale-Dependence in Nickel Alloys

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The concern of this work is the estimation of the flow stress for single-crystal Nickel-Aluminium alloys. Although they have a regular crystalline structure, they comprise a "matrix" (the gamma phase), containing significantly harder aluminium-rich "inclusions" (the gamma-prime phase). The concentration of deformation in the gamma-phase is associated with local strain gradients, and hence to an enhanced flow stress which is sensitive to the scale of the microstructure. The present work studies the effect of scale on the effective flow stress, by employing the recent Fleck-Hutchinson reformulation of strain-gradient plasticity together with methodology for calculating effective properties, initiated by Talbot and Willis

and Ponte Castaneda. The presence in the theory of the equivalent plastic strain as an internal variable introduces some novelty into the analysis.

A Comparison of Nonlocal Continuum and Discrete Dislocation Predictions for a Composite Material

E. Bittencourt, A. Needleman, M.W. Gurtin and E. Van der Giessen

Discrete dislocation plasticity analyses of a model composite material subject to simple shear show that the aggregate stress-strain response depends sensitively on whether or not there is a vein of unreinforced matrix parallel to the shear direction. If such a vein exists, the aggregate stress-strain response is essentially that of the matrix and there is no size effect. On the other hand, when all slip planes are blocked, hardening is associated with the density of geometrically necessary dislocations needed to accommodate rotation of the reinforcement and, furthermore, there is a large Baushinger effect on unloading due to the internal stresses that develop. The same boundary value problems are also analyzed using the nonlocal plasticity theory proposed by Gurtin (2002). Our calculations show that the effect of reinforcement morphology on the stress-strain response of the model composite material is captured for both loading and unloading. Implications for the phenomenological modeling of dislocation plasticity in small volumes and for the choice of nonlocal boundary conditions are discussed.

Debonding of Short Fibres Among Particulates in a Metal Matrix Composite

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In unit cell-model studies of failure in a composite the assumption of periodicity implies that identical failure occurs in each cell. As most studies have had one fibre in each cell, the situation represented has been one where all fibres debond from the matrix simultaneously. In the present investigation unit cells are considered that contain a number of short fibres or particulates, where some of them do not debond.

The numerical analyses are carried out to represent fibre-matrix debonding in an aluminium alloy reinforced by aligned, short SiC fibres. The metal matrix is represented as an elastic-plastic solid, while the short fibres are either rigid or elastic with a high elastic modulus. The cell-models are axisymmetric, thus giving a reasonable representation of the fibre geometries as circular cylindrical, and special boundary conditions for transversely staggered unit cells are employed, as this allows for the more general distribution of the different fibres and particulates among each others. The predictions for debonding fibres among different particulates with stronger bonds are compared with predictions for fibres that all debond.

Thermodynamics of Damage and Damage Evolution

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The primary role of damage mechanics is to estimate the effect of meso- and micro-scale cracks on the onset and mode of structural failure and the residual strength of aged or damaged structures. Deformation due to meso- and meso-cracks in quasi-brittle are typically small in comparison to the elastic deformation. The difficulty in modeling this process is that the material texture within the meso- and micro-cracks propagate is not homogeneous as required by the fracture mechanics. The disorder on the meso-scale is quenched (grains and grain boundaries) and imparted by the meso- and micro-cracks. Thus, the disorder changes with the density and patterns of cracks. Hence, the task of damage mechanics modeling is to estimate the nucleation, propagation and clustering of many meso- and micro-cracks of random geometry and sizes, which may interact.

Despite the disorder damage mechanics in the limit of a meso-cracks that do not interact, when the texture disorder does not affect the evolution process, and the dynamics of crack propagation can be ignored thermodynamics of dissipative processes when the thermodynamics of damage and fracture mechanics must be related. Following the Irwin's quasi-static model the propagation of a crack depends on the relation between the release energy rate, G, and free energy, R. According to the thermodynamic of the same quasi-static model the entropy production is, $\bar{T}\eta_p = (G - R)\dot{D}$, where $\bar{T}$ is the temperature that was kept constant at the surface of the volume and D a measure of accumulate damage.

The release energy rate, G, is on the meso- and micro-scale is not equal to the J-integral since the material is not heterogeneous. Since the thermodynamic affinity $\mathcal{A} = G - R$ is necessary to simulate the process of crack propagation on the lattices of different sizes. The affinity is the better parameter than the meso- and micro-scale than the stress. The thermodynamics with internal variable, which is the measure of damage D, and $\mathcal{A}$ as the conjugate force, can be used as the basis of the process on the macro-scale.

During the quasi-static damage evolution of a damage tolerant specimen subjected to uniform tensile stresses due to controlled applied elongation most of the hardening phase is driven by the nucleation of meso-cracks and their stable propagation. Close to the peak of the macro-stress and strain a large cluster (macro-crack) becomes the primary "force" of the dissipative process. The cooperative processes drive the damage evolution during the softening phase.

Non Linear Multiscale Material Modeling: from Periodic Homogenization to Eshelby Based Mean Field Methods

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Various techniques that allows to build the macroscopic behavior of materials from the local constitutive equations of phases, constituents and interfaces are reviewed and illustrated by some examples.

The periodic homogenization method is exploited to analyze creep behavior of SiC/Ti Metal Matrix Composites, including the fiber/matrix debonding and the thermo-elasto-viscoplastic behavior of titanium polycristalline matrix, treated by crystal plasticity through a second scale change based on mean field methods. The importance of texture description in the composite matrix is underlined by two kinds of transverse loading conditions.

Simplified macroscopic models are built up using the Transformation Field Analysis developed by Dvorak. A new corrected version is exploited for the same MMC's, leading to a macroscopic constitutive framework that includes damage effects at the fiber/matrix interface and the polycristalline crystal plasticity based matrix behavior.

Finally a discussion is developed around the use of tangent approaches for a better description of average stress redistributions in the Eshelby based mean field methods. For a typical but "stiff" example, a comparison is made between various localization rules. It is shown that tangent methods (incremental or affine) using the "correct" anisotropic terms in the Hill polarization tensor, deliver a much too stiff overall behavior. Contrarily the "uncorrect" isotropic approximation delivers a much softer response, more consistent with the reference exact solution. Discussing the vanishing of anisotropic terms under radial loading allows us to really question the usefulness of the "correct" anisotropic tangent modeling.

ADVANCES IN COMPOSITE MATERIALS IV

In Honor of Professor George Dvorak

SESSION T4J

Dynamic Response of Bulk Amorphous Metal Rods Reinforced with Refractory Metal Wires

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Cylindrical rods, being considered as possible projectiles for armor penetration, have been investigated through compressive Kolsky bar experiments. These rods are composed of a zirconium-based bulk amorphous metal matrix reinforced with longitudinal wires of either tungsten or tantalum to increase their mass density. Experiments were also conducted on the pure matrix material. Results of previous experiments were used to characterize the response of the tungsten and tantalum that was used for the wires. From these experimental results on the constituents a finite element model of the composite was developed and used for simulating the experiments. Experiments show that the tungsten-reinforced composite tends to fail by longitudinal splitting of the wires whereas the tantalum-reinforced composite is remarkably ductile. Simulations performed using ABAQUS are used to try to interpret these differences in response.

The Incompressible Limit in Linear Anisotropic Elasticity, with Applications to Surface Waves and Elastostatics

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Incompressibility is established for three-dimensional and two-dimensional deformations of an anisotropic linearly elastic material, as conditions to be satisfied by the elastic compliances. These conditions make it straightforward to derive results for incompressible materials from

those established for compressible materials. As an illustration, the explicit secular equation is obtained for surface waves in incompressible monoclinic materials with the symmetry plane at $x_3 = 0$. This equation also covers the case of incompressible orthotropic materials. The displacements and stresses for surface waves are often expressed in terms of the elastic stiffnesses, which can be unbounded in the incompressible limit. An alternative formalism in terms of the elastic compliances presented recently by Ting (2002) is employed so that surface wave solutions in the incompressible limit can be obtained. A different formalism, also by Ting (1999), is employed to study the solutions to two-dimensional elastostatic problems. In the special case of incompressible monoclinic materials with the symmetry plane at $x_3 = 0$, one of the three Barnett-Lothe tensors $\mathbf{S}$ vanishes while the other two tensors $\mathbf{H}$ and $\mathbf{L}$ are the inverse of each other. Moreover, $\mathbf{H}$ and $\mathbf{L}$ are diagonal with the first two diagonal elements being identical. Many interesting physical phenomena can be deduced using this property. For instance, there is no interpenetration of the interface crack surfaces in an incompressible bimaterial. When only the inplane deformation is considered, the image force due to a line dislocation in a half-space or in a bimaterial depends on the magnitude, not on the direction, of the Burgers vector.

Nonlocal Dispersive Model For Wave Propagation In Heterogeneous Media

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Nonlocal dispersive model for wave propagation in heterogeneous media is derived from the higher-order mathematical homogenization theory with multiple spatial and temporal scales. In addition to the usual space-time coordinates, a fast spatial scale and a slow temporal scale are introduced to account for rapid spatial fluctuations of material properties as well as to capture the long-term behavior of the homogenized solution. By combining various order homogenized equations of motion the slow time dependence is eliminated giving rise to the fourth-order differential equation, also known as a "bad" Boussinesq problem. Regularization procedures are then introduced to construct so called "good" Boussinesq problem, where the need for continuity is eliminated. Numerical examples are presented to validate the present formulation.

Generalized Hashin-Shtrikman Variational Principles

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The H-S principles are extended by introducing eigenparameters, which can act out role of either plastic strains, or relaxation stresses. The generalized H-S principles enable us to establish new variational principles in the nonlinear analysis of structures using the original idea of Prof. Dvorak. The numerical analysis will then follow from such principles streightforward: Finite elements do not need any arrangement, while extraordinarily advantageous boundary elements are even in nonlinear analysis of that type very effective (this is not true generaly). Recall that the problems using the TFA mostly lead to the system of linear equations, or, if constraints are used on design variables, they lead to pseudo-linear systems of algebraic equations. Couple of examples could be presented.

Scale and Boundary Conditions Effects on Elastic Moduli of Composites with Imperfect Interfaces

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Effects of scale and boundary conditions on the planar elastic moduli of composites are investigated using finite element analysis. The planar analysis may represent a transverse response of a unidirectional fiber-reinforced composite (plane strain), or a thin plate with disks (plane stress). The inclusions are assumed to have circular cross-sections of constant diameter. They are either arranged periodically or randomly in the matrix. In the analysis we consider three different inclusion/matrix interface models: perfectly bonded interface, imperfectly bonded interface modeled by frictionless sliding and separation, and interface represented by a thin interphase.

We study apparent properties of such composites. Apparent properties are material properties calculated using a "window of observation" smaller than the Representative Volume Element (RVE); the size of this "window" determines the scale. Effective properties are obtained using the RVE. In this analysis we consider several different scales (i.e. window sizes), different material mismatches,

and three types of boundary conditions to investigate how these factors influence apparent properties. The boundary conditions include traction boundary conditions (uniform stress), displacement boundary conditions (uniform strain), and mixed boundary conditions (involving a special combination of the above two boundary conditions).

Symposium on

Mechanics of Fibrous Composites

In Honor Of
Professor C. Herakovich

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MECHANICS OF FIBROUS COMPOSITES

In Honor Of Professor Carl Herakovich

SESSION W3S
Stress Analysis of Composites

The Nonlinear Response of a Damaged Composite Shell Subjected to Internal Pressure

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Recent studies of unstiffened aluminum shells with longitudinal cracks and subjected to internal pressure have shown that a nonlinear shell analysis and an elasto-plastic fracture mechanics crack growth criterion can reliably and accurately predict the crack growth characteristics of aluminum shells. The introduction of composite materials to future aerospace vehicles requires that a similar analysis methodology be developed to assure the structural integrity and residual strength of composite structures subjected to internal pressure.

The proposed paper will describe the results of an experimental and numerical study of an unstiffened graphite-epoxy shell structures with a longitudinal crack and subjected to internal pressure. The crack growth characteristics will be described and the nonlinear shell analysis methodology will be discussed. The results of the composite shell will be compared to the results of similar aluminum shells, and the differences in these response characteristics will be emphasized. The aluminum shells had self-similar crack-growth characteristics, and the composite shell had non-self-similar crack growth characteristics. The physics of the crack growth characteristics observed in the experiment will be used to identify the damage growth characteristics of the composite shell and to formulate a damage growth criterion for internally pressurized composite shells with damage. The nonlinear shell analysis will also be described.

Keywords: composite shells, internal pressure, damage propagation, nonlinear analyses

Vortex-induced Vibrations of Deepwater Composite Risers

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Vortex-induced vibrations (VIV) of composite risers in deepwater exploration and production operations are studied in this paper. Composite material constitutive equations are first constructed with dynamic mechanical properties of the rate-dependent polymer matrix. A cylindrical laminate composite shell theory is used to establish the composite riser structural stiffness with damping dissipation. Governing equations for composite riser dynamic motions with viscoelastic constitutive equations are then developed for a composite riser structure subject to combined axial tension, and wave and current loading. A computational algorithm is developed to account for the riser material and structural rate-sensitivities and damping in a dynamic platform environment. Numerical results have been obtained on dynamic deformations and stresses of a production composite riser in a 3,000 ft tension-leg platform (TLP) subject to prescribed waves, current and VIV loading. The effect of resin matrix viscoelastic dissipation on composite riser dynamics, especially the VIV mode and critical frequency, has been determined. The relative contributions of fluid-structural damping and composite material damping on riser VIV are investigated. The influence of the composite riser VIV on deepwater platform top tensioners and bottom stress joints is also discussed.

Keywords: Composite Risers, Vortex-Induced Vibrations, Deepwater Operations, Dynamic-Mechanical Properties

Durability and Damage Tolerance Design and Analysis Methods for Composite Structures

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Aerospace vehicles are designed to be durable and damage tolerant. Durability is largely an economic life-cycle design consideration whereas damage tolerance directly addresses the structural airworthiness (safety) of the vehicle. However, both durability and damage tolerance design methodologies must address the deleterious effects of changes in material properties and the onset of microstructural damage that may occur during the service lifetime of the vehicle. This presentation will review design criteria and certification requirements for aircraft and spacecraft. The current state-of-the-art in design and analysis methods will be illustrated by reviewing the results of a recently completed NASA technology development program. Finally, the unanticipated structural failure of the liquid hydrogen cryogenic fuel tank of the X-33 experimental reusable launch vehicle will be explained through damage tolerance analyses.

A Simple, Comprehensive Nonlinear Thermodynamical Theory of Elastic Shells

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This talk develops a nonlinear thermodynamical theory for arbitrary elastic shells in which approximations are made only in the First Law of Thermodynamics (Conservation of Energy) and in the associated constitutive relations. The approach is straightforward: the three-dimensional equations of motion and the Second Law of Thermodynamics (Clausius-Duhem Inequality) subject to external loads and heating are written in integral-impulse form and then specialized to a shell-like body. This requires neither formal expansions in a thickness coordinate nor a priori kinematic hypotheses such as those associated with the names of Kirchhoff or Cosserat. The resulting two-dimensional, time-dependent equations involve stress resultant and couple tensors $\mathbf{N}$ and $\mathbf{M}$, translational and rotational momentum vectors $\mathbf{L}$ and $\mathbf{R}$, an entropy resultant S, an average reciprocal temperature T, and an average transverse temperature gradient G. The unkonwns $\mathbf{N}$, $\mathbf{M}$, $\mathbf{L}$, $\mathbf{R}$, and S are defined in terms of thickness-weighted integrals, but T and G are defined in terms of the surface values of the three-dimensional absolute temperature. A power identity yields, automatically, definitions of extensional and bending strain tensors $\mathbf{e}$ and $\mathbf{k}$ whose local rates are conjugate, respectively, to $\mathbf{n}$ and $\mathbf{m}$, "back-rotated" forms of $\mathbf{N}$ and $\mathbf{M}$. Once an elastodynamic (kinetic plus strain) energy of the shell is defined, the introduction of a free energy introduces an additional unknown F, an entropy couple conjugate to G. Enforcement of the Second Law for all possible thermodynamic processes, à la Coleman and Noll, plus the key assumption that the time derivative of F is a function of the state variables only, leads to a complete and consistent set of simplified constitutive relations. In the present approach there is just one entropy inequality and just one energy equation, in contrast to that of Green & Naghdi who introduce an hierarchy of such equations, essentially one for each director they introduce. The introduction of a dynamic mixed-energy density via a Legendre-Fenchel transformation provides a simple and logical way to introduce a *constitutive* form of the Kirchhoff Hypothesis that avoids certain unnecessary constraints (such as no thickness changes) imposed by the classical *kinematic* Kirchhoff Hypothesis.

A Robust Design Approach to Thermal Twist in Composite Tubes

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The major contribution to both thermal shear coefficient of thermal expansion (CTE-xy or axy) and coefficient thermal tube twist (CTE- q or aq) is the error in angular alignment of the layers in a n-layer laminate. The two ways of reducing these CTE's are 1) to reduce the error at each layer and 2) to reduce the sensitivity of laminate CTE to the angular error of each layer. Taguchi and many others have demonstrated the superior efficiency in the latter approach [Taguchi and Roy]. In this study, we have used Monte Carlo simulations and closed-form sensitivity analysis to investigate the effect of nominal ply layer angle on the shear and twist CTE's. The results were used to reduce the sensitivity of laminate CTE to the angular error of each layer and thereby decrease these CTE's.

MECHANICS OF FIBROUS COMPOSITES

In Honor Of Professor Carl Herakovich

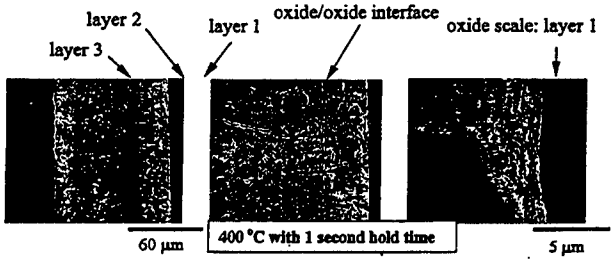
SESSION W4S
Experimental Mechanics of Composites

Oxidation and Time Dependent Effects in Modeling Life in TMCs

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Mechanical performance of Titanium Matrix Composites (TMCs) degrades at elevated temperatures because of the changes in physical properties of the composites due to matrix oxidation and phase transformation. These physical properties of the composites should be taken into account in the life prediction model. The objective of this study was to improve an existing life prediction model (A Local Fiber Failure Stress model) by incorporating relevant material parameters into the model. To achieve this goal, isothermal fatigue tests were performed on $[0/\pm 45/90]_s$ SCS-6/TIMETAL 21S composite at temperatures 400°C and 500°C, and with 1, 10, and 100 seconds hold times. The composite lives at 400°C and 500°C increased with increasing hold time. However, the 100 seconds hold time at 500°C significantly reduced the life compared to 1 and 10 seconds hold time. It was also observed that the matrix oxidation was accelerated under applied load as shown below. In addition, the surface oxide thickness suggested that the oxidation was much easier and faster at 500°C than 400°C. Several modifications were made to the life prediction model. The modified model produced a better correlation between the new single parameter value (SPV') and the number of cycles to failure.



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Delamination Associated with Ply Cracking in Multidirectional Continious Fiber Composites Laminates

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The fracture process of composite laminates under monotonic tension and tension fatigue loading involves sequential accumulation of damage in the form of matrix cracking, edge delamination prior to catastrophic failure (see e.g. Crossman and Wang 1982; Jamison et. al., 1984; O'Brien, 1982, 1985). Local delamination initiates at matrix ply cracks due to a high interlaminar stress concentration at the crack tips, whereas edge delaminations originate from the load- free edge of a composite plate. These through-thickness failure modes can be detrimental to the strength and stiffness of composite laminates. Therefore, a prediction of their onset strain and growth is of a certain importance.

Based on shear-lag type arguments transverse ply cracking in cross-ply type laminates have been intensively modeled with varying emphases on the crack spacing saturation (Parvizi and Bailey, 1978), the statistical characteristic of crack formations (Fukanaga et al., 1984; Laws and Dvorak, 1988), determination of the shear-lag parameters and the in-plane stiffness reduction (Nuismer and Tan, 1988; Han and Hahn, 1989; Zhang et al., 1992) as well as the influence of the stacking sequence (Zhang et al., 1992; Xu, 1995). Dharani and Tang (1990) described a consistent shear-lag analysis in order to determine the interlaminar shear and normal stresses at the matrix crack tips inducing delaminations. Delamination occurs when the maximum interlaminar shear stress reaches a critical value. Furthermore, since 1992 (Zhang, Herrmann, Fan, Soutis) the so-called equivalent constraint model (ECM) was proposed and has been applied to a quantitative examination of constraining effects on the transverse ply cracking and its induced delamination.

Therefore, in this paper the constraining influences of the nearest-neighboring ply group of the core 90°-plies and the rest constraining plies on the stiffness reduction of the constrained 90°-plies and on the strain energy release rate due to a local delamination are investigated. Thereby, three equivalent laminates (TLM), $[\Phi_m|90_{2n}|\Phi_m]_T$ and $[S'^L|90_{2n}|S'^R]_T$, where proposed to examine the constraining mechanics of the constraining plies of the center 90°-plies group on due to transverse cracks induced

delaminations, where S^L, S^R, S'^L and S'^R are sublaminates, respectively. The microstress and microstrain fields in the cracked and delaminated five-layer and three-layer model laminates were obtained by using the first-order shear laminate theory. The explicit expression for the stiffness reduction of the constrained 90°-plies was derived as a function of the delamination length and the transverse crack spacing. The strain energy release rates associated with a local delamination as well as with matrix cracking vary linearly with the first derivatives of the in situ damage effective function IDEF, introduced for characterizing the extension stiffness reduction of the constrained 90°-plies with respect to the delamination length and the crack spacing, respectively. Moreover, it was shown for the examined laminates that the nearest neighboring ply group of the 90°-plies primarily affects the stiffness reduction of the constrained transverse plies and also the normalized strain energy release rate, whereas the influences of the other constraining layers are ignorable. Consequently, the three-layer model laminate consisting of the 90°-ply group and its two next neighboring ply groups could be used to analyze the in situ reduced stiffness of the constrained transverse plies and the strain energy release rates due to a delamination and a matrix cracking in the $[\ldots|\varphi_i|\Phi_m|90_n]_S$ laminates. Thus, a more complicated ply-by-ply analysis for a complete laminate is not needed.

Progressive Failure Analysis of Internally Pressurized Elliptical Composite Cylinders

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New concepts for reusable launch vehicles may well include fiber-reinforced composite cylinders as tankage for containing liquid fuels [1]. Because of aerodynamic and structural considerations, tanks with noncircular cross section designs may be used. One of the critical issues to be considered in the design of laminated fiber-reinforced composite tanks is failure due to leakage through the tank's wall. The internal pressure resulting from these fuels can produce enough matrix cracks in the various layers of the composite material so there is a continuous path for the fuel to escape. To prevent this hazard, it is essential that the conditions under which leakage is likely to occur be known. Noncircular cross sections present a particular challenge because the varying radius of curvature with circumferential position can lead to high stresses at specific locations around the circumference [2]. Obviously, with endcaps or domes, boundary conditions at the ends of the cylinders will cause particular axial locations to have higher stresses than others. The combined effect of axial and circumferential locations of high stress lead to, essentially, stress concentrations. Initial cracking will begin at these locations of stress concentration, and as the pressure is increased, cracking will progress from these locations and perhaps even begin at other locations. This paper uses a progressive failure analysis, based on the STAGS finite-element code, to study the problem [3]. The code allows a high degree of latitude in selecting material failure and material property degradation schemes. It is the purpose of this paper to illustrate the predicted initiation and progression of matrix cracking, on a layer-by-layer basis, for cylinders with an elliptical cross section and for several wall lamination sequences. It is shown that for the cases considered, not every layer cracks and thus leakage will not occur. These results are based on using several failure criteria.

[1] The work reported on herein was supported by grant NAG-1-01072 from the Mechanics and Durability Branch of the NASA-Langley Research Center.

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Ground Impact of a Sandwich Plate

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In order to apply failure criteria for composite sandwich plates, the full three-dimensional state of stress must be known. However, a finite element analysis with solid elements requires too many degrees of freedom. Therefore, two-dimensional plate type models need to be used with a capability for accurate computation of not only in-plane stress components but also the transverse stress components.

Under certain circumstances, when the face sheets are thick, when the plate is loaded by a concentrated or partially distributed load, or when the plate is on an elastic foundation, taking account of the direct transverse strain in the face sheets and the transverse shear strain in the face sheets in the expression for the strain energy allows one to obtain a higher accuracy of the stress computation.

A model for such a plate must assume or lead to the nonlinear tro ugh the thickness variation of the in-plane displacements both in the core as well as the face sheets. The authors introduce simplifying assumptions with respect to the variation of the transverse strains in the thickness direction of the face sheets and core of the sandwich plates. It is assumed that within the face sheets and the core the transverse strains do not depend on the z coordinate, but they can be different functions of coordinate x, y and time t in each face sheet and core. The assumed transverse strain together with displacements of the middle surface of the plate are the unknown functions of the problem, that are computed by the finite element method incorporating the von Karman strain-displacement relationships. The displacements in terms of the unknown functions are obtained by integration of the strain-displacement relations with the assumed transverse strains, and the constants of integration are chosen to satisfy the conditions of continuity of the displacements across the borders between the face sheets and the core. The in-plane stress are computed from the constitutive equations, and the improved values of transverse stress components are computed by integration of point wise equations of motion.

A problem of cylindrical bending of a simply supported plate under uniform load on the upper surface is considered, and comparison is made between the displacements, the in-plane stress and the improved transverse stresses with corresponding values of exact elasticity solutions

Keywords: sandwich plates, elastic foundation, through-the thickness strains, finite elements

Response of Particle Reinforced Aluminum MMC to Axial-torsional Loading

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The effect that various loads have on a 6092/SiC/17.5p-T6 particulate reinforced aluminum composite is discussed. In addition to the mechanical response from tensile, compressive, shear, and nonproportional loading, yield loci in the axial-shear stress plane have been constructed using axial-torsional loading of a thin-walled tube. Yield loci were determined by multiple yield probes of a single specimen using a 40E-6 equivalent offset strain definition of yielding. Yield points were found after unloading rather than under load. Cyclic tensile straining to increasingly higher amplitudes indicated a modulus reduction of 16% prior to fracture, strongly suggesting accumulation of internal damage, but no change in the elastic Poisson's ratio was observed. Cyclic compressive loading resulted in no observable change in modulus. Cyclic shear loading lead to a minimal shear modulus reduction of approximately 6%. The initial yield locus in the axial-shear stress plane had an eccentricity in the compressive stress direction that is known as a strength differential. The strength-differential was measured to be 55% and is believed to be associated with thermal residual stresses from processing. After shear and tensile prestraining subsequent yield loci were constructed and hardening was observed to be primarily kinematic.

We acknowledge financial support from NSF Career Award 9875414.

MECHANICS OF FIBROUS COMPOSITES

In Honor Of Professor Carl Herakovich

SESSION R3S
Micromechanics of Composites

The Effect of Platelet Distribution on the Modulus of Nanoclay Composites

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Composites using nanoclay platelets as reinforcements have been of great interest to many researchers. The clay platelet is an ultra thin (1 nm) silicate film with lateral dimensions up to 1μm. It has been found that with a small volume fraction of the clay platelet, the mechanical properties of the composite can be significantly enhanced if the platelets are well dispersed and that no improvements would be obtained if the platelets are lumped together. In this study , we aim to investigate the effect of platelet distribution on the modulus of the composite. Both the spacing and the amount of overlap between the adjacent platelets are considered. A two-dimensional unit cell is adopted to determine the spacing effect on the modulus of composites as shown in Figure1. The planes of the platelets are bonded to the matrix and parallel to the loading direction. The platelets and the matrix are assumed to be linear elastic and the stress distribution in the platelets and matrix are obtained using the shear-lag model. The calculated modulus of the composite with respect to platelet spacing is shown in Figure 2. It can be seen that the modulus of the composite increases as the spacing between platelets becomes more uniform which coincides with the current experimental observation.

Keyword: nanoclay composites, modulus, spacing, shear lag model.

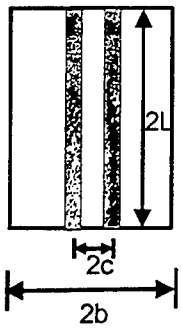


Fig. 1: A unit cell adopted to study the spacing effect on the modulus of composites.

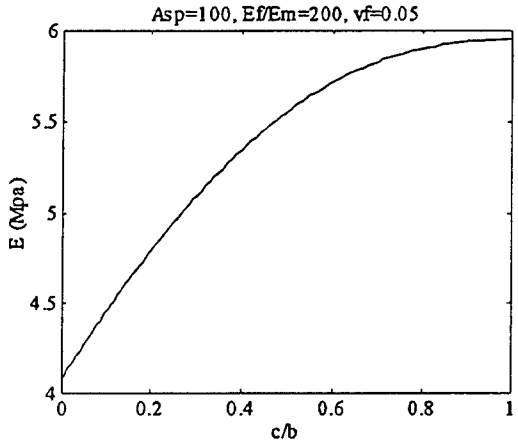


Fig. 2: Spacing effect on the modulus of nanoclay composites

High-Fidelity Micromechanics of Periodic Multiphase Materials

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A new high-fidelity micromechanics model has been developed for the response of multiphase materials with arbitrary periodic microstructures, Fig. 1 [1,2]. The model's analytical framework is based on the homogenization technique, but the method of solution for the local displacement and stress fields borrows concepts previously employed in constructing the higher-order theory for functionally graded materials [3]. Resulting closed-form macroscopic constitutive equations valid for both **uniaxial** and **multiaxial** loading of periodic materials with elastic and inelastic constitutive phases, obtained from the developed approach, can be incorporated into a structural analysis computer code. The model makes possible accurate simulation of the average stress-strain response of heterogeneous materials such as ceramic, metal, and polymeric matrix composites employed in the aerospace, electronic and biomedical industries. In addition to the excellent predictive capability of the macroscopic response, illustrated in Fig. 2 for a gr/al unidirectional composite under transverse biaxial tension/compression, the model also predicts the internal or micro-level stress and strain fields with very good accuracy in both elastic and inelastic regions. This predictive capability is demonstrated through comparison with elasticity and plasticity analytical solutions and finite-element results for axisymmetric, axial shear, and transverse loading.

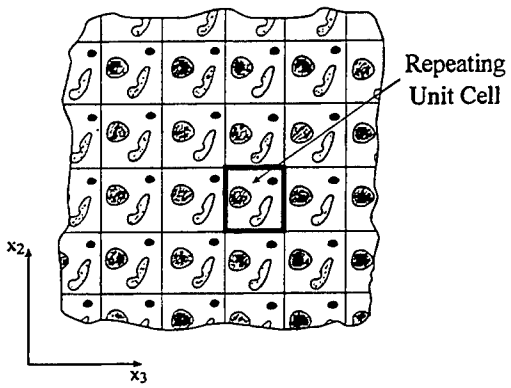


Fig. 1: Multiphase material with periodic microstructure.

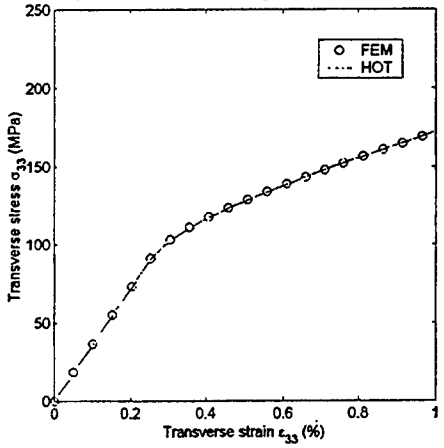


Fig. 2: Macroscopic stress-strain response under combined biaxial loading [2].

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Keywords: high-fidelity, micromechanics, homogenization, inelasticity

Moving-Window Analysis of Composites with Random Microstructure

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Material properties are often represented by average, or homogenized, values in calculating macroscopic behavior. This practice, based on the assumption of a representative volume element, generally ignores the micro-scale fluctuations that occur in many real materials. When considering the macro-scale behavior of these materials, such as the displacements, average strains and average stresses of structures where the loading and boundary conditions are at a much larger scale than the microstructure, this assumption yields valid results. This assumption is less valid, however, for some of the recently emerging applications of composites to very small-scale systems (e.g., MEM's or thin-film coatings). Furthermore, even for large-scale structures, the use of effective material properties does not yield an accurate measure of local stresses that are often linked to critical structural behavior. This presentation will provide an overview of recently developed techniques for evaluating random variations in the local mechanical properties and stresses in composites with random microstructure, based on digitized images of the composite microstructure. This is achieved through stochastic simulation of the material properties, where each sample realization of the simulation process generates material properties and local stresses that are statistically identical to these quantities in the original microstructure. A major advantage of moving-window techniques is that all of these results are based on the originally obtained digitized microstructures. The accuracy in these results will be discussed in the context of finite element convergence and micromechanical modeling techniques.

A Fully Thermo-Mechanically Coupled Theory for General Microstructures

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The development of a micromechanical model for generalized microstructures with full thermo-mechanical coupling is presented. The model considers the combined effects of the mechanical and energy equations at the microstructural level. The impetuous for this work has been the analysis of energetic composite materials (high explosives).

The model is based on the analysis of a periodic representative volume (RVE). The microstructure within the RVE is further subdivided into an arbitrary number of subcells. The behavior of the material within the different subcells can be modeled using elastic, plastic, viscoelastic, viscoplastic, or damage constitutive models. The fields within each subcell are approximated by piecewise constant temperatures and linearly varying displacements. Based on these subcell fields the equations of equilibrium, energy (in the absence of heat conduction), and interfacial continuity are satisfied in an average sense. The resulting system of governing equations exhibits full coupling between the deformations and the thermal effects at the microstructural level and hence at the macroscopic level. The proposed model is analytical and provides closed-form expressions for the effective macroscopic kinematic and thermal behavior of a particulate composite.

The influence of the thermo-mechanical coupling on behavior at both the macroscopic and microscopic levels is considered. The presence of the coupling can lead to significant localization of the thermal and deformation response within different regions of the unit cell. It is shown that the presence of inelastic deformations in conjunction with thermo-mechanical coupling effects can result in appreciable deviation from an isothermal, inelastic analysis.

Transient Moisture Diffusion Analysis of Fiber Reinforced Composites

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A new approach has been developed, based on an inverse analysis technique, to determine critical moisture diffusion parameters for a fiber reinforced compos-

ite. This technique incorporates two distinct features: direct experimental observations of the weight gained by a composite material exposed to a humid environment, and highly detailed computational analyses that capture the actual heterogeneous microstructure of the composite. The latter feature was carried out by modeling more than one thousand individual carbon fibers that are randomly distributed within an epoxy matrix. The verification and efficacy of this technique was established by conducting an experiment on a high-grade IM7/997 carbon fiber reinforced epoxy to determine the maximum moisture content at saturation and the diffusivity of epoxy. With the inverse analysis, the time duration required to estimate these moisture diffusion parameters could be drastically reduced as compared to conventional procedures. Subsequently, the established models were employed to characterize transient moisture absorption process within the composite. Here, it was demonstrated that modeling the heterogeneous microstructure of the composite is critical for obtaining accurate diffusion parameters, and an analytical model with effective properties does not produce correct transient moisture absorption behavior. Furthermore, the evolution of stress fields due to moisture induced volumetric expansion was quantified. It was observed that high stress concentrations develop in regions of fiber concentration. These regions then act as potential failure initiation sites that can lead to lower damage tolerance.

Project sponsored by US Army Research Office

MECHANICS OF FIBROUS COMPOSITES

In Honor Of Professor Carl Herakovich

SESSION R4S
Damage in Composites

On a Damage Mesomodel for Laminates: Physical Basis, Micro-meso Relations and Limitations

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Building methods to predict the behavior of laminated structures until final fracture constitutes a major challenge in the design of composites. A damage mesomodel has been under development at Cachan for the past fifteen years (Ladevèze, 86; Herakovich, 98). It is based on the assumption that any laminated structure can be considered as a stacking sequence of two basic constituents: the single layer and the interface. Another assumption is that damage is constant throughout the thickness of each mesoconstituent. This mesomodel has been identified in terms of both the ply and the interface for numerous materials.

Here, the damage mesomodel is revisited in the light of numerous works, both experimental and theoretical, done in micromechanics. A fiber/matrix debonding mechanism needs to be added to the classical micro scenarios of transverse matrix microcracking and diffuse inter-ply delamina-tion. The crucial point is the discussion of the homogenization assumption leading to the meso-model. We will prove the validity of this assumption for common engineering stacking sequences both under the usual micromechanics hypothesis of prescribing a uniform plane projection of the macrostrain and under steep gradient effects encountered near the edges.

Keywords: laminate, micromechanics, mesomechanics, damage

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Residual Stresses in Functionally Graded Composites

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The prediction of effective mechanical properties of metal ceramic composites is dominated by the constitutive behavior of the constituent phases and their relative proportions. For more accurate assessments of residual stresses, and other contributing mechanisms leading to damage, as well as estimates of the ultimate reliability of a material, the effect of local microstructure must be taken into account. In this work a mathematical model is developed for functionally graded architectures in fiber-reinforced composites. Both local and global stresses and plastic strains are developed as a result of the thermo-mechanical loading which mimics the temperature and pressure loading associated with consolidation processing of a composite. The microstructure is approximated by multiple layers with varying fiber volume fractions. Both square packing and a more random arrangement are investigated. A micromechanical analysis is performed on each layer using the generalized method of cells [1] micromechanics model. The composite effective properties are then calculated using a solution technique that parallels lamination theory. This model extends previous work [2] by allowing for a non-symmetric layered structure to describe the microstructural architecture. The model is applied to a Si/C-Ti material system. Case studies of various pressure and temperature loadings are tested in the model.

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A Consistent Thermodynamic and Coupled Impact Damage-viscoplastic Model for MMCs

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A coupled constitutive model of viscoplasticity and ductile damage for impact related problems has been formulated within the framework of thermodynamic laws and nonlinear continuum mechanics. It is implemented in the explicit finite element code ABAQUS and the in-house code DNA (Damage Nonlinear Analysis). The model includes linear thermoelasticity, a dynamic yield criterion of a von Mises type and a damage criterion, the associated flow rules, non-linear strain hardening, strain-rate hardening, temperature softening due to adiabatic heating, anisotropic ductile damage and failure. The linear elastic constitutive equation for the damaged material is written according to the principal of strain energy equivalence between the virgin material and damaged material. This model is based on the non-local theory of plasticity and damage that incorporates microscale interstate variables and their higher order gradients at both macroscale and mesoscale. It also incorporates thermomechanical coupling effects as well as the internal dissipative effects through the rate type covariance constitutive structure with a finite set of internal state variables. For each of the physical phenomena included in the model, one or several material constants are required. However, all material constants are identified from relatively simple uniaxial tests without the use of numerical simulations. The calibrated model is verified and validated through numerical simulations of various dynamic problems.

Interface Crack and Dynamic Delamination

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Woven S-2 fiber glass/vinyl ester composites are being considered for use in hybrid composite armor systems

for ground vehicles. Dynamic delamination during impact loading is of particular interest and it is desirable to determine whether or not the delamination resistance (or toughness) is rate dependent. A technique using the split-Hopkinson bar is developed to determine this resistance of the material to Mode I loading. The average dynamic energy release rate is obtained for an average crack tip velocity of about 300m/s (the crack tip velocity is estimated to be in the range of 300 to 1200 m/s). The average dynamic energy release rate is compared to the Mode I R-curve, which is obtained by the traditional double cantilevered beam (DCB) static test. The results indicate that delamination toughness can be approximated accurately by using the toughness data obtained from quasi-static tests. In addition, the results serve to highlight the requirements for using a split-Hopkinson bar to study the phenomenon of delamination propagation in composites.

Keywords: Dynamic Delamination, Hybrid Composites

Damage Mechanics and Delamination: Application to Low-energy Impact

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In damages induced by low-velocity impact, delamination is coupled with transverse micro-cracking. In the used meso-scale approach, the laminated structure is described as a stacking sequence of homogeneous layers through the thickness and interlaminar interfaces. The main damage mechanisms are described: fiber breaking, matrix micro-cracking and debonding of adjacent layers. The single-layer model includes both damage and inelasticity. The interlaminar interface is defined as a two-dimensional model, which ensures traction and displacement transfer from one ply to the next. Its mechanical behavior depends on the angle between the fibers of two adjacent layers [1]. For the interface, the identification uses several delamination propagation tests (DCB, MMF and ENF) and initiation (edge delamination test).

Here, the application of the meso-model to low-velocity impact on laminates is discussed. This is a challenging case. Transverse cracks occur in each unidirectional ply; these cracks tend to be centered on the puncture / plate contact zone, and then propagate outwards along the fiber directions. This configuration creates a "double-helix" surface in space with a conical shape. This makes it possible to visualize the periphery of the double helix by means of an ultrasound evaluation, which can be analyzed in terms of both distance and amplitude. The simulation results revealed a prediction of the damage cone which is consistent with experimental findings [2].

Keywords: laminates, delamination, damage mechanics, experimental comparison

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Symposium on

Fluid Mechanics and Multiphase Flow

In Honor Of
Professor D. Joseph

Organizer:
Professor Y. Renardy
(Virginia Tech)

FLUID MECHANICS AND MULTIPHASE FLOW I

In Honor Of Professor Dan Joseph

SESSION M3C

Dynamics of Particle Sedimentation in a Confined Channel

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The sedimentation of two particles in a confined liquid container is considered in this study. It is shown that as the particle body force (weight), F, increases, the motion of the particles become unsteady and complex. Computational analysis of this system reveals a series of transitions to a low dimensional chaotic state through period-doubling bifurcations. More careful analysis reveals the co-existence of two time-periodic states in a range of parameter F. The initial steady state becomes unstable at a critical value of F giving rise to a time-periodic state, T1, through a Hopf bifurcation. As F increases, the limit cycle

T1 becomes globally unstable as it co-exists with a second time-periodic state, T2. The T2 state undergoes period-doubling bifurcations as F increase leading the system to a low-dimensional chaotic state. The relation between the various states revealed in this study to the previous experimental and computational observations will be discussed.

A Simplified Two-fluid Model Based on Equilibrium Approximation

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We present a simple, two-way coupled formalism for simulating multiphase flows. In this model, the disperse phase is treated as a continuum whose velocity can be determined via a rigorous first-order Equilibrium Eulerian expansion. The model is therefore analogous to the dusty gas model in that it explicitly expresses the particle velocity in terms of the fluid velocity rather than solving additional momentum equations for it. The dusty gas model, however by assuming the fluid and particle velocity to be the same, ignores the preferential accumulation of the discrete phase in regions of high strain, and thus neglects the high-wave-number momentum forcing back on the flow. The equilibrium Eulerian expansion for the disperse phase velocity systematically accounts for the deviation from the local fluid velocity and thereby captures preferential accumulation, and other relevant physics, correctly. The validity of the expansion is limited to small particles, however, it provides a precise mechanism for the inclusion of the back effect of particles on the surrounding fluid. To verify the equilibrium expansion, we have performed direct numerical simulations of particles and bubbles in the canonical problems of isotropic turbulence and a turbulent channel flow, where "true" particles moved according to their Lagrangian equations of motion are compared with "test" particles moved according to the equilibrium particle velocity. The equilibrium approximation for particle velocity provides a clean mechanism for two-way coupling and a rigorous set of equations for the description of multi-phase flow turbulence, in the limit of a dilute dispersion of small particles. Two-way coupled DNS of two-phase flow were performed for the case of isotropic turbulence and turbulent channel flow and the results are compared with those of corresponding single phase DNS.

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On Thermal Instabilities in a Viscoelastic Fluid

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Thermal instability of a horizontal layer of fluid heated from below has been extensively investigated in the case of Newtonian fluids and to a lesser extent in viscoelastic fluids. The recent renewed interest in this area is due to potential applications such as the growth of crystals in a space environment. The two mechanisms responsible for instability is the density variation generated by the thermal expansion of the fluid and the surface tension gradients due to temperature fluctuations at the upper surface of the layer. Investigation of the former mechanism is referred to as the Rayleigh-Bnard problem while investigation of the latter is called the Marangoni problem.

In this work we investigate the Bénard-Marangoni problem for a viscoelastic Jeffreys' fluid layer bounded above by a realistic free deformable surface and by a plane surface below. Results for the Maxwell fluid are deduced as a special case. Our main objective is to examine the role viscoelastic effects and surface deflection may play in the Bnard-Marangoni coupling. The corresponding problem for Newtonian fluids was analysed by Benguria and Depassier. Previous works for viscoelastic fluids have considered instability due to buoyancy alone, surface tension alone, and combined Bénard-Marangoni convection, all without surface deflection.

We have found surface deformation to be destabilizing for oscillatory disturbances with the result that the overstable mode can be observed for lower values of the relaxation time and higher values of the retardation time as compared to disturbances without surface deflection. When the lower boundary is free but plane, an analytic treatment has identified an oscillatory disturbance with zero critical wavenumber which is not found in the absence of surface deformation.

Electrospinning of a Viscoelastic Jet

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Electrospinning uses an external electrostatic field to accelerate and stretch a charged polymer jet, and may produce ultrafine "nanofibers". Many polymers have been

successfully electrospun in the laboratory, but theoretical modeling has proved to be a difficult undertaking. Recently, a slender-body theory has been proposed for Newtonian jets. A problem arises, however, with the boundary condition at the nozzle, and an unrealistic "ballooning instability" precludes well-behaved solutions. In this talk, we will first describe a slightly different Newtonian model that avoids the instability. Then we will discuss how viscoelasticity of the fluid affects the stretching of the jet and the molecular conformation inside. We will also examine the stability of the polymer jet and compare it with the "draw resonance" in conventional fiber spinning.

FLUID MECHANICS AND MULTIPHASE FLOW II

In Honor Of Professor Dan Joseph

SESSION M4C

The Direct Numerical Simulation of the Motion of Settling Ellipsoids in Fluid

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In this talk, we discuss a methodology allowing the direct numerical simulation of the interaction between incompressible viscous fluid and the rigid bodies of general shape, which are moved by the hydrodynamical forces and gravity. The simulation methods rest essentially on the combination of:

1. Lagrange multiplier based fictitious domain methods which allow the fluid flow computations to be done in a fixed flow region.
2. Finite element approximations of the Navier-Stokes equations occurring in the global model.
3. Time discretizations by operator splitting schemes in order to treat optimally the various operators present in the model.

The above methodology is particularly well-suited to the direct numerical simulation of particulate flow, such as the flow of mixtures of rigid solid particles and incompressible viscous fluids, possibly non-Newtonian. We conclude this talk by the presentation of the numerical results of settling ellipsoids in incompressible viscous fluids.

Migration of Spheres in Poiseuille Flow in a Circular Pipe

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The motion of rigid spheres suspended in a pressure-driven flow of a Newtonian fluid in a circular tube is studied by using 3D direct numerical simulations based on an ALE Galerkin moving finite element technique. We solve a system of differential equations governing the motion of the fluid and the dispersed solids. These equations are coupled through the no-slip boundary condition on the particle surface and the hydrodynamic forces acting on the particles. Our numerical results agree quantitatively with the experimental ones in the literature. Effects of the independent parameters controlling the particle migration, which are the blockage ratio, the flow Reynolds number, and the solid-liquid density ratio are systematically investigated. During the particle migration, the mechanism of the fluid inertia, the wall confinement, the local flow shear rate, the particle slip velocity, the particle size, and the particle rotation are extensively examined through the stress distribution on the particle surface under different flow conditions. The interaction between particles are also investigated in this study.

Onset of Air Entrainment in Cusp and High-Speed Wetting Flows

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Joseph et al. (1991, JFM) found eigenfunction solutions descriptive of cusp flow and Benney & Timson (1980, Stud. App. Math.) have shown that these same eigenfunctions apply to high-speed wetting flows (180 degree contact angle). Both these solutions apply strictly only to the case of a stress-free interface. We show how to generalize their analyses to include interfacial stresses. The result is a rather easily solvable integral equation for interface shape forced, to leading order, by the interfacial pressure field. Its homogenous solution is the eigenfunction solution found by Joseph et al. and Benney & Timson. We utilize this equation together with lubrication models for the gas-phase flow to generate both steady and time-dependent solutions for the gas-liquid interface shape and the gas pressure field. This is applied to both cusp and wetting flows. Of prime interest is the onset of

air entrainment. We look in particular at optical fiber wetting, which is an important part of the optical fiber manufacturing process. This is typically carried out at very high capillary numbers, O(1000). We hypothesize that this is possible because of amelioration of stresses by the diffusion of the gas phase into the liquid. (The process geometry, its small scale, order 100 microns, and an imposed pressurization of the liquid are also important.) An analysis is carried out using realistic diffusion rates and solubilities. Air entrainment thresholds are found that are consistent with industrial practice and observations.

Modelling of the Depletion of Sand Packs Filled with Live Heavy Oil

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When sand packs filled with live heavy (viscous) oil at high pressure are depleted, gas and liquid hydrocarbons are produced. If the produced total volumetric flow rate is constant, pressure first sharply decreases with time (single-phase region), while later it decreases slower (two-phase region). The transition between these two regimes is often characterised by a local minimum in pressure, due to supersaturation of the liquid. Gas mobility estimated by Darcy's law is much lower (10^{-6} to 10^{-5}) than what would be expected from the conventional Corey correlation. This deviation points towards the existence of dispersed flow.

Models are presented that describe this depletion experiment. A first model consists of mass balances of oil, (free) gas in bubbles, and dissolved gas. The mass transfer between dissolved and free gas is modelled trough a linear kinetics closure term. A second model has an additional equation for the number conservation of bubbles in the liquid. This requires the explicit modelling of bubble nucleation and diffusional growth. The models are solved using a volume-averaged approach that yields a set of coupled ordinary differential equations that are solved numerically.

Results from both models are in good agreement with experimental results obtained for different depletion rates. However, the models need the tuning of parameters (that are later kept constant) that represent details of the physical processes, such as for example the density of nucleation sites and their activation energies. Additionally, the results show the need to derive a theory for the mobility of the gas phase in the porous medium, possibly linking this mobility to the morphology and size-distribution of connected gas elements or bubbles.

The developed models are a first step towards new reservoir simulation models that are better suited than those included in current simulation tools to predict the process of primary heavy oil recovery.

Analogies in the Transient Momentum and Energy Equations for Particles, Bubbles and Drops

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It is well known that the lagrangian transient equation of motion for spheres for creeping flow conditions is composed of three terms: the steady-state term, the added/virtual mass term and the history/Basset term. The last two terms are transient and arise from the potential flow of the fluid around the sphere and from the diffusion of vorticity correspondingly. In particular, the presence of the history term results in constituting the equation of motion of the sphere an integrodifferential equation (and hence, more complex to solve analytically or numerically). In a previous paper, we have solved the transient heat/mass transfer equations around a sphere at the limit of creeping flow conditions (very low Pe) and discovered that there is a history term associated with the process of heat or mass transfer. The added mass term in the momentum equation arises from the potential flow around the sphere and, because of this, an analogous term does not exist in the transient energy equation. This study examines the analogies of the form of the transient equations for momentum and energy at zero and finite Reynolds and Peclet numbers for spheres and ellipsoids as well as the effect of the shape of the particle on the form of the transient terms. It also addresses the question as to when the contribution of these history terms is significant in the heat and mass transfer processes from particles, bubbles and droplets.

Keywords: transient equations, analogy, particles, bubbles, drops.

Front Propagation in Dilute Sedimentation: Particle Simulations and Model Continuum Equations

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Recent advances in understanding the scaling of velocity fluctuations in creeping flow sedimentation have direct implications for macroscopic modeling of such flows. The identification of particle concentration stratification as a controlling parameter for the fluctuations extends to the hydrodynamically induced particle diffusivities as well. This stratification thus affects macroscopic flow details, such as the concentration profile of the sediment front. We investigate the particle diffusivities and their effects via dilute-limit simulations of cells with no-slip side-wall pairs and no-flow image bottoms. Simulation results are compared with solutions to model continuum equations which include stratification-dependent particle diffusivity.

Steady and Unsteady Computational Simulations for Internal Condensing Flows

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The computational investigation in this paper explores a new technique for steady and unsteady internal condensing flows in the annular/stratified regime. Simulation capabilities for both steady and unsteady interface laminar/laminar situations are presented for film condensation on the bottom wall of a small-to-moderate gap channel. The unsteady simulations employ a suitable adaptive grid and numerical solution of the appropriate interface tracking hyperbolic equation (which is a suitable extension of the type used in level-set or VOF methods for gas/liquid flows without phase-change). At each time-step, the scheme locates the interface, solves the Navier-Stokes equation in each phase, satisfies the full non-linear conditions at the phase-change interface, and satisfies the necessary inlet, outlet, and wall conditions.

The stability and instability of various exit condition dependent steady solutions are inferred from direct unsteady simulations and this leads to insights into the flow mechanisms that determine the eventual quasi-steady flows. The flow's sensitivity to the frequency content of persistent noise in the inlet data is also considered. These results improve our understanding of the role of vapor compressibility, interfacial waviness, and associated heat-transfer rates.

A Projection Scheme for DNS of Rigid Particulate Flows

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A formulation is presented for the direct numerical simulation of freely moving rigid particles in fluids. The approach is an adaptation of our previous scheme (Patankar et al., Int. J. Multiphase Flow, 2000, v26, p1509) and does not rely on any models for fluid-particle interaction. The entire fluid-particle domain is assumed to be a fluid and a rigid motion constraint is imposed in the particle domain. The formulation can be implemented by an immersed boundary and a fractional time-stepping technique. It is suitable for quick computations and can be employed for DNS, LES or RANS type simulations of turbulent particulate flows.

Simulation-Based Risk Management of Data for Rapid Mass Flows

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Our research effort integrates mathematical modeling, high performance computing and database management,

for hazard mitigation of rapid mass-flows at volcanoes. This program contains three main thrusts: (1) developing realistic simulations of geophysical mass flows; (2) integrating data from several sources, including simulation results, remote sensing data, and GIS data, and (3) extracting, and organizing information in a range of formats and fidelity, including audio, visual, and text, to scientists and decision-makers involved in risk management.

In this talk, we focus on aspects of modeling and computing. Pioneering work of Savage and his colleagues formulated a model of debris flow and rock avalanches that is analogous to the shallow water system, the principal difference being the momentum source terms in the model. To date, numerical simulations of the governing equations have considered flow over a relatively simple topography. Here we present a parallel, adaptive grid simulation framework to solve the model system. Our simulations incorporate topographical elevation data from specific volcanoes that we study. We also describe a data management scheme that facilitates processor communication and data retrieval.

Averaged Equations for Particle Flow by Numerical Simulation

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The application of formal averaging methods to multiphase flows produces a set of equations that is not closed, as the number of unknowns exceeds that of available equations. The closure of these equations is the chief theoretical problem to be surmounted if a workable and useful set of averaged equations is to be formulated. Prof. Joseph is and has been a strong promoter of the use of numerical simulations in multiphase flow, and in particular of the derivation, by such means, of power-law relationships of which the Richardson-Zaki relation is the most famous example.

In the same spirit, in this work the above-mentioned closure problem is reduced to the calculation of coefficients which can be approximated by power laws deduced from numerically executed ensemble averaging.

After a brief presentation of the numerical method used for the simulations, the nature of the particle stress in a spatially non-uniform viscous suspension will be described. It will then be shown how the closure of this stress can be reduced to the determination of several coefficients, numerical results for which will be presented.

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FLUID MECHANICS AND MULTIPHASE FLOW IV

In Honor Of Professor Dan Joseph

SESSION T4C

Breakup of Viscoelastic Filaments

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The lecture compares various constitutive models for viscoelastic liquids in surface tension driven breakup of a filament. Results on finite time breakup or the absence of it and similarity solutions describing the approach to breakup are discussed. We consider a variety of models including the BKZ, Johnson-Segalman and Phan-Thien Tanner model. Depending on the specific model, three possible behaviors are possible: absence of breakup, breakup induced by surface tension and a new type of breakup, which is driven entirely by elastic forces and does not require surface tension.

PROST: a Proper Representation of Surface Tension for the Volume-of-Fluid Method

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Volume-of-fluid (VOF) methods are popular for the direct numerical simulation of two liquids undergoing interfacial breakup and coalescence. When the capillary force is the dominant physical mechanism, past VOF methods lack convergence with spatial refinement, or converge to a solution that is slightly different from the exact solution. A well-known example is that of spurious currents for the simulation of a spherical drop with zero initial velocity. In our algorithm VOF-PROST, we develop an accurate representation of the body force due to surface tension, which effectively eliminates spurious currents. There are several components to this procedure.

Mechanical Response of TSM Resonators to Contact with Stratified Viscoelastic Overlayers

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A mathematical analysis of the mechanical response of thickness-shear mode quartz resonators (TSM) to contact with a stratified, multi-layer, viscoelastic liquid bulk is presented. For simplicity, the results for a two-layer case are discussed in more detail. By solving the governing system of equations under appropriate boundary conditions, the fundamental resonance frequency of the loaded system is computed. The resulting shift from the resonance characteristics of the unperturbed resonator is related to the properties of the contact medium, enabling real-time, in-situ interrogation of the inertial and viscoelastic properties of the contact medium. This analysis extends the results of Nwankwo and Durning on homogeneous systems to inhomogeneous viscoelastic overlayers.

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Deformation of Bubbles in Three-Dimensional Viscoelastic Flows

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A three-dimensional finite element scheme that uses the level set method to track the interface and the Marchuk-Yanenko operator splitting technique to decouple the difficulties of governing equations is used to study the motion of Newtonian bubbles in viscoelastic liquids. The viscoelastic liquid is modeled via the Oldroyd-B model. Using our numerical scheme, the deformation of bubbles rising in viscoelastic liquids is analyzed as a function of Capillary number (Ca) and Deborah number (De). We find that there are limiting values of the parameters Ca and De, above which the bubble assumes a characteristic shape with a cusp-like trailing edge. The front of the bubble however remains round as the local viscoelastic and viscous stresses act to round the bubble. Asymptotic analysis is preformed to understand the role of viscoelastic stresses in the formation of cusp shaped trailing edge.

FLUID MECHANICS AND MULTIPHASE FLOW V

In Honor Of Professor Dan Joseph

SESSION W3C

Electrohydrodynamic Fibration of Droplet Suspensions-Direct Numerical Simulations

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Direct numerical simulations are used to examine the effect of electric fields on the behavior of a suspension of drops in a channel. The effect of electric field is modeled using the "leaky dielectric" model, coupled with the full Navier-Stokes equations. The governing equations are solved using a front-tracking/finite volume technique. The interactions of two drops are controlled by two effects. The first is attractive motion due to a charge distribution on the surface of the drops. The second effect is fluid motion driven by tangential stresses at the fluid interface. The fluid motion depends on the relative magnitude of the permittivity and conductivity ratios. When the permittivity ratio is higher than the conductivity ratio, the tangential forces induce flow from the poles of the drops to the equator. If the center of two such drops lies on a line parallel to the electric field, the flow drains from the region between the drops and they attract each other. When an electric field is applied to many drops suspended in a channel flow, drops first attract each other pair-wise and some drops move to the wall. If the forces are strong (compared to the fluid shear) the drops can form columns or fibers, spanning the channel. Electronic "fibration" of suspensions has been observed in a number of systems, including dispersion of milk droplets and red blood cells. Although most of the simulations carried out so far are for two-dimensional systems, fully three-dimensional simulations show that the results are similar to the two-dimensional ones, except that the rate of accumulation at the walls is slower. Large scale computations with many drops, as well as simulations of a wider range of parameters are in progress.

Polymer Droplet Interactions: the Case of Coalescence

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Interactions between polymer droplets are studied because they are important when dealing with mixing of polymers. The competition between rupture and coalescence is what determines the final size of suspending droplets. As an example, shearing at a constant rate may result in a well defined droplet radius varying like the inverse of the shear rate [1]. Coalescence also takes place at smaller rates and may also lead to well defined distribution of droplet sizes varying as a known power of the shear rate [2]. Rupture of newtonian droplets has been the source of an extensive work in the literature whereas coalescence is still rather mysterious. The nonlinearities in the deformed shapes of elongated droplets or coalescing ones seem to be a major difficulty, therefore small deformation theories have often been used to predict such behaviours (see for example Ref. [3]). Experiments are scarce and are often needed in order to obtain inform ation about such systems. In addition they may be combined with other effects such as the influence of compatibilisers or viscoelastic effects, which are often present in blends.

In this study we consider quiescent polymer blends and study the interactions between droplets. Particular attention is paid to the coalescence of two newtonian droplets. The experiment, carried out under a microscope, gives access to a collision time which is studied as a function of the viscosity ratio. Three regimes are found, covering six decades of viscosity ratio [4]. A theory is proposed to explain the three regimes, based on the local viscous dissipations at the nip, as compared to the driving power of surface forces. This allows to recover two of the three regimes, the last one been predicted from a previous analysis [5]. This method can also allow one to measure the interfacial tension using droplet coalescence, simply by measuring the collision time.

Finally, in order to investigate the problem further, we propose to use PIV measurements to have access to the flow field [6]. This is important for people carrying out numerical simulations, in particular because the flow field is shown as a time-dependent one. Regions of elongational flow are exhibited, and seem to invade the resulting droplet as time goes on. The time dependence of velocities at particular points and the neck distance are shown.

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Direct Numerical Simulation of an Electro-Rheological Channel Flow

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Electro-Rheological (ER) fluid can be considered as a concentrated suspension of micron-sized particles in a fluid. In the presence of a strong electric field, these particles become polarized and give rise to qualitative changes in the flow from a Newtonian fluid to a viscoplastic yielding solid. The mechanical behavior of ER fluid has been conventionally described by the simple Bingham plastic fluid. However, it only gives a macro-scaled picture of a suspension flow. On the other hand, point-dipole model has been also used to simulate the particle interactions where the hydrodynamic force is approximated by the Stokes law. In this paper, we have performed a direct numerical simulation of the steady flow of an ER fluid in a 2D periodic channel in order to directly simulate the hydrodynamic force on the inter-particle motion. The suspending medium has a constant viscosity and there are about up to 2000 solid particles (50domain. Hydrodynamic interactions between the particles and the fluid are directly computed by using the combined formulation of the fluid-particle mixture, and the multi-body electrostatic

interactions are solved by existing point-dipole model. We have studied the flow behavior and particle motions with variation of electric field intensity and volume fraction. The particle motions and flow fields obtained from the present DNS are qualitatively compared with the visualization by experiments and other numerical simulations based on a simple model. The present DNS of ER channel flow has been considered to be prohibitive due to the limited computing power. We have attacked this challenging problem and showed that DNS can be a useful tool for the simulation of visco-plastic regime of ER fluid

Keywords: Direct numerical simulation, Electro-rheological channel flow, Point-dipole model, Combined formulation

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St-Re Relationship of the Laminar Flow around a Freely Falling Cylinder

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In the present study, the quantitative relationship between St number and Re number of a freely falling cylinder in an infinite domain are sought at the Re number between 40 and 160, where the flows are two-dimensional and laminar, using a two-dimensional unstructured finite element method simulation of the incompressible Navier-Stokes equations. The interactions between the falling cylinder and the surrounding fluid are implicitly treated by the combined formulation which was proposed by T. Hesla (1991). In order to efficiently find an accurate solution of the flow around a fixed cylinder at the Re number range, the mesh adaption technique based on H-method is employed such that the initial coarse triangle is subdivided into the finer triangles in a local region where the velocity gradient is larger than a post-processed value which is a function of L2 norm of the velocity gradient in the field. Then, the adapted unstructured grid for the simulation of a fixed cylinder is used for the analysis of a freely falling cylinder. From the present numerical study, it has been confirmed that the St-Re relationship for the fixed cylinder agrees very well with the existing experimental results and the numerical simulation. For the freely falling case, it has been found that the corresponding St number for a Re number between 40 and 160 is smaller than that for the fixed cylinder case. This mechanism has been revealed by showing that the freely falling cylinder experiences more favourable pressure gradient than the fixed one due to the transverse motion resulting in the retardation of the vortex shedding.

Keywords: St-Re relationship, Freely falling cylinder, Mesh adaption, Combined formulation

This work has been supported by BK21 Project, Ministry of Education, Republic of Korea.

DNS Study of Transient and Turbulent Mixing Induced by the Rayleigh-Taylor and Richtmyer-Meshkov Instabilities

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Turbulent flows are ubiquitous in nature, occurring in settings as varied as exploding stars, experiments with intense lasers, and in fluid dynamics facilities. Using a direct numerical simulation database, we investigate the energy transfer process as well as the interaction of different scales of the flow induced by Rayleigh-Taylor instability. The analysis illustrates the dependence of the energy transfer and interacting scales on both inhomogeneous directions as well as on the spectrum in the homogeneous plane (Cabot and Zhou, 2002). To provide much needed guidance in developing subgrid models for large-eddy simulation of this kind of developing flow, we will stress the effects of unresolvable scales on the observable quantities, such as the mixing profiles of heavy and light materials. Spectral eddy viscosity and backscatter will be evaluated (Zhou and Cabot, 2002).

We have recently developed a theoretical treatment for modeling transient and turbulent mixing induced by the Rayleigh-Taylor and Richtmyer-Meshkov instabilities that is generally applicable to widely differing settings. We will report on the key areas in developing our model. First, we describe the mixing transition that separates transitional flows from fully developed turbulence. Second, we address the structure within the mixing layer, treating the full range of scales from the size of the domain at the largest scale to the smallest Kolmogorov length scale. By means of illustration, we will show examples of our model applied to three very different settings: 1)

incompressible fluid dynamics experiments at approximately atmospheric pressure, 2) ultra-high pressure supernova (SN) explosion hydrodynamics, and 3) high pressure laser experiments scaled to reproduce aspects of the SN dynamics. The spatial scales and time scales in these diverse settings differ by as much as 14-16 orders of magnitude, yet our general turbulence description is found to be adequate. The key issue of when does scaling – the fundamental underpinning of scaled experiments – break down will be addressed.

Keywords: Mix, Turbulence, DNS, subgrid-scale

W. Cabot and Y. Zhou, Degree of locality of energy transfer and interacting scales in flow induced by Rayleigh-Taylor instability (to be submitted to Phys. Rev. E)

Y. Zhou and W. Cabot, Influence of subgrid scales on resolvable mixing and dynamics (to be submitted to the special issue of Phys. Fluids in honor of Prof. Daniel D. Joseph).

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Single-phase Fingering in Porous Media Revisited

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I consider a low-viscosity fluid (e.g. water) displacing a high-viscosity fluid (e.g. a polymer solution) with which it is miscible from a saturated porous medium. It is well known that any initial planar front between the two fluids tends to broaden into a mixing layer because of dispersion effects and to be unstable to small disturbances in the otherwise one-dimensional planar velocity and pressure fields.

Most fluid-mechanical analyses of this phenomenon start from a Darcy (continuum) representation for the flow variables and assume the medium to be homogeneous. Those approaches that address the pore-scale inhomogeneities of a porous medium rarely consider the actual flow fields and associated mixing within the pore space; most represent the medium by simple network models, usually two-dimensional; the most seemingly successful of these are based on percolation and DLA theory. Rarely is the coupled problem, where mixing affects the fluid rheology, treated adequately.

My presentation will review a variety of effects and associated idealised results that are relevant to the real physical problem of predicting the behavior of the advancing front; these will include Taylor diffusion at the pore scale, dependence of mechanical dispersion on viscosity gradients and Darcy-scale inhomogeneities, and non-Newtonian fluid rheology. One simple consequence is that the dispersion process has to be regarded as scale-dependent; ways of expressing this formally will be discussed.

Effect of Viscous Heating on Linear Stability of Viscoelastic Cone-and-Plate Flow: Axisymmetric Case

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The effect of viscous heating on the linear stability of torsional flow of a viscoelastic fluid is analyzed. We consider an Oldroyd-B fluid subjected to a steady shearing motion in a cone-plate system with small gap. Previous experimental and analytical results show that in the isothermal case the flow is unstable to short wavelength disturbances for values of the Deborah number greater than some critical value. In this paper we show that viscous heating, which is characterized by a radially averaged Nahme number, has a stabilizing effect on both long wave and short wave disturbances. This is in qualitative agreement with experimental results.

Viscous and Viscoelastic Potential Flow Analysis of Kelvin-Helmholtz Instability on a Liquid Column

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It is well known that the potential flow analysis can be applied to flows generated from rest state. This may

hold even for viscous and viscoelastic flows when applied to stability problems of interfaces between fluids (Joseph and Liao 1994; Joseph, Belanger and Beavers 1999; Joseph, Beavers and Funada 2002; Funada and Joseph 2001). Here the viscous potential analysis is made to the stability of a liquid jet, Kelvin-Helmholtz instability.

The results are compared with those for inviscid case; the growth rate of axisymmetric disturbances decreases as the viscosity increases.

The analysis is then made for viscoelastic fluids. It is found that the critical velocity of jet becomes lower than that of viscous jet.

Real Time, 3-dimensional Imaging of Gas-Liquid-Solid Flows using Electrical Capacitance Tomography

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In this study, a 3-dimensional image reconstruction technique for imaging two- and three-phase flows using electrical capacitance tomography (ECT) has been developed for the first time. A 3- dimensional sensitivity matrix is constructed to replace the 2- dimensional sensitivity matrix commonly used in Linear Back Projection (LBP) for electrical capacitance tomography. The 3-dimensional image reconstruction problem is then solved based on multi-criterion optimization using an analogue neural network, referred to as neural network multicriteria optimization image reconstruction technique (3D-NN-MOIRT). NN-MOIRT, early developed in this work, has also capability of three-component identification in three-phase systems using a double-sigmoid function. The technique has been tested on a capacitance data set obtained from simulated measurement as well as experiments using a 12-electrode sensor. The performance of the technique has been analyzed, and has shown good accuracy and consistency. The technique is then applied for real time, 3-dimensional imaging of gas-liquid-solid flows in bubble column reactors. The hydrodynamic characteristics of the three-phase flow system including the bubbly flow structure, bubble velocity, and gas and solids concentrations' variations are deliberated based on the ECT images obtained in this study.

Free Energy Characterizations of Mechanical Incompressibility in Thermal Viscous Flow

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Many viscous fluids expand and contract while not apparently experiencing any measurable effects of mechanical compression. The historical modeling advantage and the computational advantage of removing rapid timescales associated with sound waves has led to important models for "weakly compressible flows". Fundamental stability analyses and proper mathematical formulations are due to Daniel D. Joseph. The Boussinesq equations for laboratory-scale, buoyancy-driven convection phenomena, and the anelastic model for density-stratified atmospheric phenomena, continue to play fundamental roles in science and engineering. Yet, these models do not apply to molten optical or polymeric fiber processing; this motivates our derivation of an alternative class of models which follow from degeneracy conditions applied on the free energy formulation of the compressible Navier-Stokes system. We do not explicitly alter the irreversible physics which are governed by second-law inequalities on viscosities and thermal conductivity. The four free energy formulations of compressible theory yield four distinct models, which we derive and analyze in detail. We first show that only two models preserve the Gibbs inequalities that characterize local well-posedness, linearized stability of the rest state, and non-negativity of squared sound speed, bulk modulus, and specific heat at constant volume. We then parametrize the linearized dispersion relation and eigenfunctions of compressible theory, and show how each mechanical incompressibility model arises in a well-defined limit process. We close with comparisons of the models and compressible theory nearby thermo-mechanical equilibrium.

Symposium on

Topics in Mechanics of Materials

In Honor Of
Professor W. Knauss

Organizers:
Prof. K. Ravi-Chandar (University of Texas)
Prof. C. T. Liu (Edwards Air Force Base)

TOPICS IN MECHANICS OF MATERIALS I

In Honor Of Professor Wolfgang Knauss

SESSION R2M

Finite Step Rate Corrections in Stress Relaxation Experiments

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The material response to a constant strain rate followed by a constant strain differs from the response to an ideal step to a constant strain for short relaxation times. Due to experimental limitations, the ideal constant strain history cannot be achieved. As a result, the short time data obtained after the ramp has to be corrected in order to obtain reliable estimates of the material response function, e.g., the relaxation modulus $G(t)$ at times shorter than approximately ten times the ramp time. Assuming a relaxation modulus of the form, $G(t) = G_0 e^{-\left(\frac{t}{\tau}\right)^{\beta}}$, we compare two methods of correction to the stress relaxation data obtained after a linear ramp. S. Lee and W. G. Knauss use an iterative scheme based on the assumed validity of the Boltzmann superposition principle. We compare this with the approach postulated by Zapas and Craft in which the "true" relaxation time becomes $t - t_0/2$ where t is the experimental time of the step and t_0 is the finite time required to apply the step in strain. Although $t - t_0/2$ provides a good correction for times greater than t_0, only the Lee-Knauss model can be accurately used for "true" times less than approximately $t_0/2$. For our assumed function, we find that the difference between responses obtained from the simulation of the ramp to strain and the true strain response is approximately 6.5% at t_0. This difference becomes less than 0.5% after the Lee-Knauss correction. For the Zapas-Craft approach, we find that the correction is actually better than the Lee-Knauss approach to "true" times just slightly greater than $t_0/2$, but this approach cannot be used for shorter times. We also compare the results from both correction methods on the shape of the "true" curve by comparing the parameters G_0, β and τ obtained by curve-fitting the corrected curves with the input parameters to the above equation.

Also, it is often desirable to have a similar correction available for large deformation responses. However, the Lee-Knauss method is valid only for linear viscoelastic systems and the Zapas-Craft approach has not been rigorously evaluated for large deformations. We examine the possibility of extending both approaches within the context of the BKZ single integral nonlinear viscoelasticity theory.

Rate-Dependent Rubbery Behavior of a Structural Adhesive

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This paper describes the development of a nonlinear viscoelastic model that can account for rate dependence at large strains. The model was based on tensile and shear experiments on a urethane structural adhesive. The most striking observation was that the stress-strain behavior at large strains was rate dependent. As a result, a rate dependent rubbery shear modulus was added to Popelar's shear modified free volume model. This was very effective in predicting ramp shear behavior over a range of strain rates and temperatures. The correspondence of model results and tensile data was reasonable below 20% strain. At higher strains, the model over predicted the stress levels for a given strain. This may have been due to the accumulation of damage, which has yet to be included in the model. The model was unable to capture the effect of salt water on the tensile behavior of the urethane.

The VBO Model for a Semi Crystalline and an Amorphous Polymeric Solid

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As solid polymers replace other materials in load-bearing applications, they must be as reliable as their

predecessors. It is therefore necessary to characterize the polymer by suitable tests and to make a constitutive model that can be used in inelastic analyses. The viscoplasticity theory based on overstress (VBO) will be illustrated vis--vis the homogeneous deformation of amorphous polyphenylene-oxide (PPO) and semi-crystalline high-density polyethylene (HDPE). Engineering stress and strain are reported.

As expected, monotonic loading exhibited nonlinear rate sensitivity and a region with small changes of the tangent modulus, the flow stress region. Rate sensitivity continues to manifest itself upon unloading from tension and loading into compression. It is also shown that the recovery strain at zero load increases with an increase of the unloading strain rate magnitude. The relaxation drop and the accumulated creep strain increase with an increase of prior strain rate. Both polymers have a fading memory for the initial conditions and the prior history.

The viscoplasticity theory based on overstress (VBO) is a state variable theory. A flow law and growth laws for two stress-like state variables form a set of three nonlinear first order differential equations. The solutions have two important regions, 1) around the origin, where the behavior is quasi elastic, and 2) the long-term asymptotic solution which corresponds to the flow stress region. It is shown that VBO exhibits a fading memory of the initial conditions and of prior history.

A numerical matching of VBO to the data shows excellent simulation during monotonic loading including creep and relaxation episodes for both polymers. However, the unloading of VBO is much steeper than the unloading seen in experiments. Various modifications of VBO are under consideration to improve the modeling of the unloading behavior.

Keywords: Polymers, relaxation, creep, rate sensitivity.

On the Thermodynamics of Fracture in Viscoelastic Media

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This paper presents a description of the thermodynamics of fracture in viscoelastic media. Utilizing the thermodynamics of the classical linear elastic fracture problem as a framework, the problem is extended to consider a viscoelastic medium. Due to the ductility encountered in viscoelastic media, the crack tip region is modeled with a damage dependent nonlinear viscoelastic cohesive zone, rather than as a single point. Both local and global thermodynamic analyses are performed for the bulk material, and the cohesive zone. These analyses result in explicit statements of the energy dissipation due to bulk viscoelasticity, cohesive zone viscoelasticity, and crack growth on both the micro- and the macroscale. These expressions are then calculated for an example problem by using a nonlinear finite element algorithm equipped with a micromechanically-based viscoelastic cohesive zone model.

Nonlinear Viscoelastic Behavior of Polymers

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Polymeric materials have found increasing use in engineering applications where they function as the primary load-carrying member. In such applications, prediction of the long-term durability is of crucial importance. Traditional characterization of the constitutive properties of these materials has been through either creep or relaxation experiments under either uniaxial or shear deformations; the resulting characterization provides the uniaxial (or shear) creep compliance or relaxation modulus. Such experiments are very easy to perform, since they are identical to typical tensile or shear tests performed to characterize elastic materials, with the only difference appearing in monitoring the variation of the stress or strain as a function of time. Generalization of this idea to multiaxial stress and deformation states must be accomplished by considering the bulk deformations. Measurement of the bulk modulus or compliance requires a sensitive dilatometer; experimental problems associated with such experiments are usually circumvented by assuming that the bulk deformations are time independent. This assumption is justified by the observation that the change in the bulk modulus is small in comparison to the change in the shear modulus by two to three orders of magnitude. However, some models of nonlinear viscoelastic behavior indicate a strong coupling of the bulk deformation and extensional or shear relaxation behavior. Thus, there arises a critical need for experimental determination of the influence of dilatational deformations on relaxation; in particular, it is desirable to design experiments where adequate control can be established over the applied deformations as well as measure the bulk and shear relaxation behavior. In this paper, we demonstrate a very simple experimental configuration where the shear and bulk relaxation moduli can be measured simultaneously with ease in a single experiment. We describe the confined compression experimental configuration that enables the simultaneous

measurement of the bulk and shear relaxation moduli; the procedure for the determination of these moduli from the experimental measurements is described. While the procedure for the decoupling of the bulk and shear relaxation behavior in linearly viscoelastic materials is simple and explicit, special considerations that arise in the characterization of nonlinearly viscoelastic materials are also described. Finally, a demonstration of the technique is provided through measurement of the viscoelastic behavior of polymethylmethacrylate.

TOPICS IN MECHANICS OF MATERIALS II

In Honor of Professor Wolfgang Knauss

SESSION R3M

Fracture Behavior of a Self-Healing Polymer Composite

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Inspired by biological systems, in which damage triggers an autonomous healing response, a polymer composite material that can heal itself when cracked has been developed. This paper investigates fracture mechanics issues consequential to the development and optimization of this new class of materials. The self-healing material under investigation is an epoxy matrix composite, which utilizes embedded microcapsules to store dicyclopentadiene (DCPD) as a healing agent and an embedded *living* catalyst. When the composite cracks, the microcapsules rupture and release the healing agent into the damaged region through capillary action. As the healing agent contacts the embedded catalyst, polymerization is initiated which then bonds the crack face closed. The efficiency of crack healing is defined based on the ability of a healed sample to recover fracture toughness.

Fracture toughness is measured using a tapered double-cantilever beam (TDCB) test, which ensures controlled crack growth along the centerline of the brittle epoxy specimen. The tapered geometry is designed so that the sample compliance changes linearly with crack length and the fracture toughness measurement is independent of crack length. Effects of microcapsule size and concentration are studied with a view towards improving healing efficiency and understanding toughening mechanisms. By optimizing the amount of microcapsules, healing efficiencies of over 90% are obtained. The influence of catalyst concentration, healing agent chemistry and epoxy composition are also investigated and found to have a significant impact on the healing kinetics.

Scale Effects on the Fracture of Ice

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An understanding of the fracture behavior of ice is sought over many scales. Lab- to structural-scale fracture tests of lake and sea ice sheets using edge cracked ice plates ranging from lab-scale up to 30 m and 80 m, respectively, has been completed. The scaling knowledge thus gained is used in this talk to examine the compressive failure of ice sheets during structural indentation and the vertical breakthrough or penetration of floating ice sheets. The influences of ice temperature, ice thickness, ice type, rate and fracture mode will be included.

This talk will concentrate on scale effects associated with the radial fracture, cleavage fracture, and penetration, of ice sheets.

Thermoviscoplastic Modeling and Numerical Analysis of Size Effects in Dynamic Tension Tests

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Advances in experimental techniques and numerical codes have allowed during the last decades for a more detailed analysis of specimen behavior during high strain rate and impact testing of variety of materials like advanced industrial alloys, composites and ceramics. It is well known that a specimen for impact materials testing must be optimized concerning its dimensions. The main reason is to reduce strain gradients due to the effects of elastic-plastic wave propagation. On the other hand, when a Split Hopkinson Bar (SHB) in tension is applied, the net displacement of the specimen ends is very limited, usually from 2.0 to 3.0 mm. In order to reach relatively large deformations the specimen gage length must be very short, for example to reach maximum strain 0.5 the specimen length must be reduced to dimensions from 4.0 mm to 6.0 mm. Consequently small diameters or lateral dimensions must be applied to assure one dimensional deformation. Such small lengths substantially perturb idealized

material behavior to be determined. For example, Luders bands typical for materials with the upper and lower yield point disappear and formation of necking is perturbed as well.

Since the authors of this contribution are interested in testing of sheet metals at high strain rates the situation is even worse, because reduction in length causes transition from one-dimensional strain to plane strain conditions where the instability mode is substantially perturbed.

So the main motivation of this study was to perform a systematic analysis, numerical and analytical, to find differences in behavior of short and long specimens loaded in dynamic tension. For this purpose precise constitutive relations were applied which include effects of strain hardening, rate and temperature sensitivity on the flow stress, [1].

The FE explicit code ABAQUS has been applied that include thermal coupling by application of adiabatic conditions of deformation. Several specimen lengths from 10 mm to 40 mm, and several velocities from 10 m/s to 100 m/s (nominal strain rates) were assumed in FE calculations. It has been confirmed that short gage length substantially perturbs the "material behavior" to be determined. Moreover, the critical Impact Velocity (CIV) in tension has been confirmed as a material property. The latest stage of specimen deformation is, of course, failure. This study may be classified as an example of Dynamic Failure Mechanics, a discipline in the stage of early development, no initial cracks are assumed. A solid is loaded in a short time interval, and a more or less uniform plasticity field develops. But after a short time, because of local stress concentrations temperature gradients appear caused by adiabatic heating, and localization of plastic field leads to failure.

References

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Keywords: Dynamic tension test; Size effects; Critical Impact Velocity; Failure criteria in tension.

Some Thermodynamic Considerations in Memory Materials

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Although Thermodynamics is not always considered as part of the task in formulating Constitutive Equations, it can play a vital role in distinguishing viable formulations from those which are not so viable. An examination is made of the role of thermodynamics in some formulations appropriate to viscoelasticity and to plasticity. It is argued that such formulations tell us things about the behavior of such materials which would not come out of a non-thermodynamic formulation. The role of energy and of entropy in damage is discussed.

Using the Formal Structure of Plasticity at Finite Strains to Model the Thermomechanical Behavior of Amorphous Polymers Around Their Glass Transition

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The behavior of amorphous polymers around their glass-transition temperature has several very interesting characteristics. As all polymers, amorphous polymers experience a very large change in rigidity over a very small interval of temperature. This change of rigidity may occur within 10 to 20 degrees centigrade. Very large plastic ("permanent") deformations below the glass-transition are fully recoverable when heating to above the glass transition. These polymers exhibit rate dependence both below and above the glass transition, even though there is a substantial difference between the glassy and rubbery responses. Under load control, at small loads the polymers tend to exhibit recovery (shrinking toward an equilibrium configuration), while at large loads these polymers tend to creep. Under strain control, large loads tend to relax toward an equilibrium, while small loads tend to rise to this same equilibrium. These characteristics are combined into a response model for PMMA that spans 50 degree temperature range containing the glass-transition temperature.

TOPICS IN MECHANICS OF MATERIALS III

In Honor Of Professor Wolfgang Knauss

SESSION R4M

Dynamic Fracture in Multi-Layered Materials Subjected to Low-Speed Impact

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Model layered materials involving a combination of transparent polymers and metals were tested to understand the nature and sequence of complex dynamic failure modes in layered and sandwich structures. For heterogeneous three-layer systems, inter-layer cracks (delamination) always appeared first. These cracks were shear dominated and could be intersonic even under moderate impact speeds. Opening intra-layer cracks kinking from the inter-layer cracks propagated into the weak core layer of the model three-layer system and eventually branched.

For the homogeneous layered materials, three-layer and two-layer, bonded Homalite/Homalite specimens featuring different bonding strengths were tested. Opening dominated intra-layer cracks radiated from the impact point. Mixed-mode inter-layer cracking (interfacial debonding) was initiated when the intra-layer cracks approached the interface with a large incident angle. The dynamic interaction between inter-layer crack formation and intra-layer crack growth (or the dynamic equivalent of "Cook-Gordon Mechanism") was visualized for the first time.

The Role of PMMA in Ballistic Impact Response of Layered PMMA/PC Composites

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Impact response against a .22-caliber fragment simulated projectile was investigated on monolithic PMMA and PC, and their layered composites of various configurations. Despite the brittle nature of PMMA upon tensile loading, its ballistic performance exceeds PC at a plate thickness of 12 mm and higher. In addition, layered PMMA/PC composites exhibit better ballistic impact strength than that obtained for the layered PC/PC composites and their monolithic components of equivalent total thickness. PMMA plates thicker than 9 mm display distinct shear-mode cracks. Initiation of cracks rather than crack propagation appears to be the dominant mechanism during the early stage of fracture events in PMMA. This is consistent in both monolithic PMMA and PMMA/PC composites. Determinati on of the effect of impact velocity upon the mode of failure of monolithic PMMA is also included. Yield strength values of monolithic PMMA and PC obtained from quasi-static compression measurements are utilized for correlation with their corresponding dynamic impact response.

Dynamic Crack Propagation in Functionally Graded Materials

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Failure behaviors of inhomogeneous materials are investigated using suitable crack growth models in finite element analyses. First, several failure growth models for crack nucleation and growth are evaluated. It appears that cohesive model which governs the traction-displacement relation of crack opening surfaces is most effective in complex material systems such as functionally graded materials. The cohesive model is tested in several sample problems. A double cantilever beam crack model is used to investigate the dynamic crack propagation behavior within elastic-plastic FGMs. Various decohesion conditions, including constant maximum traction and decreasing maximum traction from elastic phase to elastic-plastic phase, are examined to assess their suitability. The simulation results show that the crack propagation behaviors are highly dependent on the variation style of maximum traction within FGM region (described with the power-law exponent). Larger the exponent, which means maximum traction decreases faster from elastic region to elastic plastic region, leads to lower resistance of crack propagation. Evolutions of various time-dependent energy components during the crack growth are also monitored. Plastic dissipation at the crack tip has a large contribution to the total work of fracture. In a separate multi-layer model, failure in the metal-ceramic FGM layer caused by

dynamic impact load is investigated. Under the compressive impact load, multiple crack initiation and growth occur spontaneously. Our results show that, under an impact load, energy dissipation will be much larger if a metal-ceramic FGM layer, instead of a pure ceramic layer, is used as a protective component in a multi-layer structure. In addition, the paper also presents the measurement procedure based on an inverse analysis technique to determine fracture parameters. This method uses the propagated crack length and time-dependent strain measurements as input.

Mode III Steady Dynamic Propagation of a Crack with a Rate and Temperature Dependent Cohesive Zone

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The steady state dynamic propagation of a crack in a heat conducting elastic body is numerically simulated. Specifically, a mode III semi-infinite crack with a non-linear temperature dependent co-hesive zone is assumed to be moving in an unbounded homogeneous linear thermoelastic continuum. The numerical results are obtained via a semi-analytical technique based on complex variables and integral transforms. The relation between the thermo-mechanical properties of the failure zone and the resulting crack growth regime are investigated.

The main result of the paper consists in showing that, by some reasonable assumptions concerning the temperature dependence of the cohesive zone properties, the predictions of a continuum theory of dynamic crack propagation can change significantly from those of purely mechanical approaches. In particular, the results shown herein indicate that the temperature dependence can cause the appearance of forbidden ranges of crack speed, this being a type of instability that to date has only been predicted via atomistic simulations.[1] In addition, while using a critical crack opening displacement fracture criterion, the results show that a cohesive zone behavior which is both rate and temperature dependent is characterized by high values of cohesive stress in the interior of the cohesive zone. Often, these high stresses appear to be significantly larger than the material's ulti-mate strength. This is therefore a strong indication that the fracture criterion should be changed so as to allow the cohesive zone to fail in at least two ways: (*i*) because a critical opening displacement has been reached; and/or (*ii*) because a critical cohesive stress has been reached. If such an extended fracture criterion were used in conjunction with the cohesive zone models presented herein, one can expect that the cohesive stress overshoot discussed earlier along with a maximum stress condition would provide a mechanism for the fragmentation of the cohesive zone. In other words, one can envision that a (fully connected) cohesive zone will evolve into a fractured cohesive zone, that is, a region with at least two cohesive zone segments separated by a fully fractured surface. In such a situation the observable physical crack tip would propagate through cohesive regions inter-rupted by fully cracked regions. Crack speeds should therefore be expected to be oscillating crack speeds rather than resembling a behavior typical of a steady-state regime. Furthermore, it would not be unreasonable to expect that the same physical mechanism (i.e., cohesive zone fragmenta-tion) can limit the maximum speeds achievable by the system. To date, this kind of behavior has only been qualitatively predicted via atomistic simulations. The authors feel that the calculations presented herein, along with a modified fracture criterion limiting the maximum allowed cohesive stress, support the conjecture that said predictions can be achieved within a continuum mechanics framework.

[1] See, for example, M. Marder and S. P. Gross (1995), "Origin of Crack Tip Instabilities", *Journal of the Mechanics and Physics of Solids*, Vol. 43, pp. 1-48.

Shear Wave Loading of Steel Plates with Mid-Plane Cracks

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Pressure-shear plate impact experiments are conducted as a means for subjecting a crack to plane wave loading in shear. For these experiments the steel target plate (AISI 4340 VAR, 200 C temper) has a mid-plane fatigue crack that has propagated half-way across the diameter. The thickness of the flyer plate and the distance from the impact plane to the mid-plane crack are chosen such that the initial compressive pulse passes through the crack plane before the leading shear wavefront arrives. In this way the crack plane is subjected to a plane wave that imposes essentially step-wave loading, in shear at normal incidence. By rotating the shearing direction relative to the line of the tip of the crack the loading can be varied continuously

from pure mode II to pure mode III. To monitor the motion at a point on the rear surface of the target plate a combined normal and transverse displacement interferometer has been modified to minimize the effects of rotation of the surface on the quality of the interferometer signals. After the experiment the specimen is sectioned to observe the advance of the crack. Scanning Electron Microscopy (SEM) and Electron Back-Scattered Diffraction (EBSD) are used to monitor, respectively, the trajectory of the fracture and the rotation of grains near a band of deformation and failure. Simulations using ABAQUS Explicit are performed in an attempt to interpret the behavior in terms of mechanistic models of plastic deformation and failure.

Measuring the Decohesion Law of a High Explosive Material

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The plastic bonded HMX (PBX) high explosives are composed of the energetic crystal (HMX) and a polymeric binder. Previous experimental observations showed that the fracture process in the sugar mock, a simulant of the PBX 9501 high explosive, is completely different from that in brittle solids, even though the high explosive material PBX 9501 is quite brittle under tension. A close examination of the fracture surface revealed that before crack initiation and propagation, a very large damage region is developed ahead of the crack tip. Since such a damage region is very narrow, it can be modeled as a stress briding zone. Due to the presence of the sizable bridging zone, conventional fracture mechanics is no longer applicable. Stress bridging has to be considered explicitly in order to understand of fracture processes in the PBX~9501 high explosive and the sugar mock. The key element of the bridging model is the so-called stress-bridging law, or the decohesion law, which can only be dedtermined through experimental measurement. In this study, fracture experiments on PBX~9501 high explosive using an optical technique were conducted. From the experimental measurement, we determined quantitatiely the stress-bridging law, which characterizes the relationship between the bridging stress and the opening displacement cross the bridging zone. In this talk, detailed experimental observations and results will be presented, and the effect of loading rate on the bridging process will be discussed.

TOPICS IN MECHANICS OF MATERIALS IV

In Honor Of Professor Wolfgang Knauss

SESSION F2M

Crack Propagation in Functionally Graded Material

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Bi-material interfaces are often sites for structural failure due to delamination initiated crack formation and growth resulting from large material mismatch induced shear stresses. Functionally bonding layers are intended to mitigate this tendency. Compared with homogeneous material models, few analytical solutions exist for cracks growing along the interface between functionally graded material layers. Nearly all existing solutions are for a static crack or assume quasi-static crack growth (ignoring inertial effects). This talk discusses recent progress on analyzing dynamic, transient crack growth along a functionally graded interface. The analysis, which is based upon an asymptotic approach valid for functionally graded material properties modeled as a perturbation of a reference homogeneous material, assumes anti-plane symmetry, but in principle other fracture modes can be treated similarly. Since there is a dirth of analytical solutions for dynamic, transient crack growth in functionally graded material against which to guage the range of applicability of the asymptotic solution, the method is bench marked against the corresponding static problem for which a few analytical solutions exist. The results suggest that the asymptotic solution is rather robust, and they indicate how one might wish to grade material properties through a functionally graded bonding layer to enhance the composites resistence to crack growth.

Investigating the Deformation and Failure Mechanisms in Bi-Material Systems under Tension

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Bonded sandwich laminates are being used widely in various industries. They have been successfully used in aircraft and space structures, pipes, chemical tanks, ship hulls, and in other structural applications in which a high strength-to-weight ratio is a desirable feature.

Joining structural components with adhesives provides a number of advantages. Bonding does not require rivet holes, which are stress raisers and may cause premature failure either under static or fatigue loading. In fact, it has been shown that the fatigue strength of a stiffened panel in an aircraft structure is considerably improved when the stiffeners are bonded to the panel. The bonding of damping materials to metal sheets, to form a sandwich structure, currently is being considered as an effective way to control noise-induced fatigue (sonic fatigue) of airframes. In solid rocket motor design, the bonding of insulation materials to motor casings is used to protect the casing from high temperature after the motor is fired.

It is well known that there are imperfections existing in bonded systems. These imperfections may be produced during the fabrication process of the systems. In analyzing the strength of the bonded system, the localized imperfection may be idealized as a crack in the material. In addition to the imperfections, cracks also can be developed in the material by service loads during the life of the structures. In determining the residual strength or the remaining service life of a bonded structure with cracks, the constitutive behavior of the bonded systems needs to be determined.

In this study, the strain distributions and the constitutive relations in a bonded bi-material specimen under a constant displacement rate of 0.0254 cm./min. were determined using computer aided speckle interferometry techniques. Two different viscoelastic materials were used to make sandwiched specimens. The two outer layers of the specimen are made of a particle-reinforced rubber, whereas the middle layer is a non-reinforced rubber. The heights of the outer layer and the middle layer are 5.08 cm. and 0.254 cm., respectively, the thickness of the specimen is 0.508 cm., and the width of the specimen varies from 0.508 cm. to 2.58 cm. The experimental data were analyzed and the effects of specimen geometry on strain distributions and failure mode in the specimen were discussed.

Some Recent Developments and Applications of Image Correlation in Experimental Micromechanics

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Some recent efforts on developing a more robust and reliable surface deformation measurement tool by digital image correlation will be reviewed. Methodologies in assessing and reducing both intrinsic and extrinsic errors in image-based strain mapping measurements will be discussed. The talk will focus on the challenges and strategies of how to extract highly non-uniform deformation field information and how to process contaminated or degraded digital images often encountered in scanning electron and probe microscopy. Successful applications of the improved technique in micromechanics study of various heterogeneous material systems will be demonstrated.

Micromechanics of Microstructurally Small Surface Cracks in Polycrystals

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Two-dimensional plane strain finite element calculations with a planar double slip crystal plasticity model are presented for crack tip sliding (CTSD) and crack tip opening (CTOD) displacements of microstructurally small transgranular surface cracks in a polycrystal subjected to monotonic and cyclic loading, including tension-compression and shear. The material has a nominal stress-strain behavior of 4340 steel. The CTOD and CTSD are computed for stationary crystallographic surface cracks with various realizations of crystallographic orientations of surrounding grains for nominal stress levels below the macroscopic yield strength. It is found that (i) the opening displacement is dominant for remote tension even for crystallographic cracks oriented along the maximum shear plane in the first surface grain, (ii) there is a strong dependence of the CTOD on the proximity to grain boundaries, but lesser dependence of the CTSD, (iii) the elastic solutions for CTOD and CTSD are valid below about 30% of the 0.2% offset-defined yield strength, (iv) the cyclic crack tip displacement varies in a different manner for tension-compression than cyclic shear with regard to encounters of grain boundaries, and (v) the crack tip

exhibits ratcheting phenomena that affect local mixity of sliding and opening displacements under cyclic loading conditions.

Numerical Simulation of Hydrogen-induced Interfacial Decohesion in Nickel-base Alloys

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The mechanics of hydrogen-induced decohesion along the interface of an elastic inclusion imbedded in a ductile matrix is studied in an effort to understand the micromechanics of hydrogen embrittlement in nickel-base alloys that fail by ductile intergranular fracture initiating at grain boundary carbides. The thermodynamic theory of decohesion of Hirth and Rice in its "fast separation limit" is employed to describe the cohesive properties of the inclusion/matrix interface in the presence of hydrogen. A model for transient hydrogen transport through the plastically deforming matrix, the elastic inclusion, and the opening interfacial channel coupled with interfacial debonding and large-strain deformation in the surrounding matrix is presented. Solution to the coupled elastoplasticity/decohesion/transient transport problems is sought in a unit cell under plane strain uniaxial loading. Interfacial separation is modeled through cohesive elements and is simulated incrementaly within the updated Lagrangian formulation scheme used to model bulk material elastoplasticity. The numerical results are used to analyse: a) the interaction of decohesion with matrix softening; b) the relation between bulk and interfacial energy expenditures; and c) the importance of parameters such as strain rate and relative magnitude between interfacial and bulk diffusivities on the propagation of the interfacial crack. For material data pertaining to alloy 690, it was found that hydrogen accelerates the propagation of interfacial debonding thereby assisting plastic flow localization in the surrounding matrix. In general, hydrogen was found to decrease both the macroscopic stress and strain at which void initiation commences.

Pressure and Strain-Rate Dependence of Glassy Polymers

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Dynamic plastic response of glassy polymers is a complex process and depends on several factors such as the induced strain, strain-rate, pressure and temperature. In the present study, in order to better understand the response of amorphous polycarbonate as a function of strain-rate and pressure, quasi-static and dynamic compression tests are conducted. The quasi-static response of PC is investigated on a servo-hydraulic test machine at strain rates $\sim 0.001/s$. In the intermediate strain-rate regime ($\sim 1000/sto3000/s$), *nearly* adiabatic compression tests are conducted using the split Hopkinson pressure-bar. Since temperature plays an important role in governing the dynamic plastic response of polymers, nearly isothermal tests are also conducted by deforming the specimen incrementally in the split Hopkinson pressure bar. In order to investigate the behavior of polycarbonate at strain rates in the range of $10^5 - 10^6/\text{sec}$, high strain-rate plate impact pressure-shear experiments are conducted. In these experiments thin sheets ($\sim 150\mu m$) of polycarbonate are sandwiched between two hard elastic plates and impacted by an elastic flyer plate. Moreover, by a suitable design of the sandwiching plates, a step drop in normal pressure is induced during the high-strain-rate deformation process. The step-drop in pressure allows us to investigate the evolution of flow stress of polycarbonate to changes in applied normal pressure. By combining the results from the three series of tests a better understanding of the pressure and strain-rate dependence of polycarbonate is obtained.

TOPICS IN MECHANICS OF MATERIALS IV

In Honor Of Professor Wolfgang Knauss

SESSION F3M

Measurement of Creep Compliance by Nanoindentation

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Two methods to measure the linear creep compliance of time-dependent materials are proposed and validated using nanoindentation. Two different bulk polymers, Polymethyl Methacrylate (PMMA) and Polycarbonate (PC), were used in the validation study; though it is expected that the methods developed herein can be used for very small amounts of materials and heterogeneous materials. Both Berkovich and spherical nanoindenter tips were used to indent into the material. Two loading histories were used: (1) a ramp loading history with constant loading rate, in which the total load and the indentation displacement were recorded as functions of time; and (2) a step loading history, in which the indentation displacement

was recorded as a function of time. Analysis of the linearly viscoelastic material response is performed to extract the surface local creep compliance function for the two materials under two different loading histories. The limit of linearly viscoelastic behavior for each of the two materials was determined through the observation of the indent impression after complete unloading; it is postulated that linearity is achieved if indentation impression does not exist after fully unloading. The creep compliance functions measured from the nanoindentation were compared with those from conventional uniaxial tension or torsional tests. Results from nanoindentation tests agree generally well with data from conventional tests. It has thus validated the techniques of measuring linear creep compliance in the glassy state using nanoindentation with Berkovich and spherical indenter tips. These methods have the potential to be used for very small amounts of materials, very small structures such as Micro-Electro-Mechanical-Systems (MEMS), gradient materials with material properties varying spatially, and heterogeneous materials such as nanocomposites and human bones.

Dynamic Compressive Stress-Strain Behavior of a Soft Rubber

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Rubbers are widely used in shock-absorption applications. However, their dynamic mechanical responses under impact loading conditions are rarely addressed. In this study, the dynamic compressive stress-strain curves at various strain rates of an EPDM rubber were determined with a modified split Hopkinson pressure bar (SHPB). In order for the specimen to deform homogeneously at a nearly constant strain rate under dynamically equilibrated stress, a pulse-shaping technique was employed. The validity of the dynamic experiments on such a soft material was monitored by a high-speed digital camera for homogeneous specimen deformation, and by piezoelectric force transducers for dynamic stress equilibrium. The resulting dynamic stress-strain curves for the EPDM rubber show non-linearly with strong strain-rate sensitivity. A dynamic constitutive model for this rubber has been developed based on a strain energy function theory, which agree with the high strain-rate experimental results well.

Some Surprising Phenomena in Fracture of a Viscoelastic Triangular Lattice

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A semi-infinite crack growing along a straight line in an unbounded triangular-cell lattice and in lattice strips is under examination. Elastic and standard-material viscoelastic lattices are considered. Using the superposition similar to that used for a square-cell lattice [Slepyan, L.I., 2000. Dynamic factor in impact, phase transition and fracture. J. Mech. Phys. Solids, 48, 927-960] an irregular stress distribution is revealed on the crack line in mode II: the strain of the crack-front bond is lower than that of the next bond. A further notable fact about mode II concerns the bonds on the crack line in the lattice strip deformed by a 'rigid machine'. If the alternate bonds, such that are inclined differently than the crack-front bond, are removed, the stresses in the crack-front bond and in the other intact bonds decrease. These facts result in irregular quasi-static and dynamic crack growth. In particular, in a wide range of conditions for mode II, consecutive bond breaking becomes impossible. The most surprising phenomenon is the formation of a *binary crack* consisting of two branches propagating on the same line. It appears that the consecutive breaking of the right-slope bonds – as one branch of the crack – can proceed at a speed different from that for the left-slope bonds – as another branch. One of these branches can move faster than other, but with time they can change places. Some irregularities are observed in mode I as well. Under the influence of viscosity, crack growth can be stabilized and crack speed can be low when viscosity is high; however, in mode II irregularities in the crack growth remain. It is found that crack speed is a discontinuous function of the creep and relaxation times.

A Finite Integral Approach for the Thermoelastic Properties of Multiphase Composites

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This paper presents a micromechanical model for unidirectional fibrous composite using a finite integral formulation on the basis of the strain-compatible volume-average (SCVA) method developed by Gan and Orozco [1]. Unlike the finite element and finite difference methods that divide matter or space into smaller pieces, this method took the opposite route (i.e., dealing with problems like how to assembly separate pieces into a unit). The primary unknowns involved in were density-type quantities like strains and their first derivatives at each subcell. The fundamental equations governing the boundary value problem appeared in their original integral format. Strain compatibility was enforced in average sense such that displacement at subcell center points could be evaluated using the strains. In fact, for some micromechanical analysis tasks, there is no need for computing the displacement at all. In addition, displacement and traction continuity relationships among neighboring subcells were established in terms of materials constitutive properties, average local strains and their derivatives. The effective constitutive relationship was derived from the average local stresses and strains using volume average method. The shear-coupling effect of the SCVA method was preserved in the new finite integral method. The integral approach taken by the new method made it be capable of dealing with more generic subcell types. An innovative implementation adopted in this study enabled it to work with triangular and quadratic shapes, which is essential to represent the curvature fiber shape accurately. Overall thermo-elastic properties of composites with different microstructure were predicted using the new approach. Results were compared to that of other micromechanical models including GMC [2], SCVA and the finite element based approach in terms of accuracy, convergence and computational costs. Keyword: Micromechanics, Solid Mechanics, Composite Materials, Thermoelasticity

[1] "A Strain-Compatible Method for Micromechanical Analysis of Multi-Phase Composites", H. Gan, C. E. Orozco, C. T. Herakovich, *Intl. J. of Solid and Structures*, (37) 5097-5122, 2000.

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The Effect of Temperature History on Behavior of PA6 and PA66

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Polyamides, in particular PA6 and PA66, are widely used in production of fibers. One of the most important properties of fibers is the shrinkage magnitude, observed when they are exposed to elevated temperature and/or moisture. It has been commonly accepted that the amount of shrinking of the PA66 fibers is considerably smaller than that of the PA6 fibers. This made the former somehow more attractive for the applications in clothing industry, where the geometric stability plays an important role.

In this paper we show that this commonly accepted observation is a misconception resulting from the improper shrinkage testing procedure, as defined by the standard.

Fibers made from the two materials have been deep-frozen immediately after the spinning, using liquid nitrogen, and consequently stored at temperature below $-20°C$. At these conditions the molecular mobility of the amorphous phase is virtually prevented, preserving the entire fiber shrinkage potential. The shrinkage measurements were then performed at different temperature histories, using the newly designed apparatus, which allows real-time measurements of the fiber shrinking kinetics.

The experiments showed that the shrinkage magnitude of the two materials is roughly the same, when they are heated from below $-20°C$ to $140°C$ in a single step. This indicated that the shrinkage kinetics of the PA66 is considerably higher than that of the PA6, resulting in an apparent lower shrinkage of the former, if the experiments start from the room temperature. Based on the studies of the fiber shrinkage kinetics at different temperature histories we proposed a new model of the fiber mechanically induced higher-order structure.

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APPLIED MECHANICS SYMPOSIUM

In Honor Of Professor A. W. Leissa

SESSION W2H

Structural Mechanics: Then and Now

Arthur W. Leissa
Ohio State University

The speaker will be comparing how research in structural mechanics was conducted three or four decades ago with the present, from his own experiences, along with what topics were of great interest then, compared to now.

Buckling of Rectangular Plates Subjected to Nonlinearly Distributed In-plane Loading

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The problem of buckling of a rectangular plate subjected to *uniformly distributed* in-plane compressive loading goes back to the work of Bryan in 1891. The same problem but with *linearly varying* loading was first treated independently by Timoshenko and Boobnov about 90 years ago. Recently, for the first time, this problem was solved exactly by Leissa and Kang. The problem treated here is buckling in the presence of loading *nonlinearly distributed* along the plate edges, and it is considerably more complicated in that it requires that first the plane elasticity problem be solved to obtain the distribution of in-plane stresses. Then the buckling problem must be solved in the presence of stresses varying in both directions. This problem was first solved approximately by Van Der Neut in 1958 for half-sine loading and by Renoy in 1969 for parabolic loading. Here this problem is solved *exactly* for the first time using a power series method.

Keywords: buckling, nonlinearly distributed load,plates,rectangular plates

Nonlinear Dynamics of Aeroelastic Systems

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Aeroelastic systems are those that involved the coupled interaction between a convecting fluid flow and a flexible elastic structure. The nonlinear dynamical response of such systems is of great current interest. Currently operational aircraft are known to encounter limit cycle oscillations (LCO) in certain flight regimes and relatively simple experimental wind tunnel models have been designed to exhibit LCO as well. The LCO may be either beneficial or dangerous for the safely of the aircraft. The results of several wind tunnel experiments are discussed and compared to those from mathematical models. The physical models include (1) an airfoil with control surface freeplay; (2) a delta wing with structural geometrical nonlinearities due to plate-like deformations; and (3) a very high aspect ratio wing with geometrical structural nonlinearities due to coupling among torsional twist, transverse bending and fore-and-aft bending. In addition, the theoretical advantages of modeling the aerodynamic flow field in terms of a set of global modes and also using a novel form of the harmonic balance method are emphasized. A recent theoretical result for large shock motions in a viscous transonic flow around an oscillating airfoil undergoing LCO is presented to illustrate the results to be obtained by such methods.

Shear Deformation Factors and Shear Locking

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Shear deformation coefficients have been defined in numerous ways in the last century, beginning with being the ratio of the maximum shear stress to the average shear

stress on cross sections. The formulation of this presentation leads to shear deformation factors obtained by setting the strain energy for a beam as represented by the theory of elasticity equal to the strain energy for a one-dimensional beam based on technical beam theory. These shear deformation coefficients form a symmetric tensor with principal axes that, in general, differ from the principal axes of the tensor for moments of inertia. The coefficients are functions of the material properties and vary with the beam thickness. The effect of plate thickness on shear locking tends to be countered by the variation with thickness of the shear coefficient. A finite element formulation will be described that permits the shear coefficients to be calculated for a cross section of arbitrary shape.

Keywords: shear deformation, shear coefficients, shear factors, shear locking

Time-dependent Boundaries for Vibrating Threads

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Threads in textile machines are characterized by neglectable bending stiffness and mass flow across system borders. Within a multibody system, they represent couplings between machine components which are generally modeled as force elements. Oscillations of threads become more and more important as one aspect of textile machine performance, especially in connection with the tendency of growing operating speeds.

The way how to obtain and to solve the non-linear equations of motion of the thread oscillations is lined out. In order to transform the partial differential equations with time-dependent boundaries into a system of ordinary differential equations an approach is introduced tracing back to Ritz and basing on the idea of separation of variables. Differing from the classical method, the shape functions depend on time, with the purpose of scaling the non-constant intervals between the boundary conditions to constant intervals.

Machines cannot be run with any desired working speed. There are several reasons for the limitation of the maximum speed, for example the material strength or fatigue limits of certain components or instable vibrations of elastic components. For textile machines, another very important stability limit is the defective mesh formation process because of thread vibrations or violation of geometric restraints. In order to optimize the working process of a machine, mechanical and mathematical models that can reproduce all important physical effects are required. In this contribution, an efficient method to describe and to simulate the vibrations of threads in textile machines and their influence on the machine components is introduced. This is part of a general theory within the method of elastic multibody systems treating couplings in machines with neglectable bending stiffness with their flow across system borders. Another industrial application are printing or paper machines with their oscillating paper streams.

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APPLIED MECHANICS SYMPOSIUM

In Honor Of Professor A. W. Leissa

SESSION W3P

Fracture Mechanical Assessment of Interface Cracks with Contact Zones in Piezoelectric Bimaterials under Thermoelectromechanical Loadings

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An interface crack $c \leq x_1 \leq b$, $x_3 = 0$ with a frictionless contact zone $(a,\ b)$ of an arbitrary length at the right crack tip between two semi-infinite piezoelectric spaces under the action of a remote electromechanical loading and a temperature flux is considered. Assuming that all fields are independent on the coordinate x_2 co-directed with the crack front, the stresses, the electrical and the temperature fluxes as well as the derivatives of the jumps of the displacements, the electrical potential and the temperature at the interface are presented via a set of analytic functions in the $(x_1,\ x_3)$-plane with a cut along the

crack. Due to this representation firstly an auxiliary problem concerning the determination of a condition permitting a transition from a perfect thermal contact to a separation has been solved for a piezoelectric bimaterial regarding an electrically permeable or an electrically insulated open part of the crack. In the first case the obtained condition defines the direction of the heat flux while in the second case it shows the heat flux direction and the admissible values of the electrical flux.

For the case of an electrically permeable interface crack with a thermoelectrically permeable and mechanically frictionless contact zone an inhomogeneous combined Dirichlet-Riemann boundary value problem as been formulated and solved exactly. Stress and electrical displacements intensity factors are found in a clear analytical form which is especially straight for a small contact zone length. A simple equation and a closed form analytical formula for the determination of the real contact zone length have been derived and compared with the associated equation of the classical (oscillating) interface crack model defining the interpenetration zone of the crack faces. It appears to be that an electrical flux has no influence upon the fracture mechanical parameters in this case, and moreover, the electrical intensity factory disappears for the real contact zone length.

For an electrically impermeable crack and for the same remaining conditions at the interface mentioned above the inhomogeneous combined Dirichlet-Riemann and Hilbert boundary value problems have been formulated. For the considered electrical conditions at the crack faces the joint solution of these problems only leads to the complete determination of the electromechanical fields in the near crack tip region. The closed form solutions of the mentioned problems are presented in the form of Cauchy integrals, and the stresses and the electrical displacement as well as the derivatives of the mechanical displacements and the electrical potential jumps at the interface are given in an analytical form which becomes especially simple for a small contact zone length. The fracture mechanical parameters are obtained as well for an arbitrary contact zone length.

The procedure of the determination of the real contact zone length for an electrically impermeable crack has specific features in comparison with the traditional way because for a wide range of electrical flux values a set of positions of the point a exists, for which a normal displacement jump in the crack region $(c,\ a)$ is nonnegative and the normal stress in the contact zone is nonpositive. The transcendental equations for the determination of the boundary points of the mentioned set are obtained and the real contact zone length has been found by use of an additional condition based upon theorem of the minimum of the potential energy.

For a numerical illustration of the obtained results a bimaterial Cadmium Selenium/Glass has been used, and the influence of the heat and the electrical fluxes upon the contact zone length and the associated stress intensity factors has been illustrated both for an electrically permeable and an electrically impermeable crack.

Isospectral Vibrating Systems

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Two systems are said to be isospectral if they have the same natural frequencies. The study of isospectral systems forms an integral part of the theory of inverse problems in vibration; families of isospectral systems appear as solutions of inverse problems in which there is insufficient data to yield a unique vibrating system.

This paper concerns the free, undamped, infinitesimal vibration of a discrete elastic system about an equilibrium configuration. The frequency equation for such a system has the form $(K - xM)y = 0$, and may be reduced using standard procedures to $(A - xI)z = 0$. The matrix A, which is symmetric, is called the mass-reduced stiffness matrix.The necessary and sufficient condition fortwo systems M, K and M', K' to be isospectral is that their A's satisfy the equation $A' = QAQ^*$, where $*$ denotes transpose. However the search for isospectral families demands that M,K and M',K' have the same form. For example K and K' are both tridiagonal or both pentadiagonal, with particular sign configurations, while M and M' are diagonal and positive. If Q is arbitrary, then this form will not be preserved. This means that we must search for those orthogonal transformations which preserve the required form. We study two procedures, one based on shifted QR factorisation, the other on Toda flow.

Mechanics of Lightning Destruction

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The main purpose of this paper is to present the mechanics of lightning destruction to masonry structures. To do this, the appropriate principles and physical data derived from the apparent diverse fields of geophysics, fracture mechanics, thermodynamics, and electrical field theory, are cast in a unified damage model.

Lightning is a transient, high-current discharge produced in thunderclouds. Cloud-to-ground lightning (streaked or forked lightning) has a plasma channel a few centimeters thick, is many kilometers long, and has peak temperatures reaching 30 000 K. Typically, the total discharge between a cloud and ground (the flash) lasts about 0.5 s, during which the discharged electric potential between the cloud and ground is of the order of 10^8 V. During this discharge, the average ground-directed (leader) current is about 100 A.

Lightning is both beneficial and destructive. Lightning is beneficial because it produces the ozone layer that protects earth's inhabitants from the destructive ultraviolet rays of the sun; it produces about 40% to 50% of the earth's nitrogen needed for plant growth; and it ignites forest fires, after which there is new and healthier growth. Lightning is destructive because it causes about 500 human injuries and 100 deaths in the United States each year; it disrupts power and communication systems; and it leads to failures of unprotected structures. This latter phenomena can occur in masonry structures with inadequate lightning protection. Just as rocks can explode when thrown into a hot fire and trees can explode when struck by lightning, concrete building blocks, bricks, and portland cement concrete can crack suddenly when subjected to the thermal shock of a lightning strike. What masonry solids have in common is that water is entrained in their substructural cavities. In portland cement concrete, for instance, capillar cavities containing water average about 500 nm in diameter; and the water content of lightweight concrete is about 10% by volume. With sudden joule heating caused by a lightning strike, the entrained water pressure in such solids increases at approximately constant volume until a critical pressure is reached, a pressure that causes the multiple cavities to suddenly and tramatically open, which initiates extensive crack propagation and structural failure.

This analysis herein is divided into three major topics: Fracture Mechanics, Thermodynamics and Heat Transfer, Lightning-Generated Heat Flux. The recent physical data needed for accurate analysis includes: lightning current and duration, a summary of thermal properties of concrete in various forms (slabs, blocks, etc), and soil resistivity data including its sensitivity to the frequency of current excitation. The use of these data with the analysis is illustrated with two case studies involving lightning destruction of building foundation walls.

Keywords: fracture, lightning, masonry structures, thermal shock

Characterization of Helicoidal Structural Properties via an Energy Approach

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The paper investigates the characterization of helicoidal structures in viscous, low speed fluid as a first attempt to simulate and study the biomechanical engineering properties of DNA fluid-structure interaction. Employing a helicoidal shell model with a nonlinear twist, the energy stored in the model subjected to viscous, low speed organic fluid loading is examined. A variational energy principle is adopted to determine the structural engineering properties of the model subject to external loading. The dynamical responses of energy distribution and bending will be characterized with respect to the stiffness and twist of the structure. Discussion on the possibility of matching DNA sequential characteristics with respect to the nonlinear dynamical responses will be presented.

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Free Vibration Analysis of Corner Supported Rectangular Plates with Symmetrically Distributed Edge Beams

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Using the superposition method an analytical type solution is obtained for the free vibration frequencies and mode shapes of rectangular plates given pinned support at the corners and with the edges stiffened by means of beams. The edge-beams are symmetrically distributed about the plate central axes.

In view of the symmetry, only one quarter of the plate is analyzed with the modes falling into three families. These are modes fully symmetric, or fully anti-symmetric, about the main plate central axes, or symmetric about one axis and anti-symmetric about the other.

In the early part of the paper, following the work of Timoshenko for static plate problems, a complete set of

dimensionless plate-beam interaction parameters is developed. These parameters permit taking into account the effects of edge-beam lateral and torsional stiffness. They also permit incorporating into the analysis the effects of beam lateral and rotary inertia. Any of these effects can be deleted, if desired, in order to determine its significance in comparison with the others.

Solutions for the forced vibration problems (building blocks) utilized in each of the three mode family studies are described in detail. Steps required in generating the eigenvalue matrix are explained. Convergence tests performed in preliminary calculations are presented.

Fortunately, many limiting case eigenvalues which must be approached as beam properties approach limiting values of zero and infinity are known. These limiting values are utilized to verify the analytical procedure.

Computed eigenvalues and mode shapes are presented for a number of plate-beam systems of realistic geometries. It is anticipated that these results will prove valuable to other researchers or designers who may wish to compare their findings against those reported here.

Keywords: Rectangular, Plate, Edge-beam, Vibration.

APPLIED MECHANICS SYMPOSIUM

In Honor Of Professor A. W. Leissa

SESSION W4P

Vibration of a Cluster of Beams in Viscous Fluid

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A cluster of tubular beams immersed in a fluid is commonly termed tube bundles. Lots of industrial structures like heat exchangers, nuclear reactor cores and pools for the storage of spent fuel contain tube bundles. The analysis of the dynamic behavior of such tube bundles needs the study of the interaction between fluid and tubes.

A variety of mathematical models have been and are being developed to predict the dynamic behavior of the tube bundle for its global movement, even for the movement with strong variations between two adjacent tubes. Nevertheless, the fluid in the bundle is always simplified into a perfect one. Namely, the viscosity is neglected in all the models.

However, in some important applications, the viscosity of fluid has to be taken into account. An example is the Fast Neutron Breeder Reactor, in whose cores the quite viscous liquid sodium is chosen as coolant and submerges fuel rods.

In the present paper, a new model is presented with respect to such a tube bundle, in which fluid is considered as viscous and incompressible, and tubes as the Euler-Bernoulli beam. Modeling is based on two-scale expansion and homogenization technique. The final governing equations consist of three equations. Three unknown functions are the pressure of fluid and two components of bending deflection of tubular beams. It is found that these equations are similar to those obtained by the author in 1998 for the non-viscous fluid, but one more viscous term is added in each equation. In other words, the governing equations for viscous fluid can be degenerated into those for non-viscous fluid if the coefficient of viscosity vanishes. It is further shown that a velocity potential can be introduced as a fundamental unknown instead of pressure in the fluid region. This introduction ensures the symmetry in the corresponding finite element formulae. It is interest that the flow of the viscous fluid is limited in a plane perpendicular to the axis of beams. This phenomenon is quite simpler than in the non-viscous case, in which an axial flow appears in the bundle. On the contrary with general knowledge, viscosity does not increase the amount of the fluid added on tubes. The added fluid area fraction is an important parameter in applications. Its expression is analytically formulated based on the solution of a local problem.

Damping in Brittle Matrix Composite Laminates with Matrix Cracks

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The paper elucidates the process of cracking in angle-ply CMC and predicts its effect on the loss factor. Two cracking scenarios are considered, namely through-the-thickness cracks and cracks limited to single layers and terminating at the layer interface. In angle-ply CMC, the mode of cracking is determined by the laminate construction. In balanced symmetric $[-\theta/\theta]_k$ or $[-\theta_m/0_n/\theta_m]_k$ laminates cracks may originate along one of the material symmetry planes. Tunneling cracks are parallel to the fibers, while the bridging cracks are perpendicular to the fibers.

If the cracks propagate in the self-similar mode, i.e. without changing their initial orientation, the solution is available based on the analysis of Sih, Paris and Irwin. The issue of the direction of the crack propagation, i.e. the

analysis discarding the assumption of self-similar cracks, may be treated based on the direction of the maximum stress in front of the crack in an anisotropic material. The present investigation is limited to the case where bridging or tunneling cracks develop in a self-similar manner along the material symmetry planes.

The damage in $[-\theta/\theta]_k$ laminates occurs in the form of tunneling or bridging cracks simultaneously forming in all layers. When these cracks reach the layer interface they can either terminate or continue the propagation forming through-the-thickness cracks.

The mode of damage, i.e. bridging or tunneling cracks, is analyzed for $[-\theta/\theta]_k$ laminates. Subsequently, the approach to the evaluation of the increase in damping is suggested for the case of bridging matrix cracking, while the change in damping in the case of tunneling cracks is shown to be small. In the case of $[-\theta m/0_n/\theta_m]_k$ laminates, both the stiffness and damping are analyzed for two possible scenarios. The first possibility is tunneling cracks in the inclined layers and bridging cracks in the longitudinal layer. The second possibility is through the thickness bridging cracks propagating from the longitudinal layers into the inclined layers.

It was found that in a single lamina the lamination angle of 45° represents a boundary between damage in the form of bridging cracks (lower values of the angle) and tunneling cracks (higher values). The loss factor in laminates with bridging cracks is much higher than the factor obtained for the intact lamina, mainly as a result of energy dissipation along the damaged fiber/matrix interface sections adjacent to the cracks. The density of matrix cracks has a very significant effect on damping. For example, in a typical SiC/CAS material the loss factor in the case corresponding to the saturation of bridging cracks (crack spacing = 0.125mm) is about twice the factor for the case of the crack spacing equal to 0.250mm.

Keywords: CMC, damping, matrix cracks, interfacial friction.

The Use of Asymptotic Modeling in Vibration and Stability Analysis of Structures

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The use of springs with very large stiffness to model constraints in vibratory systems has been a popular approach to overcome the limitations on the choice of permissible functions in the Rayleigh-Ritz method. The maximum possible error resulting from this asymptotic modelling can be determined by using positive and negative stiffness values, or in general terms using positive and negative penalty functions. This paper illustrates how this method could be used to determine the critical loads of structures.

Vibrations of Oblique Shear-Deformable Plates

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Free and forced vibrations of moderately thick, transversely isotropic plates, when loaded by lateral forces, are analyzed. First-order shear-deformation theories of the Reissner-Mindlin-type are considered, see e.g. [1]. A numerical routine based on the best suitable direct BEM of frequency domain analysis of plates under rather general boundary conditions is developed. A step forward in efficiency is obtained if the Green's function of the rectangular, simply supported base plate is applied. It has been shown in [2] that the time reduced equations of hard hinged polygonal plates reduce to those of a background Kirchhoff plate, which has effective (frequency dependent) stiffness and mass, and is loaded by effective lateral and in-plane forces and by imposed fictitious "thermal-type" curvatures. This analogy holds even for the shear forces and bending moments if inertia is negligible. Furthermore, it can be shown that in the static case with no in-plane prestress taken into account these stress resultants for certain groups of Reissner-type shear-deformable plates are identical with those resulting from the Kirchhoff theory of the background.

Since oblique plates are structural elements of micro electronics, mechanical and civil engineering, only differing in size from the millimeter to the tens of meter range of dimensions, there is also a variety of boundary conditions to be considered. Since the above mentioned analogy is restricted to hard hinged supports of straight edges, it becomes necessary to apply, e.g., the direct boundary element method of analysis to the plate of general planform and boundary conditions. Efficiently, the Green's function of the hard-hinged rectangular shear deformable plate, with rotatory inertia neglected, enters the general formulation. The main effort is thus to study the properties and effective representations of these Green's functions and, quite important, the singularities, which must be subjected to proper integration. Likewise to results for the Kirchhoff plates, the strong singularity of the infinite domain is identified for the rectangular plate and subjected to indirect integration. The resulting direct BEM proves to be efficient, robust and in connection with proper pre- and post processors becomes an effective tool of engineering

analyses just within the limits given by the first two of the three spectral branches.

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Nonlinear Flexural Waves in Thin Layers

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Nonlinear flexural waves in thin plates or layers have been analyzed in this paper. The equation of motion of the plate is derived assuming that the motion is antisymmetric about the mid-plane of the plate and that the plate is thin. The plate is considered to be elastic. The von Karman nonlinear strains and Landau elastic constants have been used to model material and geometric nonlinearity. An asymptotic analysis of wave solution is presented using the method of multiple scales. Numerical results show harmonic generation, parametric amplification, and waveform distortion.

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Buckling of Simply Supported Rectangular Plates under Uniform Thermal and Mechanical Loading

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Buckling of rectangular plates is reasonably well understood for most important types of mechanical loadings and edge support conditions. However, the seemingly elementary problem of thermal buckling of simply supported rectangular plates under uniform heating (or cooling) along with mechanical loading has not been addressed thoroughly. In-plane restraint in at least one direction is necessary for thermal buckling to occur under uniform heating. On the other hand, *lack of in-plane restraint* in a particular direction is required for mechanical loading to develop in that direction. Thus, boundary conditions are an important consideration in many thermal buckling problems. The specific problem treated is buckling under combined uniform temperature change (heating and cooling) and uniaxial mechanical loading (tensile and compressive) with uniaxial in-plane restraint perpendicular to the direction of the mechanical load to develop in-plane thermal force.

A plate under biaxial mechanical loading can buckle when the load in one direction is more than the uniaxial buckling load in that direction if tensile load exists in the transverse direction. The key factor is the plate boundary conditions on all four edges including the in-plane restraint provided in addition to the obvious influence of the edge rotational restraint for a clamped-edge plate or lack thereof for a simply supported plate. The plate buckles into different buckling modes at different loads depending on the ratio of the thermal load to the mechanical load, the plate aspect ratio (ratio of the length to width of the plate), and on the Poisson's ratio. Numerical results are presented for a square plate made of isotropic material with a Poisson's ratio of zero for a wide range of ratios of thermal to mechanical loading. Similar numerical results would be obtained for other plate aspect ratios. For other Poisson's ratios, the shifts in buckling mode shapes would occur at different loads than for those for zero Poisson's ratio. For combined thermal and mechanical loading, an axial tensile load enables the plate to withstand higher temperatures without buckling than if no mechanical loading were present. Also, cooling the plate enables a higher uniaxial mechanical load to be sustained without buckling than if the plate temperature were not changed.

Keywords: Buckling (thermal), plates, thermal loading,

Ray Method to Investigate Transient Waves Propagating in Thin Bodies Under Impact Excitations

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The ray method for solving boundary dynamic problems on the propagation of surfaces of strong discontinuities (wave surface-strips) in thin linearly elastic bod-

ies is developed. The equations of 3D theory of elasticity are used, which are written in the ray coordinates in the vicinity of the wave surfaces by means of the theory of discontinuities and then are integrated over the coordinate perpendicular to the body median surface. It is assumed that the wave strip remains perpendicular to the body median surface all the time during its propagation; the discontinuity in the normal stress in the direction of the normal to the middle surface can be ignored as compared with those in stresses in the body middle surface and in the layers parallel to it. Such assumptions lead to the generation of two wave surfaces propagating in the thin body with the velocities of longitudinal and transverse waves of elastic bodies obeying Kirchhoff-Love hypothesis. Thus, on the longitudinal wave, the bulk deformations experience a discontinuity not only at the sacrifice of shortening-elongation of the element locating in the middle surface aligned perpendicular to the wave strip, but also at the expense of thickening-thinning of this element in the direction perpendicular to the median surface; on the transverse wave, the tangent components of the velocities directed both along the middle surface and transversely to it have a discontinuity. During the solution of problems, values to be found are represented in terms of the ray series, wherein coefficients are the discontinuities in partial time-derivatives of the desired functions, and the arc length measured along the ray is the independent variable. The ray series coefficients are determined from the recurrent equations within the accuracy of arbitrary functions to be found from the boundary conditions.

Nonlinear Interactions in Asymmetric Vibrations of a Circular Plate

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In order to investigate nonlinear asymmetric vibrations of a clamped circular plate on an elastic foundation, we consider a primary resonance of the plate with an internal resonance, in which the natural frequencies of two asymmetric modes are commensurable. The response is expressed as an expansion in terms of the linear, free oscillation modes, and its amplitude is considered to be small but finite. The method of multiple scales is used to reduce the nonlinear governing equations to a system of autonomous ordinary differential equations for amplitude and phase variables. As a numerical example we consider the case of internal resonance (a commensurable relationship between natural frequencies), $\omega_{32} \approx 3\omega_{11}$, where the first subscript refers to the number of nodal diameters and the second subscript the number of nodal circles including boundary. When the frequency of excitation is near ω_{11}, there exist at most three stable steady-state responses. Two of them are superpositions of traveling wave components and one is a superposition of standing wave components. The result shows the interaction between modes corresponding to ω_{11} and ω_{23} by showing amplitudes of the mode not directly excited. When the frequency of excitation is near ω_{23}, there exist at most three stable steady-state responses. The response is identical with the response of primary resonance in the absence of internal resonance. We could not find any other stable steady-state responses.

Keywords: Nonlinear Asymmetric Vibrations, Circular Plate on Elastic Foundation, Modal Interaction, Primary Resonanc

Vibration Analysis with a Higher Order Shear and Normal Deformable Plate Theory

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A plate theory is usually derived by expanding the kinetic and the kinematic fields as a power series in terms of the thickness coordinate z, and the plate theory is called higher-order if terms involving z^K with $K > 2$ are retained in these expansions. A challenging task is to find the least value of K so that the derived plate theory is manageable and results computed with it agree reasonably well with the analytical solution of the corresponding three-dimensional elasticity equations. The optimal value of K depends upon the aspect ratio of the plate, the boundary conditions prescribed at its edges, the applied loads, and which aspects of the three-dimensional deformations should be more accurately modeled.

By using Legendre polynomials in z as the basis functions and the Hellinger-Reissner variational principle, we derive a K-th order plate theory that is easily amenable to analysis. It accounts for both transverse shear and transverse normal deformations of the plate, and boundary conditions of normal and tangential tractions prescribed on its top and bottom surfaces are exactly satisfied. The plate theory is used to study plane travelling waves in a transversely isotropic plate with the axis of transverse

isotropy coincident with the normal to the midsurface of the plate. This allows to order the displacement components in terms of their lengths of decay, the underlying idea being to retain only the components which decay the least. Moreover frequencies of a simply supported homogeneous orthotropic rectangular plate found with the 5th order theory match exactly with the analytical solution. Also, through-the-thickness variations of different stress components computed from the plate theory agree well with those obtained from the solution of the three-dimensional elasticity equations. A comparison with a different, but simplest, identification procedure, where only the kinematic reduction map is needed, is also drawn.

Buckling of Suddenly Loaded Structures

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Dynamic stability of structures has received considerable attention in the last half of the 20th century. Several studies have been conducted and reported on structural systems, which are dynamically loaded. In these studies, attempts have been made to define critical conditions and to develop methodologies for estimating critical loads. One particular class of dynamic loads consists of constant magnitude loads applied suddenly over a finite time duration, including the extreme cases of ideal impulse and loads of infinite duration. Methodologies developed for structural configurations that exhibit sap-through buckling, under static loading will be presented. These methodologies are classified in the following three groups: (1) Equations of motion approach (see Budiansky And Roth [1]). The equations of motion are numerically solved for various load parameters, starting with a small value, to obtain the system response. The value at which there exists a large change in response is called critical. (2) Total energy-phase plane approach (see Hsu [2]). Critical conditions are related to characteristics of the system's phase plane and the emphasis is on establishing sufficient conditions for stability (lower bounds) and sufficient conditions for instability (upper bounds). (3) Total potential energy approach (see Hoff [3] and Simitses [4]). Critical conditions are related to characteristics of the system's total potential. All three approaches will be demonstrated through use of simple mechanical models. Demonstrations examples as related to actual structural configurations will include: shallow metallic arches and spherical caps, sandwich columns with laminated facings, metallic thin cylindrical shells under compression and laminated cylindrical shells under compression and pressure.

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APPLIED MECHANICS SYMPOSIUM

In Honor Of Professor A. W. Leissa

SESSION R3N

Perspectives on Multiscale Modeling, Simulation and Visualization

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The multimedia presentation is divided into three parts. In the first part, a broad overview is given of the activities related to the integration of information about material structure and processes from the various time and length scales: atomistic, molecular, nanostructures, micro, meso, and macro. Both the hierarchical approach with seamless interfaces between the different physical levels of description, and methods that can host more than one physical level of description are reviewed. In the first approach quantum mechanics, molecular dynamics, nanomechanics, micro, meso, and macro mechanics models are used. An example of the second approach is the Lattice Boltzmann equation, which incorporates atomistic, kinetic, and continuum fluid description within the same mathematical framework.

In the second part, diverse applications of multiscale modeling and simulation are outlined, including support

of improved material development, study of fracture and friction, defects, dislocations and material deformation, thin film growth, and solid-solid phase transformation. Novel mathematical tools for multiscale representations are described, along with the verification and validation approaches of numerical simulations.

The third part describes the potential of using multiscale modeling and simulation in conjunction with hierarchical sensitivity analysis and interrogative visualization in future design environments with computational steering and inverse steering facilities.

Stress Boundary Conditions for Plate Bending

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Plate and shell theories are truncated outer asymptotic expansions of the exact solution for 3-D elastostatic problems of loaded plate and shell structures. The determination of the appropriate boundary conditions for these approximate 2-D theories consistent with their order of accuracy is an important challenge to plate and shell theorists. Through the mid eighties, only asymptotic analyses such as that of Friedrichs and Dressler and the Gol'denveiser school have successfully deduced boundary conditions for plate theories from 3-D elasticity theory. These asymptotic methods all have a serious limitation. Appropriate stress boundary conditions can be derived without an explicit consideration of the inner asymptotic solution(s) (or the residual boundary layer solution(s)) only for a leading term approximation of the exact 3-D solution. The corresponding approximate inner or boundary layer solution(s) would have to be obtained before the boundary conditions for the next order outer solution (moderately thick plate/shell theory) can be determined. The process repeats itself for higher order plate theories. For displacement and some mixed edge data, the outer and residual solution of the same order must be determined simultaneously and only after the lower order outer and residual solutions have been obtained.

In this paper, edge conditions for plate bending will be derived from 3-D elasticity theory for general edge geometry and loading by a completely different asymptotic technique. For plate theories of all orders of accuracy, it takes into account the effect of the inner (or the boundary layer residual) solution by solving for each edge of the plate two canonical problems once and for all, and they can be done by an accurate numerical method if necessary. For a leading term (thin plate) theory, the stress boundary conditions deduced are shown to be independent of the inner solution and reducible to the well - known Kirchhoff contracted boundary conditions.

The Effect of Crack Plane Cohesive Zones on the Vibration of Cracked Beams

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It is well known that the presence of cracks influences the vibrational characteristics of structures, primarily by reducing the structure's stiffness in particular modes. Natural frequency versus crack geometry relationships are of interest, for example, in the assessment of the performance integrity of known cracked structures, non-destructive evaluation of the extent of cracking, and prediction of the resonant frequency in high-cycle fatigue. The reduction in natural frequencies caused by edge-cracks in linear elastic beams has been studied extensively either by deriving the exact frequency determinant, or through finite elemnet analyses for the more complicated problems with multiple cracks and non-uniform beams. The (non-linear) repeated opening and closing of the crack faces in flexural modes has also been studied and found to create higher harmonics, as well as lessen the reduction in frequency of flexural modes compared to an analysis which ignores the closure portions of the vibration cycle.

The present paper concerns a first step in understanding the effect of material, as opposed to contact, nonlinearities in the crack plane on the first few modes of vibration of a cracked beam. To keep the analysis amenable to closed form expressions, a single crack in a uniform beam is studied, the effect of crack opening and closure is not considered, and the crack plane itself is treated using the classic line-spring model in the vibration analysis. The first few modes of free vibration of cracked beams are investigated for various models of crack plane cohesive zones, including Dugdale-Barenblatt, and more general forms, as have been used in conjunction with various ductile process zone models in the literature. The rotational and shear stiffnesses used in the line-spring model are found from boundary element analyses of cracked beams with plasticity in the crack plane. The possiblilities of using such results for experimentally determining cohesive zone parameters are discussed.

Layerwise Optimization for the Maximum Frequency of Laminated Composite Plates

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A layerwise optimization approach (LOA) is proposed for designing the vibration characteristics of laminated composite plates. The idea is based on the concept of dynamic programming (DP) where an optimization process of the whole complex system is divided into multiple sequential steps of one-dimensional optimization. This is interpreted in the present study as optimizing the whole laminated plate with respect to a fiber orientation angle within each layer sequentially in the virtual plate. The advantage of LOA is obvious in computation time because it can reduce a multi-dimensional solution search problem into a series of one-dimensional search for the global optimal or nearly optimal solutions. For instance, an optimization of eight-layered plate $[\theta_1/\theta_2/\theta_3/\theta_4/\theta_5/\theta_6/\theta_7/\theta_8]$ has eight independent design variables which accompany solution search in the eight-dimensional space, and this can be significantly reduced to only eight of one-dimensional search. In numerical examples, the fundamental frequencies of laminated rectangular plates with various boundary conditions are maximized and listed in tables. These optimal solutions are compared to those obtained by the complex optimization method and other authors. A physical interpretation on the effectiveness of LOA is made in connection with the plate mechanics.

Keywords: Vibration, Plate, Laminated composite, Optimization, Natural frequency

Three-Dimensional Contact Analysis of Layered Elastic / Plastic Solids with Rough Surfaces in Dry and Wet Conditions and its Applications

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The contact mechanics of layered rough surfaces needs to be studied to optimize surface roughness and mechanical properties of contacting surfaces for tribological applications[1-4]. Small quantity of liquid present at the interface results in an intrinsic attractive force, because of meniscus contribution, which may result into high static friction (stiction) under lightly loaded conditions. Since 1995, a lot of progress has been made in the development of numerical contact models, which analyze the contact behavior of layered rough surfaces with no assumption concerning the roughness distribution. A 3-D model using boundary element method, based on a variational principle, is introduced here to analyze the layered rough surface contact involving a large number of contact points. Meniscus contribution of a liquid film present at the interface is calculated. This model predicts contact pressure profile at the interface and contact statistics, namely fractional contact area, the maximum value of contact pressure, von Mises and principal tensile stresses, and relative meniscus force. The results allow the optimization of surface roughness, mechanical properties, and liquid film thickness to reduce friction, stiction, and wear. Typical examples of layered rough surfaces contact simulated by this model are presented. The examples contain data for various surface roughness, elastic and elastic-plastic material properties, normal and tangential loading conditions, and dry and wet interfaces. Applications of this model to the magnetic storage devices and MicroElectroMechanical Systems (MEMS) are presented.

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APPLIED MECHANICS SYMPOSIUM

In Honor Of Professor A. W. Leissa

SESSION R4N

Multiwave Nonlinear Resonance Couplings - Part 2: Two-dimensional Example

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This work is concerned with nonlinear couplings in an essentially two-dimensional structure such as a thin

plate. This is treated as a relatively simple example for general multi-degrees-of-freedom problems in more than one space dimension. The chosen model is that of Kirchhoff-Love. Evolution equations describing the nonlinear couplings between quasi-harmonic modes are first deduced. Three types of elemental resonant sets consisting of triplets (triads) of quasi-harmonic modes are thus defined. Any triplet in the plate consists of a pair of bending modes and one longitudial or shear mode, whose natural frequencies and wave vectors satisfy phase-matching conditions. The role of the unstable high-frequency mode can be played by a wave of any type so that nonlinear couplings between triplets of all types are feasible. The nonlinearly coupled triads form a large-scale resonant chain, such that the nonliear oscillations in the plate arise within a finite spectral band, the width of which is determined by the spectral parameters of all interacting modes. Wave energy is predominantly transferred downwards inside this spectral domain.

Rope Torque and Wire Rope Dynamics

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Wire ropes are typically modeled as taut strings to study dynamical behavior. But a look at the static response of wire rope [1] suggests that rope torque should be included in any dynamic model. When a wire rope is stretched from its unloaded position both an axial force and axial rope torque result [2]. Rope torque causes transverse vibrations in one direction to be dynamically coupled to transverse vibrations in the orthogonal direction. The coupled differential equations have the unusual nature of being third order in the spatial variable representing the axis of the wire rope. The system is solved to determine eigenvalues and eigenfunctions. The model is flawed. The order of the equations suggests that three (3) boundary conditions are appropriate at each end of the rope, but how should three conditions be apportioned between two orthogonal displacements? To resolve this difficulty a new approach is considered that replaces the transverse coordinates with cylindrical coordinates. In such a model there is no reason to expect any boundary-condition symmetry as there is for the case of coupled transverse displacements. Using a variational calculus approach, equations and natural boundary conditions are developed. Suitable boundary conditions result, but the coupled differential equations are nonlinear. Finally, a simpler approach to solve the boundary condition dilemma is proposed. Rather than ignore the small bending stiffness [3] of a wire rope, it can be included in the model. This leads to fourth-order partial differential equations coupled by the rope torque. Now the four boundary conditions at each end can be apportioned symmetrically between the two transverse displacement variables.

Keywords: eigenvalue; rope torque; vibration; wire rope

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Moderately Large Flexural Vibrations of Composite Plates with Thick Layers

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Moderately large amplitude vibrations of polygonally shaped composite plates with thick layers are analyzed. Geometrical nonlinear effects arising from horizontally immovable hard hinged supports are taken into account. The effect of initial imperfections is included. Three homogeneous and isotropic layers with a common Poisson's ratio are perfectly bonded and their arbitrary thickness and material properties are symmetrically disposed about the middle plane. The Mindlin-Reissner kinematic assumptions are implemented layerwise, and as such model both the global and local response of composite plates. The continuity of the transverse shear stress across the interfaces is prescribed according to Hooke's law. The Berger's approximationof nonlinear strain-displacement relations are applied. By means of proper definition of overall cross-sectional rotations, a correspondence of this complex problem to the simpler case of a homogenized shear-deformable plate on horizontally restrained supports with effective stiffness and proper boundary conditions is found. The theory is applied to statically and dynamically loaded rectangular simply supported composite plates with various dimensions and material properties. Thereby, for the numerical solution the geometrical nonlinear terms of the differential equations of motion are treated as lateral forces acting on the linear elastic and homogenized shear-deformable plate with initial stiffness. The influence of layerwise cross-sectional rotations on the

nonlinear response are discussed and results are compared with an equivalent-single-layer formulation of the problem considered. The nonlinear steady-state response of composite plates subjected to a time-harmonic lateral excitation is investigated and the phenomena of nonlinear resonance are studied.

Fundamental Frequencies of Circular Plates with Internal Elastic Ring Support

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The vibration of circular plates is basic in structural design. Literature on the vibration of plates strengthened by internal ring supports mostly considered the symmetric modes. However, the asymmetric modes sometimes yield the fundamental frequency. On the other hand, the supports in reality may not be totally rigid. The present paper studies the effects of the stiffness and location of the support on a vibrating circular plate. In particular we are interested in the optimum location to maximize the fundamental frequency, and the minimum stiffness requirement to attain such maximum frequency. The minimum stiffness requirement is important in design because a savings of stiffening material can be realized without any loss of performance.

The thin elastic plate is partitioned into two regions by the elastic ring support. The governing equations are solved for each region and matched on their common boundary. Four basic edge conditions are considered: clamped, simply supported, free, and sliding. The characteristic equations are found exactly and the eigen- frequencies are obtained accurately by bisection. The results show complicated mode changes when the stiffness and the locations of the support are varied. Optimum locations are given in tables.

On the Finite Displacement Analysis of Plates

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In this paper, a numerical method is presented for the linear and geometrically nonlinear static analysis of thin plates. The method begins with the application of elasticity equations pertaining to strains, stresses, displacement components, strain energy and work due to externally applied loads. The nonlinearity is associated with the membrane strains only and the linear form for the transverse shear strains is used in the formulation. The plate geometry is defined by a quadrangular boundary with four curved edges and the natural coordinates in conjunction with the Cartesian coordinates are used to map the geometry. The geometric symmetry is exploited to analyse complex shaped plates with or without an opening. The Ritz-type method is used to derive the matrix equation of equilibrium, where the displacement fields are expressed by simple algebraic polynomials. The coefficients of the displacement fields are then manipulated to satisfy the kinematic boundary conditions. Coefficients, which do not participate in the boundary conditions, remain the unknown quantities. By considering the variation of the energy functional, the matrix equation of equilibrium is obtained. To validate the numerical results from the present method for displacements and stresses, rectangular plates having all sides fully clamped and all sides simply supported are analysed. The results are compared with the data published by Levy (1942), who solved the nonlinear plate bending problem using the *Th.. von Ka'rma'n's* equations. Results are also compared successfully with those obtained from commercially available general purpose finite element computer codes. Rectangular plate with a circular opening, circular plate with a rectangular opening and other combination of the internal and external shapes are analysed in this study and the corresponding results are discussed.

APPLIED MECHANICS SYMPOSIUM

In Honor Of Professor A. W. Leissa

SESSION F2H

An Experimental Method for Evaluating SIF Distributions During Crack Turning in Non-Brittle Materials

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Since two well crafted papers by Cotterell (1)(2) describing crack types and paths in the mid 1960's, most of the literature concerning mixed mode effects on crack growth was directed towards the establishment of fracture criteria. Then in 1979, Cotterell and Rice (3) provided an analysis which described the role of the shear

mode in crack kinking, or turning. More recently, Rubenstein, guided by experiments, postulated an analysis (4) for the turning of cracks in non-brittle materials. All of the analysis cited above was directed towards two dimensional problems, although Cotterell, in his earlier work, conjectured that his descriptions of crack growth might be extended to three dimensional problems.

Recently, the writer and his associate, while applying the frozen stress photoelastic method together with algorithms from linear elastic fracture mechanics, obtained some interesting results which appear to indicate the role of the shear mode in the turning of three dimensional cracks. The results suggest that when an initial surface crack of the Class II type as defined by Cotterell is loaded in a mixed mode state, the process by means of which it becomes a Class I crack involves the elimination of the shear mode all along the crack border by turning of the crack tip and, or, the development of river markings on the crack surface. Rubenstein's idea of the lack of sharp kinking also appears to be confirmed.

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Keywords: Crack Growth, Stress Intensity Factors, Class I and Class II Cracks, Mixed Mode Effects.

On the Dynamics of Piezoelectric Cylindrical Shells

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In the present paper we derive the equations of motion for the vibration of thin-walled cylindrical shells made of piezoceramic material (PZT) generalizing Flgge's shell theory for this type of materials. The shells are polarized in the radial direction and the electrodes are in the form of identical sectors. Such shells are used e.g. as stators in some piezoelectric ultrasonic travelling wave motors and it is therefore important to study their free and forced vibrations.

The momentum balance used in Flügge's shell theory is of course unchanged. The constitutive relations used in the theory of elastic shells are substituted by those of a linear piezo-electric material, so that additional field variables are introduced. These are subject to Maxwell's laws, which in particular have to be fulfilled by the electric field inside the shell. For a thin shell radially polarized only dielectric displacements in the radial direction are taken into account. Due to the absence of free electric charges in dielectric media such as PZT, the divergence of the dielectric displacement vanishes. This condition leads to an ordinary differential equation of the Euler type in the radial electric field, which can be solved in closed form. Together with Flgge's thin shell assumptions and with the piezo-ceramic constitutive equations this results in the equations of motion of a thin piezoceramic shell.

This system of partial differential equations is then solved for the case of electric boundary conditions in the form of a given applied voltage at the electrodes, using Fourier techniques. The electrodynamical impedances can be computed and the resonance frequencies obtained therefrom are compared to experimental data. This is an economical alternative to the use of 3d FEM calculations for shells and gives a useful engineering tool for a number of problems involving piezoelectric actuators.

Three-dimensional Exact Solution for the Vibration of Functionally Graded Rectangular Plates

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A three-dimensional exact solution is presented for the vibration of simply supported functionally graded rectangular plates. Suitable displacement functions that identically satisfy boundary conditions are used to reduce equations governing steady state vibrations of a plate to a set of coupled ordinary differential equations, which are then solved by employing the power series method. The exact solution is valid for thick and thin plates, and for arbitrary variation of material properties in the thickness di-

rection. Results are presented for two-constituent metal-ceramic functionally graded rectangular plates that have a power-law through-the-thickness variation of the volume fractions of the constituents. The effective material properties at a point are estimated by either the Mori-Tanaka or the self-consistent schemes. Exact natural frequencies, displacements and stresses are used to assess the accuracy of the classical plate theory, the first-order shear deformation theory and a third-order shear deformation theory for functionally graded plates. Parametric studies are performed for varying ceramic volume fractions, volume fraction profiles and length-to-thickness ratios. Results are also computed for a functionally graded plate that has a varying microstructure in the thickness direction using a combination of the Mori-Tanaka and the self-consistent methods.

Experimental Study of Sound Transmission Loss in Electrorheological Liquid Under Normal and Shear Stress

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Changing the mass or stiffness of the barrier can control Sound Transmission Loss (STL) through a barrier.

The first method (changing mass) is commonly used in passive noise control. The second one can be useful in active noise control

Electrorheological (ER) liquids change their mechanical properties, such us modulus of elasticity and apparent viscosity, under applied voltage. It is observed that both normal and shear stress of ER liquid increase under applied increasing strength of electrical field. At the College of Engineering Acoustic Laboratory the STL was investigated in ER liquids under applied DC Voltage. Two electrodes that allowed sound propagation through a barrier under normal and shear stress conditions were designed. In both conditions STL decreased when DC field strength was increased.

Anisotropic Elasticity Solution of Single Layered Composite Plate Under Self-equilibrating Cubically Distributed Shear Loading

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Laminated composite plates as components of a structure can be under states of severe non-uniform shear stresses. For example, laminated plates used in construction of an airplane wing can be under shear stresses during certain maneuvers of the flight. These shear stresses can be responsible for failure of the plate and consequently the structure as a whole. It is the intent of this work to study the distribution of shear stresses throughout rectangular laminated plates subjected to non-uniform shear stresses. Anisotropic plane elasticity solution of the stresses throughout a thin, rectangular, laminated composite plate subjected to a self-equilibrating cubically distributed shear stress at the two ends of the plate is obtained. An approximate solution to the problem is obtained using the Ritz method by assuming the displacement in terms of polynomial series. The plate is assumed to be a symmetric laminate and hygrothermal effects are not considered. The characteristic decay length under the shear loading is estimated for different cases of isotropic, orthotropic, and anisotropic plate.

Keywords: Composite Plates, In-plane loading, Shear loading, Ritz method

APPLIED MECHANICS SYMPOSIUM

In Honor Of Professor A. W. Leissa

SESSION F3H

Design Issues Concerning Hybrid Piezoelectric-Magnetostrictive Transducers

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There is currently a need in information technology applications for transducer materials capable of providing increasingly large displacements and forces over greater frequency bandwidths. Such requirements are likely to grow tighter over time, thus motivating the development of increasingly powerful materials and modeling techniques. This paper focuses on the development of nonlinear modeling techniques to enable the implementation of a class of transducers built on the theme of hybrid ferroelectric-ferromagnetic combinations. Of particular interest in this investigation is the study of frequency bandwidth enhancements obtainable from double-resonant designs in which a magnetostrictive element is used to control the lower resonance and a piezoelectric element is used to control the higher resonance. Because of the intrinsic ninety-degree phase difference between magnetostrictive and piezoelectric velocities, the combined frequency response exhibits no deep null between the resonances. Material characteristics and design

criteria needed to implement hybrid concepts dictate that models must include nonlinearities and coupling mechanisms both internal to the constituent materials and at the mechanical and electrical interface between them. Such nonlinear, coupled dynamics are further complicated by constitutive material hysteresis, frequency dependences, and thermal effects that must be quantified before full transducer performance can be realized in design and control settings. The proposed modeling methodology provides a unified framework to characterize reversible and irreversible domain mechanisms present in material polarization, in addition to linear and quadratic relationships to quantify the strain arising in response to the polarization. The mechanical coupling is addressed by means of wave models for the active elements as they actuate upon or are actuated by the surrounding structures. The resulting model provides a nonlinear model for multifunctional transducers capable of broadband collocated actuation and sensing. The model is implemented numerically and the results are contrasted with experimental data.

Dynamic Stability of Pre-Twisted Beams with Nonconstant Spin Rates under Axial Random Forces

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Drilling is one of the most widely used operations in manufacturing. Therefore, dynamic behavior of a drill has been an interesting topic for research. This paper investigates the dynamic stability of a pre-twisted cantilever beam spinning along its longitudinal axis with periodically varying rates and subjected to an axial random force at the free end. The spin rate of the beam is characterized as a small periodic perturbation superimposed on a constant speed, and the axial force is assumed as the sum of a constant force and a weakly stationary random process with a zero mean. Both the periodically varying spin rate and the axial random force may lead to parametric instability of the beam. In this work, the finite element method is applied first to get rid of the dependence on the spatial coordinate. To improve the solvability of the discretized system equations, the undamped autonomous terms in the equations are uncoupled by a modal analysis procedure suitable for gyroscopic systems. The method of stochastic averaging is then adopted to obtain Ito's equations for the system response under different resonant combinations. Finally, the first- and second-moments stability conditions of the beam are derived explicitly. Numerical results are presented for a simple harmonic speed perturbation and a gaussian white-noise axial force. It is found that unstable regions exist only at main resonances but not at sum-type or difference-type resonances. The effect of the spectral density of the axial random force is insignificant to the first-moment stability but will visibly reduce the second-moment stability of the pre-twisted beam.

Keywords: pre-twisted beam, nonconstant spin rate, axial random force, parametric stability, stochastic averaging method

Circular Cylindrical Shells Buckle under Pure Bending

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When a circular cylindrical shell is subjected to pure bending, it bends like a solid beam until it finally collapses. The collapse is most often conveniently explained by Brazier's theory: As the bending progresses, the cross section flattens, the bending rigidity of the beam gradually decreases, and the cylinder finally collapses as it loses load carrying capacity beyond the applied moment. The load-deflection relation follows a nonlinear equilibrium curve until it reaches a peak point where the cylinder collapses. It is therefore regarded as a structural instability belonging to the limit-point buckling. However, there doesn't seem to be any experimental results, which positively support this conjecture. Instead, most of the results indicate that the buckling is initiated as a local bifurcation buckling. The buckling patterns resemble those diamond patterns observed in the buckling under axial compression. It is also well known that the buckling load is much higher than that predicted by the theory. In Brazier's theory, the cylinder is assumed indefinitely long, whereas in experiments, the cylinder is of finite length and is supported at the ends by some sort of rigid equipment so that the flattening of the cross section tends to be constrained. Furthermore, the supported ends are usually constrained from the axial displacement, so that the bending deformation accompanies axial stretching as well as axial force. Consequently, it is difficult to accomplish a state of pure bending.

This paper presents results of a series of experiments on more than 700 specimens having various length-to-diameter and diameter-to-thickness ratios. A loading device was newly fabricated which was so designed that the state of pure bending was realized without inducing any axial forces. The results indicate that the collapse is attributed to the bifurcation buckling, rather than the limit-point buckling in Brazier's sense.

Keywords: circular cylinder, beam-like bending, bifurcation buckling, collapse

Vibration of Advanced Turbomachinery Rotating Blades Modeled as Thin-Walled Composite Beams

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The study of the eigenvibration behavior of rotating blades is an important prerequisite toward the reliable design of turbomachinery blades. The same is valid for helicopter blades and tilt rotor aircraft. In this context it should be noticed that the successful operation of the associated mechanical/aeronautical system depends largely upon the structural integrity of its rotating part. The structural integrity in turn depends upon the vibrational behavior of the blades. In this connection, the vibration- induced fatigue failure of rotor blades constitutes a major problem to the designer.

In order to enhance the dynamic response behavior, avoid the chronic problem of vibration-induced fatigue failure, reduce their weight while increasing their specific stiffness and strength, composite materials systems are integrated in their design.

Their incorporation results in the generation of a multitude of elastic couplings that render their modeling and analysis much more complex than in their standard metallic counterparts. Moreover, their effect on blade dynamic response characteristics was not yet investigated.

This work is devoted to the analysis of free vibration of rotating blades made of anisotropic composite materials. The structural model includes transverse shear, warping restraint, the nonuniformity of the blade cross-section, as well as the gyroscopic effects.

A thorough study of the implications of above mentioned non-classical effects on the free vibration response characteristics of rotating blades is carried out, and pertinent conclusions are outlined.

Keywords: Rotating Blades, Nonuniform Cross-Section, Composite Material Structures, Coupling Effects

Accurate Measurement of Stress Distributions in Anisotropic Laminated Structures. A New Method

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The best possible model available for the accurate measurement of stress distributions in elastic, anisotropic laminated composite beam-, plate- or shell-type components is three-dimensional theory of anisotropic elasticity. Due however to the complexity of the resulting differential equations, corresponding analytical solutions are very difficult if not impossible to obtain. Hence, the very few analytical solutions available in the literature deal with laminated composites having a relatively simple geometrical shape, subjected to relatively simple lateral loading, having their edges simply supported (SS) and being deformed within the small strain range (e.g., references [1-10]). One-dimensional (in the case of beams) or two-dimensional (in the case of plates and shells) mathematical models are used therefore as relatively simpler options.

The existing and widely used beam, plate and shell models are classified as *(i)* "layer-wise theories", in which the number of unknown degrees of freedom depends on the number of the layers involved, and *(ii)* conventional "smeared" theories whose number of unknowns is always kept fixed and small. The former models are evidently more accurate than the latter but, due to the large number of the degrees of freedom involved in multi-layered components, they require a considerable amount of analytical/numerical and computational effort. Using always a fixed and small number of unknowns, the smeared models overcome this difficulty. They are however reliable for the accurate prediction of global response structural characteristics only (e.g. vibrations frequencies, buckling loads, averaged displacements) and cannot be trusted when accurate predictions of corresponding detailed response characteristics (through thickness displacement, strain and stress distributions) are sought.

The new stress analysis method that this abstract is dealing with has already been applied and tested successfully, though essentially only in connection with flat composite laminated components [11-15]. The method is based on the use of generalised "smeared" laminate models that, like their conventional counterparts, make use of a fixed and small number of unknown displacement components. By incorporating however the exact elasticity distributions available for a corresponding SS structural component into its approximate displacement field, the smeared model acquires benefits of a corresponding layer-wise theory. Most importantly, the proposed smeared theory and three-dimensional elasticity yield identical results

for SS laminates, which is a unique result in the literature of two-dimensional (technical) laminate theory. It is then reasonable to expect that for different, more realistic sets of edge boundary conditions, the Saint Venant's principle applies. Accordingly, solutions and therefore detailed response characteristics that are based on such a smeared theory are very accurate away of the laminate edges whereas, near the edges, they should form statically equivalent representations of the corresponding exact elasticity results. It should be noted however that accuracy of detailed response characteristics is also recoverable near the edges on a predictor-corrector basis [14, 15].

It is believed that the new method can successfully be extended towards accurate stress analysis of anisotropic laminated composite shells and structural assemblies. Further developments are related to dynamic and stability analysis of structures and structural assemblies, to the influence that thermoelastic, piezoelectric and/or large deformation effects have on their behaviour and, among others, to the investigation of their failure modes and relevant failure mechanisms (e.g., de-lamination [16-18]). These are however challenges that may well need development and use of relevant numerical (FE) codes. The first step towards this direction has already been done [19] and showed that such FE codes can successfully be built by appropriately incorporating the outlined ideas into existing and widely used numerical formulations.

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Analysis of Wings Using Equivalent Continuum Models

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The finite element method (FEM) has gained a tremendous foothold in the aerospace industry. This is not surprising as the FE method is general, versatile and reliable.

Few other methods can match the accuracy with which the FEM can provide detailed results in the vicinity of local discontinuities (holes, abrupt variations in dimensions etc.). The method does so by repeatedly generating meshes, especially in the vicinity of the discontinuities, till an acceptable mathematical model is achieved. This is of course prohibitively expensive and cannot be used at the preliminary design stage. At that stage, often detailed stress calculations are really not needed and alternative models which can represent a structure with reasonable accuracy are often preferred. This is especially so if the quantities of interest are global response parameters such as natural frequencies, mode shapes, divergence and flutter response etc. For such cases, continuum models are increasingly being used.

In this paper, presented in honor of Professor Art Leissa, we give an overview of recent research on the use of equivalent plate models to study the free vibration of wings using equivalent plate models. The equivalent model is based on Reddy's First-Order Shear Deformation Theory. The natural frequencies are obtained using the Rayleigh-Ritz method. One key problem in the equivalent model approach is the time it takes to develop equivalent continuum models. We describe our research using neural networks to obtain the constitutive relations, for the equivalent model, in a relatively quick manner. Finally, we present our results for the multi-segment plates obtained using equivalent plate models. The multi-segment plate model is employed to study the aeroelastic response of UVAV wings.

Symposium on

Mechanics Education

In Honor of Professor R. P. McNitt

Organizer:
Professor N. J. Salamon
(Pennsylvania State University)

MECHANICS EDUCATION

In Honor Of Professor Richard P. McNitt

SESSION M3Q

Teaching Mechanics Then and Learning it Now

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Mechanics is the oldest discipline in engineering and remains central to product development and in research from the nano- to macro- to planetary-scale. In this talk, I will reflect on teaching mechanics THEN and NOW. THEN the slide rule placed a limit on significant figures; NOW the laptop computer delivers insignificant precision and automatic graphics. THEN the emphasis was on teaching: it was the student's duty to learn, the instructor's duty to deliver information; NOW learning is the objective (as if it wasn't then) of student and instructor, who must apply myriad teaching methods to suit a diverse student body. THEN only physics lectured to large classes; now we all do. THEN hands-on engineering classes were the thing (machine shop, mechanical design, materials testing); NOW, guess what, it's coming back, but ironically for the most part in a virtual way, through a computer display screen.

THEN there was "night school"; NOW there is distant learning. THEN there were Mechanics Departments; NOW they are on the verge of extinction. We outdid ourselves: mechanics is so pervasive in Aero, Mechanical and Civil Engineering that these departments have subsumed mechanics.

The Role of Demonstrations in Mechanics Education: Phenomena Driven by Surface Tension

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Demonstrations can be used in a fluid mechanics course for many purposes: to introduce a topic; to help visualize flow behavior prior to, or after, analysis in order to motivate the use and validity of applicable assumptions; to help visualize the interrelation between fluid flow, thermodynamics, and heat transfer; to relate mathematical models to actual flow behavior; to show the value and usefulness of dimensional analysis and associated dimensionless parameters; to relate abstract concepts to concrete phenomena; or to give new insight into the mechanics behind a specific phenomenon.

Surface tension is a very abstract notion. This paper illustrates successful ways that have been used in the undergraduate laboratory to demonstrate its existence as well as the behavior of ordinary phenomena in which it is important. Demonstrations that will be presented include those that show: contact angles formed by liquid drops on hydrophobic and hydrophilic surfaces; the formation of soap bubbles in air; the existence of surface tension at the interface between immiscible fluids and its use by certain species of flies and fish for catching their prey as well as by a common insect known as the water boatman to walk on water*; the formation of drops of liquid and the existence and stretching of liquid bridges; splashing caused by drops falling on pools of liquid; Marangoni flows between coalescing bubbles; waves and wakes on two-dimensional surfaces created by surface tension; and jet instabilities.

*The author gratefully acknowledges Professor N.J. Salamon's suggestion to include this example in this paper.

An Active Engagement Pedagogy for Introductory Solid Mechanics

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Advances in information technology are enabling universities to effectively integrate computers into the curriculum. Leveraging these advances, the Department of Mechanical Engineering at the Massachusetts Institute of Technology (MIT) has undertaken an initiative to transform the pedagogical format of an introductory solid mechanics course, 2.001 - Mechanics and Materials I. The new teaching paradigm, in contrast with the traditional lecture format, incorporates components of faculty-facilitated learning, hands-on experiments, group discussion, web-enabled exploration, and peer learning. Major elements of this educational reform are a set of physical, "desktop" experiments and a collection of Web-based learning modules. The new teaching format is enabled by a mobile, wireless computing initiative that provides all students with laptop computers and a new classroom, built to meet the requirements of the new paradigm. Students were taught using the new teaching methodology in fall 2001 and will be taught in this format in spring 2002. We will present specific physical experiments and demonstrate the Web-based learning modules, using in-class experiences to illustrate the utility of these tools. We will also offer our experiences with the use of laptop computers in the curriculum, with a particular emphasis on classroom computing. Current project assessment and future steps in developing the course will also be discussed.

Computer Literacy and Mechanics Education

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Computers are widely available and are equipped with powerful software and graduates are expected to be familiar with available tools. They should develop skills that will be useful during their studies and beyond. Basic computer literacy consists of three components: (1) skills for effective communication; (2) the ability to access online information;(3) skills required to perform engineering analyses.

This paper discusses how computer literacy can be introduced in basic mechanics classes. Spreadsheet programs and simple numerical techniques can improve the students' understanding of the subject matter and their problem solving capability. This approach is effective because: (1) problem solving is not limited by one's ability to obtain analytical solutions; (2) calculations are performed faster; (3) computer programming is not needed.

One of the examples considered is the free kick in soccer. Most dynamics textbooks assume that, during free flight, gravity is the only force acting on the ball. As a result, the ball follows a parabolic trajectory in a vertical plane. The drag force, proportional to the square of the velocity, opposes the motion but it is usually neglected in order to solve the problem analytically. The spinning of the ball causes the Magnus effect whereby the trajectory will not remain in the plane defined by the vertical and the initial velocity vector. The force due to the Magnus effect is proportional to the ball velocity. Numerical integration using Euler's method gives the complete trajectory. This example demonstrates that using a spreadsheet program: (1) the problem can be solved numerically when it could not be handled analytically; (2) this approach can be implemented by students. Other examples deal with the transient response of nonlinear damped multi-degree-of-freedom systems and large deflections of beams. With this approach students can study problems that are usually beyond their reach.

A Pilot Module for Web-Based Mechanics Education: Integrating Models and Experiments

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We present a description of a Web-based Educational framework for Analysis, Visualization, and Experimentation (WEAVE) and its pilot instructional module. The WEAVE has been designed with the goal of facilitating the integration of models and experiments over the internet. The development of instructional modules that use the framework is aimed at dramatically improving undergraduate labs in mechanics and other areas of engineering science. The pilot module concerns the dynamic response of a three-story building model subjected to base excitation, as well as a MATLAB code to simulate the associated ordinary differential equation. The WEAVE allows students to interactively change the inputs to the experimental system, run the experiments remotely in real-time, and tune the parameters in the numerical model. Encapsulating the instructional module is an interactive tutorial developed with the aid of interns from SHODOR, a nonprofit educational research foundation based in Durham, NC. We also present preliminary results from the use of this pilot module in our undergraduate civil engineering curriculum at Duke University.

MECHANICS EDUCATION

In Honor Of Professor Richard P. McNitt

SESSION M4Q

Computer Techniques in the Curriculum of Mechanics: Still Time for Changes

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This paper describes the author's ongoing experiences in incorporating the PCs into the Structural Mechanics program. It examines how the mechanics program has changed its approach to using the common engineering software. As elsewhere my faculty started the PC computerization using spreadsheets, simple FEM packages as well as matrix calculation tools in late 1980's clearly demonstrating the role of the computer competency of all its graduates.

All these tasks were accompanied by a common philosophy, which can be summarized in three points. The computer is only the engineer's tool - not an engineer's substitute. All engineers must be skeptical of computer-generated results and must validate solutions. Computers should be used to reinforce the students' understanding of physical behavior and engineering principles.

Being flexible and easy to use and learn spreadsheets gained widespread acceptance as an "official" tool. On the other hand students have quickly integrated Math-CAD taught by the mathematicians into several of the design courses that never used mathematical software. The speed of the integration is an indicator of its usefulness. Students can concentrate on understanding, building and examining physical and mathematical models rather than on calculations and digital results.

The fact that Math-CAD has not yet been fully incorporated into mechanics courses is difficult to explain. One of the main reasons is the resistance of the teachers. Despite this Math-CAD use is rapidly achieving a "critical mass". Its utilization in mechanics will be straightforward for problems described by ordinary or partial differential equations.

In the same time first attempts were undertaken to use multimedia technology as well as e-Learning facilities as a supplementary tool in the curriculum of mechanics mainly for lecture demonstrations, homework and testing.

Keywords: structural mechanics, spreadsheet, mathematical software, FEM, Math-CAD, e-Learninig, multimedia

The Impact of Technology and New Pedagogical Techniques in Mechanical Engineering Program at ITESM

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In this era of rapid advancement of technology, its impacts on the economic growth of our country increasingly depends upon the quality of the engineers it produces. Thus, engineering education incorporating advanced teaching strategies becomes a priority for ITESM Mission towards the Year 2005 in which the set of values, attitudes, and skills to be developed in the education of the students was established. Therefore, our mission

as an academic department at ITESM, Campus Monterrey to better educate our mechanical engineering students for innovative problem solving, is to provide not only high quality educational programs based on advanced pedagogical techniques such as Problem Based Learning (PBL)or Project Oriented Learning (POL) but also in the use of up to date information systems such as Learning Space? and Blackboard?. Currently, courses like Statics, Strength of Materials, Thermodynamics, Engineering Materials, Machine Design and Mechanical Vibrations are taught with PBL in which the scenarios are designed in such a way that these are related to real life situations for which the issues are identified and the objectives developed.

At ITESM Campus Monterrey, nearly 60 percent of the courses taught by the Department of Mechanical Engineering make use of Learning Space? as technological platform where students can get class notes, assignments, cases of study, evaluation forms, and so on. Since every student at ITESM owns a personal computer, the usage of Lotus Notes allows them to communicate in asynchronous and remote way increasing group interaction and collaborative work.

This paper describes the current educational climate regarding the state of the art in the usage of advanced teaching strategies and its effects on the learning process of mechanical engineering students.

Active-Learning Initiatives in Introductory Mechanics Courses

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The Department of Theoretical and Applied Mechanics at the University of Illinois, Urbana-Champaign has taught introductory sophomore-junior level courses in Statics, Dynamics, and Fluid Dynamics to over 1,000 students per year from different engineering departments for about a century. The lecture sections of these courses, which historically have been taught using the traditional lecture style, can now have over 200 students attending at one time. The traditional "chalk-talk" has proved less successful recently, particularly with larger lecture sections; in response, we are implementing several changes in these courses to engage students more actively.

In our Statics and Dynamics courses we are developing a set of demonstrational experiments and accompanying activities to encourage student participation. These demonstrations have to be portable and "stable" in the sense that they must work with minimal adjustment; the lectures take place outside the department, and the instructor typically has little time to set up and no time to fine-tune. We have also implemented group problem solving in smaller discussion sections for the Dynamics class, where students are able to interact with their peers to solve more complex, applied problems.

We are also beginning to redesign our Fluid Mechanics course toward (1) re-establishing a more obvious link between the lecture and the laboratory, in a sense "driving" some of the lecture material off the laboratory, and (2) creating a more active environment for students in the larger lecture portion of the course. Specific objectives include creating a set of digital videos of key points of the laboratory experiments and developing portable teaching demonstrations and illustrative software for the lecture. We will discuss the changes we have implemented in our Dynamics course, provide examples of some demonstrations with accompanying activities, and indicate continuing developments in our Fluid Mechanics course.

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Integration of Computer-Aided Engineering into Undergraduate and Graduate Mechanics Curricula

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This talk will begin with an overview of an initiative in the Carnegie Mellon Department of Mechanical Engineering to integrate computer-aided engineering concepts throughout the undergraduate curriculum. This initiative, which has evolved over approximately the past six years, is now serving as the foundation for similar efforts at the graduate level. The goal of work at the undergraduate level has been to integrate computer-aided design, finite element modeling, numerical package use and, where appropriate, computer-aided manufacturing into fundamental courses in solid mechanics, heat transfer, fluid mechanics, and other mechanical engineering disciplines. Software currently being used includes Pro/ENGINEER and SolidWorks CAD software, ANSYS finite element software, MATLAB and Mathcad numerical modeling packages, and Pro/ENGINEER CNC machining planning software. Part of the motivation for this effort is to address the need of industry for young engineers who feel comfortable using software packages. The principal goal of this work is, however, to use computer-aided engineering

concepts to further reinforce the learning of mechanical engineering fundamentals. A key skill is the use of engineering mechanics to intelligently interpret complex results from numerical packages. Several student projects will be described, as will how this initiative fits into current ABET-inspired goals for our department. Graduate program initiatives that build on work done at the undergraduate level will also be described.

Learning by Undergraduates through Participation in a Research Assistantship

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We completed an exploratory study of learning by undergraduates as they assisted in fluid mechanics laboratory research. Specifically, six undergraduate assistants worked for one to three academic quarters on preparing the experimental facility and collecting and analyzing data in the Environmental Fluid Mechanics Laboratory at Stanford University. The fluid mechanics research involved using Planar Laser Induced Fluorescence to image the concentration structures of a passive-scalar plume in a turbulent boundary layer. This approach allowed us to explore learning by the undergraduate assistants as we simultaneously completed research in chemical plume tracking.

Of the number of possible benefits, we focused on learning of the scientific concepts underlying the research-in our case, plume dispersion and turbulent boundary layers. To track changes in the undergraduates' understanding, we administered pre, mid, and posttests. Each test incorporated some of the following formats: multiple-choice questions followed by interviews, drawings, open-ended interviews with video clips, and Predict-Observe-Evaluate activities. Other data sources included student reports, questionnaires on background and the research experience, daily logs of their activities, lab notebooks, and journal entries.

Preliminary results suggest that the assistants did not make significant gains in their understanding of plume dispersion or turbulent boundary layers through participation in the fluid mechanics research. Instead, changes measured by the tests seemed to be more directly related to concurrent coursework. The assistantship may have had a secondary effect by helping them understand the material presented in classes. However, they rarely made reference to the laboratory plume or research experience generally during testing. Also, some of their misconceptions seemed to persist throughout the research experience.

Keywords: undergraduate research, plume dispersion, learning

Design in Mechanics Courses: Trials, Triumphs and Tribulations

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Motivated by a return to an engineering philosophy in engineering education and influenced by ABET, we added a design project to a series of undergraduate and one graduate mechanics courses. Introducing design as a practical application into courses in mechanics is a formidable task under constraints of student/faculty motivation and capability, course credit limits and difficulties in choosing between topics from the rich array provided in the mechanics discipline. Indeed, teaching and learning design and mechanics has lead to trials, triumphs and tribulations.

Trials were many: selecting appropriate design problems at each course level, course management methods and grading, selecting course topics and their sequence in concert with a design project, assessment of design reports and individual student work vs. team work, selection of teams, and more.

Triumphs in learning outcomes include a technologically broad, yet academically deep education for students, application of function to produce some wonderful designs or forms, demonstration of a disciplined approach to design and a new appreciation for engineering and its interface with science and math (for one: re-define assumptions and minimize their use).

And other triumphs: a goals-centered approach to teaching, the enthusiasm of some students and teams, and learning good engineering skill-sets. Tribulations: oh my. Faculty who feel uncomfortable with engineering and especially design, students who have severe difficulty learning mechanics, let alone its application, problems with team dynamics.

These issues will be discussed with an exhibition of examples and cases. For an illustration of design content for one course and student designs, go to: http://www.esm.psu.edu/courses/emch13d/design/default.htm

Importance of Automatic Post Processing of Output Data Using Text Processors in Mechanics Education

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In many engineering analysis the solution process is not quite straightforward and further steps of the analysis actually depend on the recently obtained results. Although identical result variables are obtained for many situations that might appear during the analysis their derivation might be completely different.

In order to verify their own results the students in their individual studies usually depend on available software packages. In such software a graphical representation of the results has already become a standard, however the presentation of the obtained results is still usually limited to correct numerical values only.

Therefore, I believe that at least educational packages must not provide just the correct value for each result variable but also the clue for its acquisition. An effective presentation of the derivation of the final result should thus present all essential steps accompanied not only with partial numerical results but also with all corresponding equations.

Such a history of the result development is very important because students must learn how to process from the first phase towards the final solution. As computer generated report covers all computational steps, the students can concentrate on the important aspects, as for example proper selection of the computational model, and furthermore, to carefully study the influence of a single parameter change on the final results, thus achieving so important engineering feeling for a selected problem.

Proposed presentation covers a seldom seen approach to the creation of a final report on an engineering analysis where all the obtained results, accompanied with the corresponding equations, are automatically transmitted to a desktop publishing package without any user's intervention. Practical implementation of ideas presented will be demonstrated with a geomechanical software package that has already been successfully involved in the educational process.

Symposium on

Plasticity and Damage Mechanics

In Honor Of
Professor Z. Mróz

Organizer:
Professor G. Voyiadjis
(Louisiana State University)

PLASTICITY AND DAMAGE MECHANICS

In Honor of Professor Z. Mróz

SESSION M3O
Plasticity and Cyclic Plasticity

Numerical Investigation of Macrocrack Propagation along a Bimaterial Interface in Adiabatic Dynamic Processes

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In experimental observation performed in Caltech, Pasadena (cf. A.J. Rosakis, O. Samudrala and D. Coker, Cracks faster than the shear wave speed, California Institute of Technology, SM Report 98- 17, December 1998; Science 284, 1999, 1337-1340) it has been found that the prediction of the classical dynamic fracture theory that the Rayleigh surface wave speed is the limiting speed for propagation of in-plane cracks in homogeneous, linear-elastic materials subjected to remote loading is not correct.

In very recent paper (cf. P.R. Guduru, A.T. Zehuder, A.J. Rosakis and G. Ravichandran, Dynamic full field measurements of crack tip temperatures, 2001 Mechanics and Materials Summer Conference, MMC 2001, San Diego, June 27-29,2001) it has also been shown detailed real time evolution of the transient crack tip temperature fields in two different steels (C 300 and HY 100 steels) by using the 2-D high speed camera. The crack tip temperature rise at initiation in C 300 steel was found to be about 55 K and in case of HY 100 steel, which is a highly ductile steel, above 200 K, and was seen to be a strong function of loading rate.

The present paper has been generated by these experimental results. The main objective is the investigation of macrocrack propagation along a bimaterial interface in an adiabatic process under dynamic far-field asymmetric loading. A general constitutive model of elasto-viscoplastic damaged polycrystalline solids developed within the thermodynamic framework of the rate type covariance structure with finite set of the internal state variables is used (cf. w. Dornowski and P. Perzyna, Numerical analysis of macrocrack propagation along a bimaterial interface under dynamic loading processes, 2001 Mechanics and Materials Summer Conference, MMC 2001, San Diego, June 27-29, 2001).

The Kinetics of microdamage plays very important role in this constitutive model. Fracture criterion based on the evolution of microdamage is assumed. The relaxation time is used as a regularization parameter. By assuming that the relaxation time tends to zero, the rate independent elastic-plastic response can be obtained. The identification procedure is developed basing on the experimental observations.

The finite difference method for regularized elasto-viscoplastic model is used. The edge-cracked bimaterial specimen is considered. Numerical analysis of the dynamic crack growth in different materials and solids requires the applying of discrete meshes with the heterogeneous structure. It seems to be necessary to introduce the domains with greater number of nodes in places of predicted fracture regions (cohesive band, cohesive surface etc). The convective formulation gives wide possibilities in this scope. In the convective description the difference mesh can be deformed by any superposed diffeomorphism keeping simultaneously the constancy of spatial discretization parameters. While the information about initial mesh deformation occurs in the initial configuration metrics. In this paper the analysis of solution sensibility in the dynamic crack growth problem with respect to difference mesh topology is presented. Modeling manners of fracture and fragmentation in difference meshes are presented.

Particular attention is focused on the investigation of the interaction of stress waves on the propagation of macrocrack within the interface band. The macrocrack-tip speed history and the evolution of the transient crack tip temperature fields have been obtained. Discussion of the numerical results and their comparison with experimental observations are presented.

Energy Balance and Identification of Hardening Moduli in Plastic Deformation Processes

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Phenomenological models of plastic deformation are usually formulated in terms of hardening state variables whose evolution is related to plastic strain variation. These variables occur in the free energy function and in the yield condition or dissipation function. If the state variables occur in the free energy or free enthalpy functions, they represent the energy portion associated with plastic deformation (stored energy). On the other hand, if these variables occur in the dissipation function or yield condition expressed in terms of the dissipative stress, they correspond to internal configuration dependent on plastic dissipation. The hardening modulus H is then a sum of two terms: $H = H_r + H_d$, where H_r corresponds to free energy variation and H_d to dissipation variation with changing internal configuration. We shall call these terms *the free energy hardening and the dissipation or configuration hardening moduli.*

Assume, for simplicity, that state variables are represented by plastic strain and temperature, so the specific free energy Ψ and the dissipation function D are assumed in the form:

$$\Psi = \Psi(\varepsilon^E, \varepsilon^P, T),\ D = D(\dot{\varepsilon}^P, \varepsilon^P, T) \tag{1}$$

Considering an isothermal process, we can write

$$\begin{gathered}\sigma \cdot \dot{\varepsilon}^P = \sigma_r \cdot \dot{\varepsilon}^P + \sigma_d \cdot \dot{\varepsilon}^P, \\ \text{where: } \sigma_r = \rho \frac{\partial \Psi}{\partial \varepsilon^P},\ \sigma_d = \rho \frac{\partial D}{\partial \dot{\varepsilon}^P},\ \sigma = \sigma_r + \sigma_d\end{gathered} \tag{2}$$

are the stress components related to stored free energy and dissipation. The hardening moduli H_r and H_r are expressed as follows:

$$H_r = \frac{\partial F}{\partial \sigma}\frac{\partial \sigma_r}{\partial \varepsilon^P}\frac{\partial F}{\partial \sigma},\ H_d = \frac{\partial F}{\partial \sigma}\frac{\partial \sigma_d}{\partial \varepsilon^P}\frac{\partial F}{\partial \sigma},\ H = H_r + H_d. \tag{3}$$

This expression can now be used for identification of the moduli: H_r and H_d In fact, from the mechanical test the total hardening modulus can be identified. Next, by measuring total dissipated energy $D^t = \int \dot{D}\, dt$, the modulus H_d and next H_r can be specified. The dissipated energy was determined by simulating the sample heating during deformation by means of supply of electrical power in such way that the temperature increase with time during

simulation is identical with that measured during deformation. The infrared camera was used to measure the temperature variation of the sample. When the straining and the simulation are conducted under identical conditions, then the dissipated energy can be determined in term of electrical power. Figures 1 and 2 present variations of σ_r, σ_d and H_r, H_d during tensile test of austenitic steel. It is seen that the stress σ_r tends to an asymptotic value and the related hardening modulus H_r tends to zero.

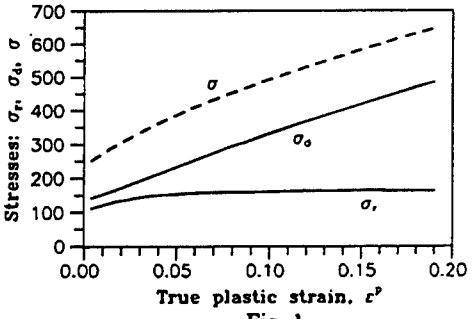


Fig. 1.

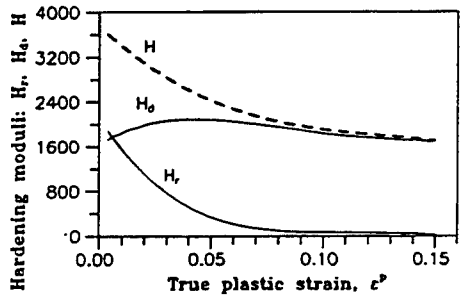


Fig. 2.

Modeling of Temperature Dependency of Ratchetting Deformation Behavior in Ferritic Steel

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Following the authors' previous study on modified 9Cr-1Mo steel at 550°C (Yaguchi and Takahashi, 2002), a series of ratchetting deformation tests was conducted in the temperature range between 200°C and 600°C. As the same as the behavior observed at 550°C, the ratchetting deformation rate was the fastest under uniaxial conditions when the stress ratio was equal to -1, under which condition no ratchetting deformation was predicted by conventional J2-type constitutive models. The inelastic constitutive model developed by the authors for the material at 550°C was extended to apply to ratchetting deformation analysis between 200°C and 600°C. A kinematic hardening rule was changed from OW . to OW . model to improve accuracy of prediction of ratchetting deformation at lower temperatures, and evolutionary laws for cycle dependent variables were also modified to express cyclic hardening behavior observed at lower temperatures. Constants involved in the constitutive model were determined for each temperature based on the results of monotonic and cyclic loading tests. The extended constitutive model was applied to simulations of inelastic behavior under various loading conditions, including isothermal and anisothermal cyclic deformation and ratchetting deformation. It was demonstrated that the present constitutive model is able to describe not only the ratchetting behavior but also the other inelastic behaviors including the anisothermal cyclic deformation with good accuracy.

Keywords: Inelastic constitutive model, Ratchetting behavior, Anisothermal deformation, Kinematic hardening rule

Reference

Yaguchi, M. and Takahashi, Y., 2002, "Ratchetting Deformation Analysis of Ferritic Steel by Viscoplastic Constitutive Model Considering Tension-Compression Asymmetry", 9th International Symposium on Plasticity, to be presented

Inverse Approach to Identification of Material Parameters of Cyclic Elasto-Plasticity for Component Layers of a Bimetallic Sheet

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The present paper proposes a novel approach to the identification of the mechanical properties of individual component layers of a bimetallic sheet. In this approach, a set of material parameters in a constitutive model of cyclic

elasto-plasticity is identified by minimizing the difference between the experimental results and the corresponding results of numerical simulation. This method has an advantage of using the experimental data (tensile load vs strain curve in the uniaxial tension test and the bending moment vs curvature diagram in the cyclic bending test [see Fig. 1]) for a whole bimetallic sheet but not for individual component layers. An optimization technique based on the iterative multipoint approximation concept [1, 2] is used for the identification of the material parameters. This paper describes the experimentation, the fundamentals and the technique of the identification, and the verification of this approach using two types of constitutive models (the Chaboche-Rousselier and the Prager models) for an aluminum clad stainless steel sheet (see Fig. 2). By this new approach, the determination of mechanical properties of a bimetallic sheet has become possible whithout performing a time-consuming process of the removal of a layer from the sheet for the preperation of the specimens. It is a considerable technological achievement. Moreover, it should be emphasized that this approach allows us to identify material parameters not only for the monotonic deformation but also for the cyclic behavior characterized by the Bauschinger effect and the cyclic hardening natures of materials.

Keywords: Material parameter identification, Inverse problem, Cyclic plasticity, Bimetallic sheet

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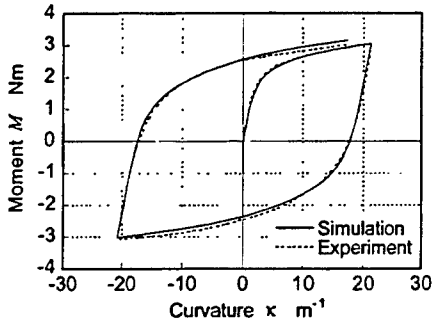


Fig. 1 Comparisons of experimental diagrams of bending moment, M, *vs* curvature, κ, and the results of simulations with the constitutive model of Chaboche-Rousselier type incorporating the identified sets of material parameters.

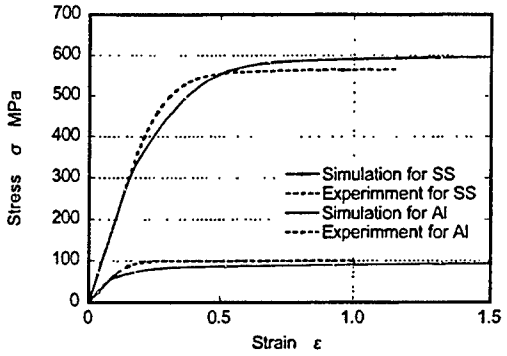


Fig. 2 Comparisons of the stress-strain curves and the results of simulations with the constitutive model of Chaboche-Rousselier type incorporating the identified sets of material parameters for the stainless steel (SS) and aluminum (Al) layers in the bimetal sheet.

Some Critical Experimental Results on Polymers

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A comprehensive set of experimental results will be presented on three polymers (Adiprene L100, Teflon and Nylon). These highly non-linear measured responses are from compression tests at a wide range of strain rates and temperatures, relaxation experiments at different levels of deformation under compression, torsion and tension-torsion loading, studies of creep in these materials, and loading-unloading experiments followed by monitoring of the deformation recovery after unloading. The last set of the experiments are used to separate visco-elastic and visco-plastic deformations. In Adiprene, the softest material of this family and which is rubber-like, the deformation is mostly visco-elastic, while in Nylon, it is predominantly visco-plastic deformation. In between, visco-elastic and visco-plastic deformations are significant in Teflon. Relaxation process will be shown to be basically an elastic one, while creep causes internal change in the material. The response of the three polymers is non-linearly dependent on strain-rate and temperature.

PLASTICITY AND DAMAGE MECHANICS

In Honor of Professor Z. Mróz

SESSION M4O

Crystal Plasticity

Crystallographic Texture and Strain Localization in Metals

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Formability of metal elements is strongly affected by material anisotropy. High formability is the ability to achieve high limit strains in metal without strain localization. In computational models used to simulate forming processes these properties depend on the assumed plastic potential. Usually, phenomenological yield functions are adopted. Anisotropy is induced by forming processes, e.g. rolling, performed to obtain the element. These processes are connected with large plastic deformations that result in crystallographic texture development in the polycrystalline element of metal. Classical models of plastic yielding do not take into account crystallographic texture directly. Physical theories of plastic yielding in polycrystalline materials are too complex to be efficiently implemented in the numerical programs.

The main aim of the study is to analyze the change of sheet formability due to crystallographic texture development. The proposed Texture-Dependent Yield Surface of n-degree will be applied. It combines basic elements of the phenomenological and physical approaches. It is formulated on the macro level but it catches main features of metal microstructure. Advantageous and disadvantageous textures will be indicated for given type of deformation process. The Marciniak-Kuczynski model of strain localization will be used. Sheet properties will be considered trough the some parameters: the Lankford coefficient R crucial for the localization by thinning and parameter P proposed by Barlat, Lian and Baudelet, crucial for necking.

Presented results will show not only the necessity of incorporating crystallographic texture to computational models of forming processes but also the possibility of controlling these processes through the usage of elements with prescribed crystallographic texture.

Keywords: Anisotropic material, Crystallographic texture, Yield surface, Strain localization

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Analysis of Serration Characteristics during Serrated Flow of 5000 Series Aluminum

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Under certain conditions, the plastic flow of 5000 series aluminum results in a serrated stress-strain response. The serrations are the result of small-scale strain localization and are also known as the Portevin-Le Chatlier (PLC) effect or dynamic strain aging. It is generally accepted that temporary locking of dislocations by solute atoms causes serrations in the stress-strain response. Forest dislocations are also thought to play a roll in pinning dislocations. The details associated with dislocation interactions and with how dislocation mobility begins, ends, and is interrupted are clearly not yet well understood.

Under tensile loading, rolled 5083 sheet aluminum specimens exhibited serrated flow for the duration of plastic deformation and at strain rates ranging from 10^{-3}–$10^{-5}s^{-1}$. For the complete deformation history, the serration widths and amplitudes were quantitatively determined. Acoustic emission (AE) was monitored at all strain rates and synchronized with stress-strain data. During plastic deformation, the most significant AE bursts were associated with local stress maxima within the vicinity of serration anomalies. It is believed that these anomalies represent larger scale dislocation motion. Several of the anomalies were also linked to macroscopically visible deformation bands propagating through the gage section of the specimen.

A Mechanistic Description of Combined Hardening and Size Effects in Crystalline Materials

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Numerous microindentation experiments in crystalline materials[1,2] have demonstrated a size effect. The hardness measured for indents smaller than 1 um [3,4] can be more than a factor of 3 greater than the hardness measured for large indents. Size effects have also been observed in torsion experiments [5] and under other loading conditions. Ashby [6] predicted that geometrically necessary dislocations [7] would be formed beneath a flat punch.

Nix and Gao [8] expanded on the Ashby concept to develop a mechanistic model that predicted the indentation size effect observed in earlier experiments. Recently, the Nix and Gao model has been extended to spherical indenters and expanded to include work hardening [4]. By reexamining the underlying dislocation mechanisms incorporated into these models, a simple method is developed to combine work hardening, radiation hardening and size effects. The mechanistic model is verified by indentation experiments in FCC metals and ionic salt crystals. However, the model over predicts hardness for indentation depths smaller than a fraction of the length scale parameter in the model. The deviation indicates that a new deformation mechanism is activated at high stresses. This deviation is found to occur at different depths and stresses in different materials.

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A Macroscopic Slip Model of Anisotropic Plasticity of Textured Sheet Metals

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A new methodology for modeling anisotropic plastic flow of textured sheet metals by a discrete set of planar macroscopic slips is reviewed. It is shown that the proposed macroscopic slip anisotropic plasticity models are equivalent to the isotropic flow theories such as those proposed by Tresca and von Mises and the anisotropic flow theories such as those proposed by Hill and others using properly simplified slip conditions and slip laws. The macroscopic slip modeling methodology provides not only a much more unified interpretation of these classical plasticity theories but also an effective framework for developing new classes of anisotropic plasticity models for textured sheet metals. A simple anisotropic plasticity model with isotropic hardening is developed following the proposed methodology and it is applied to describe the sheet metal anisotropic plastic flow behaviors of selected aluminum, copper and steel sheet metals. Experimental evaluations and micromechanical foundations of the proposed macroscopic slip anisotropic plasticity model are discussed and their applications to sheet metal formability analyses are illustrated.

Simulation of Welding with Enhanced Models of Thermal Plasmas and Thermo-Mechano-Metallurgical Processes in the Heat Affected Zone

J. Ronda, H. Murakawa, M. Ushio and G.J. Oliver

The modern simulation of welding addressed to industries should be in the form of the expert system that could be considered as the digital welding master and applicable in a welding workshop. Such industrial oriented virtual manufacturing system should consists of three models:

- Energy transmission through the welding arc that consists of thermal plasma,
- Liquid metal dynamics in a (weld pool) and melting/solidification phenomena,
- Phase transformation in solids.

We consider here the plasma that occurs during TIG welding. Such welding plasmas belong to the sub-group known as the thermal plasmas that are by definition in the local thermodynamic equilibrium (LTE) or close to that state. When plasma interacts with solid or liquid boundary, the boundary layers are non-equilibrium regions. Therefore, the region of welding arc is split into various sub-regions: cathode space charge sheath, cathode pre-sheath, arc column, anode pre-sheath, and anode space charge sheath. The arc column is quite well distributed by two-dimensional models due to the symmetry and quasi-laminar flow in the arc root. The plasma behavior in cathode and anode regions, which are turbulent in the sense of the magneto-hydro-dynamic flow not in ordinary fluid, with strong deviations from LTE, are described by three-dimensional models.

The evaluation of the real heat flux from the arc to the weld pool is important for the evaluation of a weld penetration in arc welding process. The weld penetration and

the weld shape control the weld quality. There are four driving forces for a liquid metal in the pool: the drag force of the cathode jet on the surface, the buoyancy force, the electromagnetic force due to the self-magnetic field of welding current, and the surface tension of the pool. The driving forces are dependent both on the weld metal physical properties and plasma characteristics. Therefore, the complex model of TIG welding is required for the simulation of the arc and the weld pool interactions. A unified numerical model of stationary TIG arc welding with anode melting and convection effects in the weld pool is used here.

In the heat affected zone (HAZ) a number of phenomena occur. The most important of them are: melting and solidification of a weld pool, heating and cooling, thermal dilatation, elastic and inelastic deformation, solid phase transformation, volumetric strain effects, and transformation-induced plasticity. The coupled and mathematically consistent thermo-mechano-metallurgical (CTMM) problem is formulated as a variational problem and solved by the Galerkin type finite element technique. The real microstructure is not projected into the finite element structure and thus the concept of hybrid isobaric finite elements is used to follow the idea of dispersed particles. In hybrid elements, the phase composition of a material is represented at Gaussian points where the FE system is integrated. Simplifications proposed for the phenomenological description of solid phase transformations aim at representing coupled thermo-mechanical phenomena as a chain of successive processes, ignoring secondary reactions proceeding simultaneously and involving less energy than others, and idealizing the cooling process.

Numerical results illustrate the complex model of welding consisting of three sub-models: plasma arc (heat source), weld pool, and HOZ, and are given for the TIG stationary welding benchmark problem formulated for a thick-plate.

Elasto-Plasticity of Paper

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We develop a constitutive model of paper's in-plane biaxial tensile response accounting for the elastic-plastic hardening behavior, and its orthotropic character. The latter aspect is motivated by machine-made papers, which, in contrast to isotropic laboratory handsheets, are strongly oriented. In the first part, we focus on modeling paper's response under monotonic loading, this restriction allowing us to treat the elastic-plastic response as a physically nonlinear elastic one. A strain energy function of a hyperbolic tangent form is developed so as to fit the entire range of biaxial and uniaxial experiments on a commercial grade paper. In the second part, this function is then introduced as the free energy function into a model based on thermomechanics with internal variables, while also a dissipation function is introduced to deal with the irreversible effects.

PLASTICITY AND DAMAGE MECHANICS

In Honor of Professor Z. Mróz

SESSION T3O
Viscoplasticity

On Some Applications of Unified Viscoplastic Constitutive Equations

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O.N.E.R.A. France

Macroscopic constitutive equations for structural inelastic analysis are still of a great interest for engineering applications, even if other micromechanics based approaches can also be developed and used in parallel. The present paper summarizes some recent experimental and theoretical studies related with the cyclic viscoplastic modeling of metallic materials. The framework used is recalled, based on the unified constitutive equations developed at Onera since 25 years. Two aspects will be considered more specifically , corresponding with two different domains of application and two different classes of materials:

- a 7075 aluminum alloy, in which attention was focused on the coupling effects between viscoplasticity, metallurgical changes (at the forming temperature) and Bauschinger effects in the spring-back phase of a forming process,
- a molybdenum refractory metal, TZM, studied at room temperature under complicated uniaxial cyclic loads, leading to a first set of cyclic constitutive equations that include classical and less classical isotropic and kinematic hardening models.

Viscoplastic Model Accounting for the Strength-Differential in Inconel 718

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The nickel-base alloy Inconel 718 exhibits a strength differential, that is a different plastic flow behavior in tension and compression. A viscoplastic model having its foundation in thermodynamics has been extended for material behavior that deviates from classical metal plasticity by including all three stress invariants in the threshold function. The model can predict time-dependent plastic flow in isotropic materials with or without a flow stress asymmetry as well as with or without pressure dependence. Viscoplastic material parameters have been fit to pure shear, uniaxial tension, and uniaxial compression experimental results. Threshold function material parameters have been fit to the strength differential. Four classes of threshold functions have been considered and combined axial-torsional strain-controlled loading of hollow tubes has been used to select the most applicable class of threshold function and validate the model. A J2J3 class model, where J2 and J3 are the second and third effective deviatoric stress invariants, was found to agree the best with the experimental results.

A Time/Space Multiscale Computational Method for (Visco)plastic Structures with contacts

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The process of modeling mechanical behavior - particularly nonlinear behavior, i.e. (visco)plasticity, contacts with friction, damage - has made considerable progress in the last twenty years. However, the cost of using the improved material models of classical FE codes to simulate the behavior of engineering structures could be prohibitive, particularly for cyclic loadings or for composites and, more generally, heterogeneous structures. Classical FE codes are based on incremental methods whose numerical cost, in spite of using convergence acceleration techniques, increases rapidly with the number of degrees of freedom and with the complexity of the loading history.

This paper deals with alternative computational strategies capable of solving engineering problems beyond the calculation limits of today's classical codes. The goal is to lower the calculation cost drastically while trying at the same time to increase the robustness. Here, we propose a new time/space computational method for solving (visco)plastic problems with contacts and friction. The cornerstone is the so-called LArge Time INcrement (LATIN) Method, which relies on some remarkable properties satisfied by most of the material models encountered in structural mechanics. "Micro" and "macro" quantities are defined on the interfaces arising from the decomposition of the studied structure into an assembly of substructures; the "macro" quantities are like mean values over both space and time. A main feature of the associated multiscale computational strategy, which is iterative, is to include a homogenization procedure over both space and time. This mechanics-based computational strategy is obviously suitable for parallel computing. Its efficiency and its robustness will be illustrated on several numerical examples.

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PLASTICITY AND DAMAGE MECHANICS

In Honor of Professor Z. Mróz

SESSION T4O
Gradient Plasticity

Multiple-Scale Damage Mechanisms with Inelastic Behaviour in Composite Materials

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Localized zones of damage in which the characteristic length scale governing the variations of damage falls far below the scale of the state variables of strain normally used to describe the response of the continuum is

not accounted for in classical local approaches. The use of nonlocal continua theory is used in order to introduce long-range microstructural interaction where the stress response at a material point is assumed to depend on the state of its neighborhood in addition to the state of the point itself [1-3]. An expression for the nonlocal behavior can be derived as a truncated Taylor expansion of a weighted average at the material point of the local counterpart over a surrounding volume at a small distance from the point. The authors introduce multiple scale effects through damage internal state variables and the corresponding gradients at both the macro and mesoscale levels [3]. The mesoscale gradient approach allows one to obtain more precise characterization of the nonlinearity in the damage distribution; to address issues such as lack of statistical homogeneous state variables at the macroscale level such as debonding of fibers in composite materials, crack, voids, etc; and to address nonlocal influences associated with crack interaction. The macroscale gradients allow one to address non-local behavior of materials and interpret the collective behavior of defects such as dislocations and cracks. The second order gradient, i.e. Laplacian, of both the kinematic and the isotropic hardening measures is introduced through the Helmholtz free energy and through the damage potential function. The internal state variable and the corresponding gradient terms are assumed to be independent internal state variables with respect to each other with different physical interpretations and initial conditions which allows these different physical phenomena to be identified separately.

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Numerical Treatment of Plastic Strain Localization Phenomena

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A review of the numerical methods used for the analysis of the plastic strain localization phenomena for static and dynamic cases will be presented. The proper settings of the initial boundary value problems, in particular in cases of material softening requires a regularization. It is achieved on the level of formulation of the problem by introducing different physical properties (non-local constitutive effects or higher order gradients) or on the level of numerical discretization (embedded elements). The different methods introduce so called length scale parameters which implicitly influence the width of localization.

In particular, for fast dynamic processes (those which experimentally are verified in Hopkinson bar) using rate dependent constitutive relations seems simultaneously introduce physical properties and mathematical regularization. Our attention is focused on elasto-viscoplastic constitutive properties of the materials for which the rate of deformations reaches the value of order $10^4 - 10^5$ 1/s. The set of incremental governing equations for thermo-viscoplastic effects is discussed. The solutions answer the questions on the placement and width of localization zones. Both those quantities in our formulation appears as the effects of material properties, interaction of waves, boundary and initial conditions. The results are obtained without any kind of imperfections which are used in many other formulations. The finite element discretization and computations were performed in the environment of Abaqus FE code. The number of numerical examples (1-D to 3-D) which emphasized the crucial influence of waves propagation and the dispersive properties of the material will be presented. The achievements are applicable in design and optimization of structures and details (eg. their shape) to assure the safety in crush accidents.

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High Gradient Deformations of Polycrystals - Experimental investigation

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The experimental basis of present-day theories of large plastic strains was formulated in the 1950s. Although the distribution of dislocation slips in crystals is nonhomogeneous, the phenomenological attempt to the plasticity is continuous. The grain boundaries of polycrystals are also assumed to be just obstacles. Many experiments conducted in this field in the second half of the century were summarized and criticized by J.F. Bell [1]. He analyzed

the theoretical and experimental results given in Dawson [2], and discovered a discrepancy between theory, which allows no rotation of grains, and experimental findings, where rigid body rotation of polycrystalline grains, has been revealed by X-ray and microscopic measurements.

The effects of grain rotation have been studied by Rovinski and Sinajski, who showed through X-rays that the surface grains of a tensioned Al specimen shift and rotate both continuously and by jumps. Our work has shown, with the use of micro-stereoimage techniques, that the deformation mechanism of a polycrystalline structure also has the same structure. Non-monotonous rotation of the grain was found in a tensioned strip made of the pure polycrystalline Al (99,83The rotations of grains in the specimen of Al-Cu-Mg alloy, which was loaded cyclically, were also measured [3].

This paper presents a microscopic analysis of deformations near to edges, which originate due to crack propagation or in cutting and grinding processes. The deformations are observed microscopically as polycrystalline structure patterns on the polished side plane of the specimens. Some are also seen on the polished surface plane of a thin strip after bending. The paper consists of two parts. The first part shows examples of this effect induced by different processing conditions, and the second part gives some data about the analysis of the deformation and the movement of individual polycrystalline grains.

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The Characteristics of the Solution of Cosserat Plasticity Theory

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Cosserat plasticity theory has been used to regularize the "localized solution" which is mesh-dependent in classical continuum plasticity. It had been demonstrated that in Cosserat theory the boundary value problem would remain elliptic even when the deformation localizes into a narrow band, and that mesh-independent solutions can be obtained in finite element simulations of localization problems in strain-softening solids when couple-stresses are included in an elasto-plastic continuum model.

However this conclusion is controversial. As we know, in the classical plasticity, strain localization is the outcome of the instability of the fundamental solution. As the governing field equations of a conventional continuum model loses its ellipticity, the fundamental solution becomes unstable, for a uniform stress field, there may exists an alternate localized deformation beside the uniform deformation, i.e., multiplier equilibrium states exist. Alike, if the governing field equations of the Cosserat theory remain elliptic as the deformation localizes into a narrow, we should not have multiplier equilibrium states (deformation forms). Thus for a uniform stress field, only a distributed deformation is the solution, if introducing imperfection into this uniform case, a solution slightly different from the distributed solution is obtained.

This article questions that whether there exists localization in a compressed homogenous panel, in which the softening stress-strain relation has very flat slope. Different levels of imperfection are introduced, and the load-displacement curves and the contour of equivalent plastic strain show that as the imperfection approaches zero, the "localized solution" converges to "the distributed solution". It raises the suspicion that "the localization" captured by other articles is only a concentration of deformation caused by imperfection. Secondly, we further check the case with a steeper softening slope: localization is found and the localized solution is mesh-dependent also. We conclude by showing that softening slope is a bifurcation parameter (as might be assumed) for a Cosserat formulation, but not at a predictable value. Hence non-local plasticity cannot be relied upon to predict true strain localization

Keywords: Strain Localization, Cosserat Plasticity Theory, False Strain Localization, Bifurcation

PLASTICITY AND DAMAGE MECHANICS

In Honor of Professor Z. Mróz

SESSION W3O

Damage Mechanics I

A Linked FEM-Damage Percolation Model of Aluminum Alloy Sheet Forming

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Experimentation has demonstrated that ductile damage can have a strong impact on formability of automotive alu-

minum alloy sheet. The nucleation, growth and coalescence of microvoids inherently promote the formation of through-thickness shear bands ultimately leading to failure. Therefore, understanding damage evolution during forming of aluminum alloy sheet is highly desired.

The distribution of ductile damage in aluminum alloy sheet is highly localized; thus it is questionable whether continuum-based damage models, such as Gurson's porous plasticity model can properly capture damage evolution. Furthermore, ductile damage accumulates in a stable fashion until failure occurs abruptly through catastrophic local coalescence of voids. In continuum models, this instant is generally modeled in terms of a threshold value of bulk damage, however, this average value does not reflect local damage levels within second phase particle clusters, for example.

Recently, a damage percolation model has been developed utilizing measured second phase particle distributions to model the damage evolution in aluminum alloy sheet under various forming conditions. Tessellated particle fields are used to capture the real spatial distribution of particles as well as nearest neighbor and particle clustering data. Unlike continuum-based models, in this damage percolation model, final failure occurs as a chain reaction with widespread void coalescence without any further straining once a number of primary particle clusters link-up to form a dominant crack. In the current study, the damage percolation code is linked with LS-DYNA, an explicit dynamic FEM code used to account for local compliance effects due to damage development. The linked model utilizes a Gurson-based yield surface to account for the softening effects of void damage, while the local damage development and void linkage events are modeled using the percolation code with FEM result as input data. The model is applied to stretch-flange forming which is known to be a damage-sensitive operation and the nucleation, growth and coalescence of damage in the most-likely failed area of the stretch-flange are examined during the forming process.

Anisotropic Damage Model for Brittle Materials with Different Tensile-Compressive Response

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A micromechanics-based constitutive equation for brittle materials having different tensile-compressive response is developed. The material is modelled as a linear elastic isotropic matrix containing a distribution of plane microcracks growing in the loading process. As a consequence, the material response evolves from isotropy at the natural state to anisotropy in damaged states. Under the simplifying assumption of non-interacting and self-similar propagating cracks, the analysis builds on that of Gambarotta and Lagomarsino (1993, Int J Solids Structures 30, 177-198) who proposed a coupled damage-friction model based on two internal variables, representing damage and frictional contact tractions, as orientation fields. In the present paper it is shown how simplifying assumptions on the orientation fields permit a convenient description for damage and contact tractions in terms of two second-order tensors. The evolution equations of damage and sliding are deduced from damage and frictional limit conditions and corresponding flow rules. Thus, an anisotropic damage model exhibiting different response to tensile, compressive and mixed stress states is obtained. The constitutive equations are applied to analyse the material response to meaningful loading paths. Limit strength domains for biaxial and triaxial stress states are also derived in order to verify the validity of the model. Finally, the present model is shown to be a generalization of that previously developed by Brencich and Gambarotta (2001, Int J Solids Structures 38, 5865-5892), who made the assumption of isotropic damage and used a scalar representation as a measure of the average crack size.

Keywords: brittle materials, damage model, constitutive equations, limit strength domains.

A Physically Motivated Anisotropic Representation of Damage for Ductile Materials

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A phenomenological anisotropic damage formulation for ductile porous metals with second phase particles is described through mechanisms of void nucleation, growth and coalescence. The model is motivated from fracture mechanisms and microscale physical observations. The damage rate is decomposed into void nucleation, growth and coalescence rates. The void-crack nucleation rate is a second-rank tensor related to the plastic strain rate level, the energy release rate and several microstructural parameters (fracture toughness, length scale parameter, and size, volume and fraction of second phase particles). The void growth rate is based on the Rice and Tracey model which is isotropic and has an exponential function of the triaxiality. The coalescence rate is also second rank tensor governed by the plastic strain rate tensor

and the stress state. The coalescence threshold is related to the void length scale (intervoid distance and void size) for void impingement and void sheet mechanisms. The coupling of damage with the Bammann-Chiesa-Johnson (BCJ) rate-dependent plasticity model is written within a thermodynamic framework and derived from the concept of effective stress assuming the hypothesis of energy equivalence. Finally, experimental data of cast A356 and wrought 6061-T6 AL alloys are correlated with predictive void-crack evolution to illustrate the applicability of the anisotropic damage model.

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Damage Mechanics

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A solid matter is considered to be damaged when its ability to transfer is impaired and its reliability diminished by the presence of many microcracks randomly distributed within a structure. Damage can be attributed to manufacturing processes, stresses in the structure, temperature, corrosive effect of the environment, etc. As the new microcracks nucleate and existing microcracks propagate and from clusters the damage and the probability of structural failure increase. The models of damage mechanics are of continuum or micromechanical type. They can be statistical or deterministic. The newer models of damage mechanics are based on thermodynamics of irreversible processes and fracture mechanics. These models should provide data that be using in estimates of the reliability of aged aircraft and other damaged structures, comminution of rocks in mining, drilling through the rocks in oil exploration, design of shields and structures exposed to explosions and other deformation processes made of materials showing tendency to microcracking.

Analytical Solutions for the Cam Clay Model: Drained Loading and Comparisons

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Analytical solutions have been found for the three-invariant Cam clay model based on the infinitesimal strain theory. The solutions are given for volumetric and shear strains, and hardening moduli corresponding to drained loading. Two loading histories are discussed including the simple conventional triaxial and more realistic circular loading. The triaxial paths reflect the laboratory conditions. However, the circular paths capture the main features of the real field situations, such as plane strain or earthquake loading. The solutions are subsequently compared with previously found solutions for undrained loading (Peric and Ayari, in press).

Next, the solutions are compared between drained loading along few different effective stress paths and corresponding undrained loading. The comparison is presented in terms of shear strains, hardening moduli and deviatoric stiffness. The significance of these solutions lies in its simplicity elegance, the features that are the key to making the constitutive modeling more attractive to practicing engineers. In addition, they deem the in depth analytical study of the Cam clay model possible. Finally, the physical simplicity found its reflection in the mathematical simplicity of the Cam clay model.

PLASTICITY AND DAMAGE MECHANICS

In Honor of Professor Z. Mróz

SESSION W4O
Damage Mechanics II

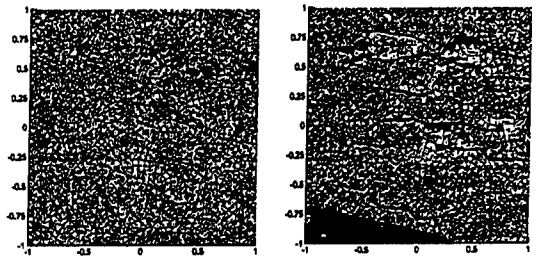
Extended Finite Elements for multiple crack growth

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A new numerical method is presented to study the growth of multiple cracks in the frame-work of linear fracture mechanics. The cracks are grown so that they remain at the critical stress intensity factor. An iterative algorithm is proposed to determine the new length of each crack. The method is coupled to a projection to the updated the crack length of each crach so that the sum of all crack growths is positive. The extended finite element method is used, which does not require any remeshing as the cracks grows. The crack geometry is arbitrary with respect to the mesh. Stress intensity factors and their derivatives are computed by the use of domain integrals. The method is applied to representative volume elements consisting of random and ordered arrays of cracks. The force deflection behavior of the representative volume element is obtained until the point of complete failure. An example of cracks

evolution is shown below: the left-hand shows the initial cracked specimen, the right shows the the final configuration.



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Modeling Impact Damage in Laminated Composites with High-Order Cohesive Zone Models

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Interface damage mechanics, or cohesive zone models, have been developed over the last decade as a method of modeling crack growth in a material or debonding between two different materials. These methods have alleviated many of the numerical problems inherent in crack modeling, including the large length scale difference between crack tips and crack areas, stress singularities, and the adaptation of crack propagation criteria to non-linear materials. Cohesive zone models can also predict crack initiation at any number of predetermined possible crack locations. However, researchers have also found that numerical instabilities in the solutions emerge if the finite element mesh is too coarse relative to the crack process radius. Consequently, these have been practical only for very small structures, on the order of tens of millimeters, without the use of supercomputers.

We will show that changing the order of numerical integration of the interface properties independently from their spatial discretization solves this convergence problem and in most cases decreases the total computation time, allowing for simulations of much larger structures. These results will be incorporated into our multi-lengthscale model for predicting impact damage in laminated composite plates.

Keywords: Delamination, cohesive zone models, composite laminates, impact

A Continuus Damage Mechanics Model for the Pre- and Post-Failure Behaviour of a Compactive Shell-Stone Used for the Restoration of the Zeus Temple in Olympia

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The mechanical behaviour of a compactive shellstone, the so-called conchyliates, is studied here. It was used for the construction of the most important monument of the early period of classic architecture in ancient Greece, the Zeus Temple in Olympia. Recently, an effort is undertaken aiming to the restoration of the monument, and as a first step the mecha-nical behaviour of the material is modeled here for both the pre- and the post-failure regime.

Based on a long series of compression tests it was observed that the load-displacement curve of the conchyliates shell-stone is characterized by either two or three distinct regimes: At small strains the material behaves almost linearly elastically. This region is terminated by an abrupt drop of the load that leads either to failure due to fragmentation of the specimens or to a third regime of deformation under almost constant external load (Fig.1).

In order to model the mechanical behaviour of conchyliates a recently introduced continuum damage mechanics theory for crushable materials is adopted [1], since the axial splitting failure mode observed experimentally, appears to be inc ompatible with the imposed boundary conditions of rigid, smooth and well-lubricated end platens. The necessity to adopt such an approach is further supported by the experimental observation that for brittle geomaterials the continuum mechanics concept of strain is not adequate for the description of the compression test and the stress-strain curve becomes meaningless after the peak load, [2]. The parameters of the model, and especially the ones describing the scaling effect of fragmentation are quantified based on a long series of compression tests using cylindrical specimens of constant height but

variable diameter. It was proved that the predictions of the theory are close enough to the experimental results.

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Effect of Particle Density on Fracture of Cementbased Composites: Lattice Analysis and Experiments

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At the meso-level individual aggregates are visible in a section of concrete. The aggregates appear to float in a matrix of cement paste. An interfacial zone with distinct properties surrounds the aggregates. A direct way of modelling fracture in such composites is by superimposing a lattice beam model on top of the material structure and assigning different properties to elements falling in the different phases of the material (in order of increasing strength and stiffness, the bond, matrix and aggregate phase). The method can be applied in 2- or 3-dimensions. Since 1D-beam elements are used in the lattice, a simple constitutive law is applied to simulate local fracture. With a local elastic-brittle failure law, global quasi-ductile response is obtained. The global ductility is however smaller than observed in experiments. In recent 2D and 3D analyses the effect of particle density on global fracture behaviour was investigated. In the model, always an interface zone of a single beam length surrounds the particles, and with varying particle density larger or smaller clusters of connected interface elements may appear. Below the percolation threshold of the bond beams, i.e. the particle density at which a connected cluster spanning the entire specimen is obtained, the stronger matrix beams govern fracturing under uniaxial tension. Above the percolation threshold the weaker bond elements govern the specimen behaviour. Now a lower strength is found.

Recently uniaxial tensile tests have been performed on small-scale concrete specimens containing various densities of glass-beads. The glass-beads were distributed according a Fuller distribution. The experiments show that the strength effect appears with varying particle content. Moreover, recent 3D analyses showed an increasing ductility in the dimensionless load-deformation diagram with increasing particle density. The same trend seems to appear in the tests as well. Further testing is currently carried out.

Load-Induced Oriented Damage and Anisotropy of Rock-Like Materials

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Theoretical model of mechanical behavior of brittle rock-like materials in the presence of an oriented damage of their internal structure is formulated and verified experimentally. This model is based on the assumption that a material response, represented by the strain tensor, can be described by means of the function of two tensorial variables: the stress tensor and the damage effect tensor that is responsible for the current state of the internal structure of the material. The explicit form of the respective nonlinear stress-strain relations that accounts for the appropriate damage evolution was obtained by employing the theory of tensor function representations. Oriented damage that grows in the material, described by the second order symmetric damage effect tensor, results in gradual development of the material anisotropy. This load-induced anisotropy of initially isotropic material was studied experimentally for uni-axially-compressed concrete and respective experimental data obtained were compared with the theoretical predictions. The validity of the theoretical model proposed was verified by using the available experimental results for various types of concrete subjected to the plane state of stress. The relevant experimental data for sandstone and concrete subjected to tri-axial state of stress were also used.

Keywords: damage mechanics, brittle materials, induced anisotropy, tensor functions.

PLASTICITY AND DAMAGE MECHANICS

In Honor of Professor Z. Mróz

SESSION R3O
Fracture Mechanics

On Thermoplastic Waves in Solids

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The mechanical and thermodynamic equations of inelastic solids contain more unknown functions than the number of such equations. For this reason further equations are needed which are called the constitutive equations. The form and variables of them are unknown, but all functions and their derivatives are possibly included which appear in the known equations. Suppose that the constitutive equations are partial differential equations the determination of which is based on the mechanical and thermodynamic behavior of solids. The following principal assumptions are set:

i) Discontinuity waves exist in the solid which propagates with a finite speed.
ii) The mechanical and thermodynamic processes are irreversible. The second law of thermodynamics is written as balance equation.
iii) Entropy production should be positive.

All the constitutive equations and the variables of them should satisfy the well-known consistency conditions of the literature. The results of the investigations are tried to be interpreted in one dimensional case.

Keywords: thermoplastic constitutive equations, discontinuity wave propagation

A Non-equilibrium Thermodynamics Model for the Crack Propagation Rate

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A non-equilibrium thermodynamics-based fracture model describes the influence of viscoplastic behavior at the crack tip on the non-steady, crack propagation rate and also recovers existing rate models for elastic materials. This model for crack propagation extends a non-equilibrium thermodynamics theory for thermoviscoplasticity [1]. The construction requires the choice of pairs of conjugate state and control variables. The crack length, l, and the force at the crack tip, G, are thermodynamic conjugate variables for fracture. The simplest possible viscoplastic model is one in which the state variables are the back stress, B, and the total strain. The applied stress and the back strain are the control variables. The values of the viscoplastic state variables during a process are described by evolution equations. The model also predicts the crack propagation rate, which is forced by a generalized affinity that drives the non-equilibrium response. The evolution equations are generated from a generalized energy function whose zero gradient manifold gives the initial unstable states or the long term stable states. The evolution is that which optimizes the generalized energy dissipation. In unstable propagation, l, is repelled from an initial unstable state. If the initial state is stable, then no growth occurs. This viewpoint is similar to that of nonlinear dynamics. The required relaxation modulus k for crack growth is proportional to the norm of the time rate of change of the plastic strain. In this model, the evolution of the internal state variables, B and l, is not derived from a dissipation potential separate from the energy, as in other thermodynamic models. No threshold values such as a yield stress or critical value of G are assumed.

Keywords: fracture mechanics, non-equilibrium thermodynamics, viscoplasticity, non-steady crack propagation

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Notch Plasticity Influence on Small Fatigue Crack Growth

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To study notch plasticity effect on small crack growth, the fatigue nucleation and crack growth rate characteristics of notched specimens of low strength aluminum alloy 5000 were examined and compared with un-notched specimen. Experimental shows that when a fatigue crack emanates from a plastically yielded field at notch root, its typical growth behavior is that the small fatigue crack first

decelerates with increasing crack length, and then accelerates. Similar trends were noted for un-notched specimens that had been subjected to the same applied loading, but crack growth rates is much slower in smooth specimens than in notched specimens when cracks are very small. Various mechanisms have been proposed to explain this special behavior of short cracks at notch, such as notch plasticity effect, and plasticity induced crack closure. They are still in debate on which is dominant in small crack growth within notch plastic field. Experimental findings and analytical results show that the notch plasticity can be of fundamental importance when a crack is close to notch root, while plasticity induced crack closure becomes dominant when the crack grows near notch plastic boundary. Plasticity effects on short fatigue crack growth is two-fold. First, it provides an additional driving force, local driving force other than applied driving force, ranging from notch root to the boundary between notch plastic and elastic field. Secondly, it produces an additional crack closure, a notch plasticity induced crack closure other than crack tip plasticity induced crack closure, which, in turn, changes effective driving force for small crack growth. force, local driving force other than applied driving force, ranging from notch root to the boundary between notch plastic and elastic field. Secondly, it produces an additional crack closure, a notch plasticity induced crack closure other than crack tip plasticity induced crack closure, which, in turn, changes effective driving force for small crack growth.

On Solder Mechanics

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This paper presents a series of most recent research works done by the author to explore the importance and extensive applications of solder mechanics to quality control and life prediction of electronic and communication products. Solder alloys have been widely used in electronic industries as "universal glue" served as the interconnection between various advanced electronic ICs and the printed circuit board. The reliability of solder joints has been intensively investigated in recent years. However, the aspects of solder mechanics have not been fully explored.

Both leaded and lead-free solders are very soft and show significant viscoplastic behaviors such as creep even at room temperature. The paradigm shift from separated constitutive modeling, traditional life prediction to unified constitutive modeling, and damage evolution-based life prediction has been critically reviewed, including the unified constitutive model with damage evolution developed by the author. However, algorithm development and numerical implementation of highly nonlinear unified constitutive models have been challenging. The author has developed a generalized return-mapping algorithm and implemented the algorithm for the developed viscoplastic constitutive model embedded into damage evolution and failure criteria as user subroutine in ABAQUS. The predictive power of the implementation has been explored by simulating the failure processes of solder joint fatigue and creep to predict both crack initiation and crack propagation. The failure characteristics have been validated by performed SEM failure analyses. The fatigue life contour and damage location under either thermal or mechanical loading have been illustrated, enabling by the implementation, which is not available in current ABAQUS code.

Another important issue is the statistical reliability of solder joints, which is related to warranty cost reduction, field return, accelerated testing, design correction, and process/quality control. First order reliability methodology has been developed by the author to bridge the deterministic and statistical approaches. The failure function and failure rate can be predicted with the parameter sensitivity analysis. Moreover, the reliability under multi-failure modes at both board and system levels has been addressed.

Surface Evolver has been extensively applied to the realistic shape prediction of various leaded and leadless solder joints. The integration of Surface Evolver with finite element technique will be presented. The material property characterization of tiny solder joints by a mini fatigue tester will be presented. Industrial practices and forces in reliability testing and database collection will be introduced.

This paper almost addresses all aspects of solder mechanics and introduces a fresh and potential research field to applied mechanics community.

Advance in Plasticity for Complex Loading Processes

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The majority of designs in engineering and building are working in the conditions of complex loading, cause ir-

reversible deformations also changes resulting to distraction. For more exact taking into accounts of materials properties, and of reserves of bearing capability of designs under plastic deformations, it is necessary to understand the essence of the processes occurred in a body and to learn how to take them into account. The realization of field tests are expensive and during these tests it is not always possible to determine the parameters of loading which with the design loses stability or collapses. However, if you will consider static problems in quasi-static statement you can solve plasticity problem more exactly. Naturally, you have to use new physical correlation of the plasticity theory included in problem's statement. Our task is creation on the experiments basis the constitutive relation between stresses and strains with using theory of processes. In practice are used more frequently the relations of the theories of plasticity based on the associated law of plasticity, in which the conception of simple and complex loading is not stipulated. However, such material's properties as trace of delay, local softening etc are significant and can change final calculation result of plasticity problem. Now impossible to find or build plasticity theory for all types of complex loading processes. However, for particular wide spread processes it is possible. In the submitted report the model of physical relations of the theory of plasticity for trajectories of mean curvature is offered. These trajectories occurred in majority plasticity problems as torsion of cores, plates loading etc.

Keywords: plasticity, complex loading, trajectory, process.

PLASTICITY AND DAMAGE MECHANICS

In Honor of Professor Z. Mróz

SESSION R4O
Composites Materials Behavior

The Plastic Anisotropy Ratio for Rolled Particulate Metal Matrix Composites

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Manufacturing processes induce plastic deformations and initially isotropic materials are transformed into orthotropic ones. The failure of such materials is conventionally described by Hill's criterion [1], which is expressed in terms of the anisotropy ratio R, i.e. the ratio of transverse to through thickness increments of logarithmic strain. According to Hill's criterion and taking into account the rotation of the orthotropy axes, inevitably accompanying the loading procedure [2], R as a function of the axial strain is expected to increase initially before it converges to a constant value. Such a behaviour was reported by Mellor [3], based on experimental results for various types of titanium alloys.

The procedure for the experimental determination of R is not yet standardized. In the present work and aiming at the quantification of R for the case of novel MMCs that are used extensively in aerospace applications, a technique similar to that introduced by Mellor [3] was adopted, as it is analytically described in ref. [4]. According to this procedure an auxiliary parameter r^p, i.e. the total width plastic strain over the total thickness plastic strain, is determined first by drawing the function $r = r(\epsilon\text{axial})$, ($r$ is the ratio of the total width to the total thickness strain) and then by subtracting the elastic strains from the total ones using the stress-strain diagram and the values of the elastic constants. The parameter r^p being known, R is determined numerically, with the aid of the following equation:

$$R = \frac{d\varepsilon_w^p}{d\varepsilon_t^p} = r^p + \varepsilon_t^p \frac{dr^p}{d\varepsilon_t^p}$$

Specimens were used made from 2124 Al-Cu MMC which is reinforced with $\sim$ 18% fine SiC particles of average diameter 3 μm, obtained by BP with the aid of a powder metallurgy process. The material was available in the form of plates of average thickness 12 mm, which were obtained from the initial isotropic material with the aid of successive rolling processes. The experience gathered from the present series of experiments fails to support the above conclusions concerning the dependence of R on the axial strain for the whole regime of specimens orientation: Indeed for specimens oriented either parallel (0-class) or perpendicular (90-class) to the rolling direction, after a transient region in which the sensitivity of the quantity measured yields strong fluctuations, the values of R converge to a constant value, as it can be seen in Fig.1, in which R is plotted versus the axial plastic strain. On the contrary, and for specimens cut and loaded at direction forming an angle of 45° degrees with respect to the rolling direction R appears to depend, strongly on the level of the applied strain, for the whole range of axial plastic strain (Fig.1).

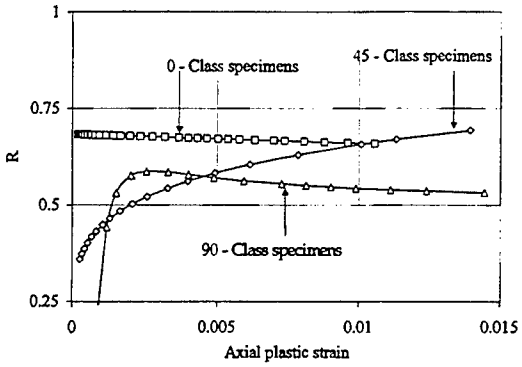


Fig. 1: The anisotropy ratio R as a function of the axial plastic strain

Such a conclusion supports the respective ones drawn by Dafalias [5] and Loret [6] concerning the orthotropic re-orientation. According to them in case orthotropic sheet metals are loaded in-plane at fixed directions different from those of orthotropic axes the preservation of symmetry and the constancy of the orthotropic axes are not a-priori given. Similar conclusions were recently drawn by Kim and Yin [7] for rolled steel specimens. They found out that the orientations of the orthotropy axes change within a few percent of the tensile strain and with the progress of the tensile strain they are aligned along the tensile loading- and the transverse direction

Taking into account the above experimental results, it is concluded that the prediction of the failure of MMCs cannot be realized within the framework of Hill's anisotropic criterion either because the assumption of constant values of the various parameters is violated or because the assumption that the yield surface evolves in a self-similar manner is not satisfactory in case of particulate reinforced materials.

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On the Moisture Sorption of Composites

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It has been experienced that in case of composites both the moisture absorption and desorption show a certain but significant hysteresis [1]. There are several possible explanations of this feature, e.g. one of them is the microcracking.

An other one could be the following. Most of the authors dealing with theoretical investigations, [2], handle the problem on the basis of the moisture diffusion neglecting the cross-coupling between heat and moisture (Soret and Dufour effects) and the coupling between diffusion and convection [3]. It can be supposed that taking into account all of these phenomena, including the changing geometry as a result of cracking, a better description can be achieved that includes also the feature of hysteresis.

The sorption process in case of immersed composite is very slow, that is why in average cases the cross-coupling between moisture and heat can be neglected. For the same reason we may leave aside the problem of second sound phenomenon and as a first approach we apply the Fick's Law. Of course, in the future the non-Fickian feature could be built into the model.

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Strengthening Mechanisms in Ti-6Al-4V/TiC Ccomposites

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The mechanisms responsible for a strength increase greater than 20% with as little as 1vol%TiC were investigated for the first time in this study of Ti-6Al-4V/TiC particulate composites. Ti-6Al-4V/TiC composites were characterized at strain rates between 0.1 s-1 and 1000 s-1 and over volume fractions ranging from 1 to 20vol%TiC. While only 1vol%TiC provided a significant increase in the yield strength, subsequent additions did not provide proportional benefit. Microscopy (optical, SEM, TEM) aided in assessing the contribution of matrix-strengthening mechanisms such as grain size and subgrain size refinement and an increase in dislocation density, mechanisms typically important to the strength metal matrix composites. Two other important mechanisms are thermal mismatch strains and load transfer from the matrix to the particle; the strength of each of these mechanisms was evaluated using the Eshelby approach. A quantitative comparison of the contribution of each of the mechanisms listed, clearly showed that none of them was responsible for the large increase in strength with only 1vol%TiC in Ti-6Al-4V. The results from this study show for the first time that carbon in solution is the most potent strengthening mechanism in the Ti-6Al-4V/TiC particulate composites. The composites followed the same strain rate dependence and hardening behavior as the monolithic Ti-6Al-4V suggesting that similar deformation mechanisms were operating. Composites tested at high strain rates failed by fracture along adiabatic shear bands; adiabatic shear bands formed more readily in the matrix of the composite as compared to the monolithic material.

Short-term Mechanical Behavior of Biaxially Stressed Wood: Experimental Observations and Constitutive Modeling as Orthotropic Multi-Surface Elasto-Plastic Material

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From the mechanical point of view wood exhibits a pronounced orthotropic behavior with large ratios of mechanical properties such as Young's modulus or strength between the respective values parallel and transverse to the grain direction. Furthermore, it is well known that strength differs in tension and compression. Though a good amount of testing has been done for uniaxial states of stress, surprisingly little was known on the general effect of multiaxial states of stress on strength until the early 1990s. Since then, biaxial experiments by Eberhardsteiner et al. ([1] and references therein) on clear spruce wood have been performed in order to obtain the failure envelope in the LR-plane[1] of clear spruce wood.

The most common model for the mathematical description of yield surfaces and failure surfaces of anisotropic materials is the elliptic failure surface after Tsai & Wu. Applying it to the experimentally obtained failure locations for spruce wood gives a reasonably good fit for the failure locations. Nevertheless, expecting linear or nonlinear elastic behavior in the pre-failure domain proves to be an insufficient representation of the mechanical behavior. As long as the material undergoes states of stress with tension perpendicular to the grain, the material actually is linear elastic. As compression perpendicular to grain occurs, a nonlinear stress path results from a proportional biaxial strain path.

Investigation of a characteristic sample with respect to loading-unloading-reloading cycles for states of stress below failure reveals behavior similar to what is known as *hardening type plasticity*. Based on a micromechanical investigation this plastic phenomenon can be explained by crushing of whole rows of cells within the wooden structure. At the microscopic level, these inelastic deformation occur in a localized manner. Nonetheless, due to the repeating microstructure caused by wood growth in annual ring patterns the phenomenon appears to be homogeneous at the experimentally investigated length scale.

Thus the experimentally observed mechanical behavior at the macroscale can be described by means of a multi-surface plasticity model addressing both failure and nonlinear stress response below failure as separate mechanisms. Prediction of failure will be performed by means

of a second-order failure envelope according to Tsai & Wu . The nonlinear stress response due to radial compression has to be covered by an orthotropic hardening type plasticity model.

Keywords: Orthotropic material, Wood, Radial Compression, Failure Envelope

[1] Eberhardsteiner, J.: Mechanisches Verhalten von Fichtenholz *Experimentelle Bestimmung der biaxialen Festigkeitseigenschaften*, Springer, 2002

[1] Following common denomination, L is the *longitudinal or grain* direction, R is the *radial* direction, and T is the *tangential* direction within the stem of a tree.

Micromechanical Modeling of Particle-Debonding Process and its Influence on the Effective Elastoplastic Behavior of Composites

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A micromechanical damage model is developed to predict the effective elastoplastic behavior and damage evolution in metal matrix composites containing randomly located spherical particles with interfacial debonding. Based on recent study by the authors, the ensemble-volume averaged homogenization procedure is employed to estimate the effective yield criterion of the said composites. The interfacial debonding initiation is determined by the local stress criterion and its growth is controlled by the arch lengths of interfacial cracks. Pair-wise particle interactions are taken into consideration. During the homogenization procedure, those debonded particles are replaced by "equivalent" anisotropic inclusions. While the whole debonding processes are simulated in terms of micromechanics framework, the evolution of overall volume fraction of debonded reinforcement is phenomenologically assumed to follow the Weibull's statistical theory. The proposed model is suitable for general three-dimensional loading conditions.

Symposium on

Continuum Mechanics and Thermodynamics

In Honor Of
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CONTINUUM MECHANICS AND THERMODYNAMICS

In Honor Of Professor Dr. Ingo Müller

SESSION W4N
Opening Session

Thermodynamics of Granular Gases

G. Capriz and G. Mullenger

Granular gases are, as are molecular gases, dilute granular systems in which the mean free path of the grains is much larger than the grain size. However, for them, collisions occur dissipatively [1]. Thus, formally, the balance equations, generally accepted, are very similar to those of extended thermodynamics, but dissipativity requires radically different constitutive relations. Concepts of granular heat and granular temperature are convenient, though their current definitions implies dependence on the observer and such dependence may be not not irrelevant here because peculiar velocities, contrary to what happens in molecular gases, may be of the same order of magnitude as the mean velocity; an 'objective' definition is required. Besides, grains may need to be gathered in families with approximately the same Reynolds tensor (rather than the same kinetic energy); thus a concept of tensorial temperature (the so called 'triaxial approach') may be of the essence. We discuss these matters and propose a possible approach.

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Transformation and Disintegration of Strongly Nonlinear Internal Waves by Topography in Stratified Lakes

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For many lakes the nonlinear transfer of energy from basin-scale internal waves to short-period motions like solitary internal waves (SIW) and wave trains, their successive interaction with lake boundaries, overturning and breaking are important mechanisms for an enhanced mixing of the turbulent benthic boundary layer. In the present paper the evolution of plane SIWs in a variable depth channel typical of a lake of variable depth is considered, the basis being the Reynolds equations. The vertical fluid stratification, wave amplitudes and bottom parameters are taken close to those observed in Lake Constance, a typical mountains lake. The problem is solved numerically.

Three different scenarios of a wave evolution over variable bottom topography are examined. It is found that the basic parameter controlling the mechanism of wave evolution is the ratio δ of the wave amplitude to the distance from the metalimnion to the bottom. In sites with a gentle sloping bottom where δ is small, propagating (weak or strong) internal waves adjust to the local ambient conditions and preserve their form. No secondary waves or wave trains arise during wave propagation from the deep part to the shallow water.

If the amplitude of the propagating waves is comparable with the distance between the metalimnion and the top of the underwater obstacle ($\delta \sim 1$), nonlinear dispersion plays a key role. A wave approaching the bottom feature splits into a sequence of secondary waves (solitary internal waves and attached oscillating wave tail). The energy of the SIWs above the underwater obstacle is transmitted in parts from the first baroclinic mode, to the higher modes. Most crucially, when the internal wave propagates from the deep part of a basin to the shallow boundary, a breaking event can arise. The cumulative effects of the nonlinearity lead to a steepening and overturning of the rear wave face over the inclined bottom and to the formation of an turbulent jet propagating upslope. Some time later, after the breaking event, a new stable stratification is formed at the site of wave destruction. The breaking criterion of ISWs is discussed.

A New Continuum Model of Crystals Incorporating Microscopic Thermal Vibration

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First, continuum-mechanical model of crystals incorporating microscopic thermal vibration is proposed. The model is derived by considering the continuum approximation of a nonequilibrium statistical-mechanical lattice model. By using the model, mechanical and thermal properties of crystals can be studied in a unified way. The model is valid in a wide temperature range including the melting point.

Second, as an application of the model, mechanical and thermal properties of waves propagating in crystals at finite temperatures are studied. Temperature dependences of the propagation velocity and amplitude ratios of several physical quantities are explicitly derived. Singular behavior of the wave propagation phenomena near the melting point is found, and its physical implication is discussed. Some of the results obtained are compared with experimental data.

A New Phenomenological Model for Stress-Softening in Elastomers

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A new phenomenological model for stress-softening of isotropic, incompressible hyperelastic rubberlike materials reported recently by Zúñiga and Beatty [1] is presented. For any specified virgin material constitutive equation, the stress-softened material response due to microstructural damage is characterized by an exponential softening function that depends on the current magnitude of strain and its maximum previous value in a deformation of the virgin material. The theory is illustrated for a neo-Hookean material; and it is shown that results derived for two non-Gaussian molecular network material models compare most favorably with uniaxial extension data provided by others.

Keywords: Mullins effect, stress-softening, elastomers, non-Gaussian molecular networks

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CONTINUUM MECHANICS AND THERMODYNAMICS

In Honor Of Professor Dr. Ingo Müller

SESSION R2B

Extended Thermodynamics/Kinetic Theory I

Grad's Moment Equations for Microscale Flows

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In the microscale flow regime, distinguished by large Knudsen numbers but relatively small Mach numbers, the behavior of a gas cannot be described by the Navier-Stokes-Fourier theory satisfactorily. While the growing interest in the simulation of microscopic gas flows has revived the interest in higher order expansions of the Boltzmann equation, e.g. Hilbert expansions , or the Burnett equations, Grad's moment equations only play a marginal role for the modeling of microscale flows. This is mostly due to the problem of assigning meaningful boundary values to higher moments. Despite this problem, there are two important reasons in favor of the Grad equations:

i.) The well-known set of 13 moment equations contains the Burnett equations, as can be seen by a second order expansion of the 13 moment equations in terms of the Knudsen number. While the Burnett equations are ill-posed (sometimes they are augmented in order to overcome this deficiency), the Grad equations are well-posed for all values of the moments which are physically meaningful . Moreover, they contain traces of all higher order contributions in the Knudsen number, a fact that might be an additional advantage.

ii.) The 13 moment equations as well as Hilbert expansions and Burnett equations cannot resolve the Knudsen boundary layer at the wall - jump and slip boundary conditions must account for Knudsen layer effects . Theories with extended sets of moments, however, are capable of describing the main features of the Knudsen layer. Since for channel flow with Knudsen numbers above 0.1 the Knudsen layer extends over the whole channel width, theories with more than 13 moments can be expected to give a more accurate description.

We shall consider various sets of moment equations (up to 48 moments in the one-dimensional case) for plane Couette flow and one-dimensional heat transfer in order to show the usefulness as well as the limitations of Grad's moment equations for microscale flows. In particular, we shall discuss the method of kinetic schemes and Grad's approach to the problem of boundary conditions.

Our results will show that approaches with increasing moment number allow for the resolution of finer details of the Knudsen layer. E.g. a theory with 26 moments gives a general description of the Knudsen layer, but fails in the description of a smaller layer (sub-Knudsen layer) at the wall, which, however, is captured when the number of moments is increased. Proper slip and jump boundary conditions for the sub-Knudsen layer would render the 26-moment equations in a useful tool for the simulation of micro-scale flows.

On the Determination of Unconventional Physical Boundary Conditions for Systems of Moment Equations

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Extended thermodynamics of moment systems provides a more realistic description of ideal gases than the conventional Navier-Stokes-Fourier theory. However, the presence of higher order moments in the theory presents an additional problem regarding the specification of their boundary values. Since solutions of boundary value problems will generally depend on such boundary data, arbitrary prescriptions of such unconventional data may lead to solutions which lost the physical significance as compared to the solutions of the corresponding problems in the conventional theory. In order to establish a criterion for the determination of such boundary data, we propose an iterative scheme, akin to the Maxwellian iteration, so that it optimizes the solution as the best approximation of the conventional theory.

Elliptic Type Second Order Quasilinear Partial Differential Equations for Stationary State Irreversible Heat Conduction Process and Their Divergency

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Non linear elliptic type second order partial differential equations were analyzed to stationary state heat conduction process with the aid of minimum principles. Investigations made for Onsager and Prigogine principles showed the deciding role of local dissipation potentials. The existence of these potentials is basically a crucial point for real processes.

The new quasilinear elliptic type pdes of second order are in total agreement with Gyarmati s integral principle for stationary state too. Treating the above questions must be applied the proper Lagrange densities and the Euler-Lagrange differential equations in the different representational pictures (to treat the variational problem).

Irreversible processes mean entropy production or simply energy dissipation. This is true for stationary states too. The Laplace s equation for heat conduction process in stationary state as an elliptic linear second order pde does not express any energy dissipation in the conservative potential field according to the minimum principles.

On the base of the new equations (one for the principle of minimum production of entropy, the other for the least dissipation of energy) one can find connecting equations between the internal energy and the entropy (entropy production!) considering the stationary state irreversible process with minimum principles. Due to the open system entropy conpensation plays an important role.

With the aid of the basic integral Green s formulas and the Gauss-Ostrogradsky formula the potential field of conservative type and the dissipative field of irreversible type can be distinguished in the above discussed cases.

An interesting and characterising feature of the stationary state heat conduction process analized with the minimum principles: Harmonic functions cannot serve as solutions for the irreversible process (for the new quasilinear second order pdes) while the max-min principle is valid.

Boundary conditions also were taken into consideration (Dirichlet and Neumann types) and discussion with heat reservoirs helps to exposure the questions on the classical thermoynamic level too.

Questions on the philosophy of science with the aid of Karl Popper s "falsification method and criterion" were discussed too regarding the new quasilinear pdes and the Laplace s pde, respectively.

Light Scattering from Extended ThermodynamicModel Equations: Binary Mon-atomic Gas Mixtures and Dense Gases

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The study of light scattering in fluids is an interesting problem within the viewpoint of theoretical physics, since it deals with a combination of well-established theories, namely: electromagnetic theory, thermodynamic theory, fluctuation theory and kinetic theory of gases.

It is well know that for liquids the balance equations of continuum mechanics supplemented by the constitutive equations of a viscous and heat conducting fluid - Navier-Stokes and Fourier laws - can describe very well the light scattering experimental data that consists of a central Rayleigh peak and two Brillouin peaks shifted symmetrically about the origin. For gases, this aim is more difficult since we have to distiguish two main regimes: the hydrodynamic regime where the continuum description holds and the so-called kinetic regime where one has to rely on the Boltzmann equation or to use the field equations of extended thermodynamic theory.

Weiss studied the light scattering problem in the kinetic regime within the framework of extended thermodynamics and showed that a good agreement between the theoretical and the experimental spectra for monatomic ideal gases could be achieved by using up to 120 field variables. Recently, we have shown for monatomic gases that a kinetic model of the Boltzmann equation compatible with Grad's 35-moment approximation can be used to describe the light scattering experimental data not only in the hydrodynamic regime but also in the kinetic regime.

The use of an extended thermodynamic theory to study the influence of the interparticle potential function on the light scattering spectra in binary mixtures of monatomic gases with disparate masses was done by one of us who developed a 26-field theory of partial mass densities, partial velocities, partial temperatures, partial pressure deviators and partial heat fluxes.

In the literature of light scattering process one can also find experimental data for dense gases, and theoretical descriptions based on Enskog's dense gas model that take into account the Burnett equations and the 13-moment method.

In this work, the main objectives are the following: (i) to analyze how the light scattering spectra in binary mixtures of monatomic ideal gases behave by changing the molar fraction of one of the constituents, and (ii) to study the dependence of the light scattering spectra on the number density in dense gases. To that end, we shall use in

the first case a model equation of the Boltzmann equation which for binary mixtures is defined in terms of 28 moments of the distribution function. This model equation is an extension of the McCormack model, since the 26 moments described above are supplemented with the partial full traces of the four-order moments. In the second case, we extend the kinetic model equation proposed by Liu, which is valid for ideal gases, to dense gases. As in the model equation of Liu the reference distribution function is a function of the gradients of velocity and temperature.

It is shown for binary mixture with disparate masses - like the Helium-Xenon mixture - that the light scattering spectrum changes from the hydrodyanmic regime to the kinetic regime by increasing the molar farction of the lighter constituent, while for dense gases a good agreement between the theoretical and experimental light scattering spectra is found for values of the pressure going from 0.022 atm to 10 atm.

Dynamics of Small Bodies in a Nonhomogeneous Gas

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The phenomen of thermophoresis is well known. In a gas with a temperature gradient, a small body will be acted on by a force in the direction opposite to the temperature gradient. If there are many such small bodies, there will be a transport of them in that direction.

The cause of thermophoresis is that the distribution function deviates from a local Maxwellian when the temperature is nonuniform. There are however two basic modes of deviation from a Maxwellian. The other mode is caused by shearing. How does shearing act on a small body?

The many studies of thermophoresis are in most cases for spherically symmetric particles. Shearing has basically no e.ect on spherically symmetric particles. For that reason we consider axially symmetric particles in a shearing gas.

First of all we find that shearing will give rise to a net energy transport to such a small particle. This means that the particle, under stationary conditions, will take on a temperature which is di.erent from that of the surrounding gas. The temperature depends on the orientation of the small body with respect to the shearing.

Secondly, we study the force acting on such a particle and we find that it is non-zero if the particle is asymmetric with respect to the plane through its center of mass orthogonal to the axis of symmetry. Consequences of this e.ect are studied.

This is work partly together with my graduate student Karl I. Borg.

CONTINUUM MECHANICS AND THERMODYNAMICS

In Honor Of Professor Dr. Ingo Müller

SESSION R3B
Shape Memory Alloys I - Theory

Fatigue of NiTi Shape Memory Alloys

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The degradation of NiTi shape memory alloys due to repeated cycling represents a serious roadblock to the performance of macro and micro scale actuators. The purpose of the present talk is to show new results on the cyclic deformation of NiTi with emphasis on the effect of microstructure. We will examine the effects of single crystal orientation, texture, and precipitate size on the overall cyclic response and local deformation mechanisms. The results indicate that crystallographic orientation has a first order effect on the degradation of NiTi shape memory alloys subjected to cyclic loading. TEM observations indicate that, depending on heat treatment, the microstructural mechanism responsible for evolution of the stress-strain response can be dislocation activity or stabilization of martensite. Although optimal heat treatments for preventing cyclic degradation have been suggested in the past, it is shown that tailoring crystallographic orientation is a much more effective means to optimize fatigue response.

Molecular-Dynamics of a 2D Model of the Austenite-Martensite Phase Transition

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A 2-dimensional molecular-dynamic model is presented for the investigation of crytalline phase transitions. The model is based on the classical equations of motion, and potential functions of the Lennard-Jones type are employed. By use of two types of particles a stable square crystalline lattice may be created. This lattice may transform into sheared variants under the influence of external loads or under a change of the temperature of the body. The transformation is interpreted as an

austenitic-martensitic phase transition. Three molecular dynamic experiments are presented on a display screen: Two temperature-induced phase transitions – for 85 particles and for 230 particles – and one load-induced phase transition for 85 particles. It turns out that these numerical experiments exhibit important characteristics known from shape memory alloys.

Dynamic Loading of Polycrystalline Shape Memory Alloy Rods

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Shape Memory Alloys (SMA) have recently been considered for applications where dynamic loading is applied. An SMA body subjected to external dynamic loading will experience large inelastic deformations that will propagate through the body as phase transformation fronts. We study the phase transformation propagation in a semi-infinite 1-D SMA rod induced by an impact loading. Some applications of this model problem include energy absorbing and vibration damping devices. The constitutive model being used is the one by Lagoudas, Bo and Qidwai. We employ an adaptive Finite Element Method (FEM) based on the Zienkiewicz-Zhu error estimator to solve the problem numerically. A model problem featuring a square pulse propagating through the rod is solved and comparisons are made to finite difference schemes of the Lax-Friedrichs type as well as to known analytical studies. The energy dissipation capabilities of SMA materials are investigated for the model problem. We then present experimental results for wave propagation in SMA rods. A split Hopkinson apparatus was used to make a uniaxial test of a NiTi specimen. The readings from the strain gauges were compared with numerical calculations using the adaptive FEM technique.

Keywords: Shape Memory Alloy, Dynamic Analysis, Adaptive FEM, Hopkinson Bar

The Evolution of Phase Transformation Fronts During Uniaxial Cyclic Deformation in Pseudoelastic NiTi

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An experimental study on the response of NiTi wire during cyclic uniaxial extension is presented. The response is analyzed for a range of ambient temperatures in the material's pseudoelastic regime. A specialized thermo-mechanical testing apparatus is used in conjunction with full field infrared imaging and laser extensometry to track the evolving transformation fronts. The results show that the local mechanical behavior is highly dependent on the front nucleation and coalescence history, as well as the ambient temperature and number of transformation cycles. Thus, the particular training procedure (cyclic shakedown) used is likely to have important implications on the material's subsequent global mechanical response, repeatability, controllability, and fatigue resistance.

Fracture of Shape Memory CuAlNi Single Crystals

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The fracture behavior of a shape memory CuAlNi single crystal loaded in tension is studied. Specimens of the single crystal are notched and loaded in tension until final fracture. Eight different crystallographic orientations of the notch and tensile axes are considered. The stress field at the notch tip triggers a cubic to orthorhombic phase transition in the crystal, which results in a set of twinned martensite plates emanating from the notch tip. As loading increases, a crack forms and grows off the notch tip, with the martensite plates continuing to appear at the growing crack. The formation of martensite and the size of the transformation zone are strongly tied to the details of crack growth. Further, in all specimens studied, the final crack direction is approximately 80° from the direction of the martensite plates.

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CONTINUUM MECHANICS AND THERMODYNAMICS

In Honor Of Professor Dr. Ingo Müller

SESSION R4B
Application of Thermodynamics

Econophysics: Calculations of Income Distributions: Cobb Douglas and (log) Normal vs. Boltzmann

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US and German income data were analyzed according to the Cobb Douglas production function, the normal and log normal distribution and the Boltzmann Lagrange function. The Lorenz distribution, the distributions of people per wage class N(w) and the income per wage class $K(w) = wN(w)$, as used for taxation, were fitted by the different models. The data of the Lorenz distribution were reproduced equally well by all functions. However, the distributions of people per wage class N(w) and of income K(w) clearly show, that income is distributed by a Boltzmann function and not a Cobb Douglas or (log) normal function.

This result has important consequences: income, economics and business cannot be calculated by a Cobb Douglas function, but are based on the stochastic laws of entropy as given by Lagrange and Boltzmann. Economic cycles like production and consumption are determined by a Carnot process, business runs like a motor. The $T - S$ diagram determines efficiency and stability of a company.

Systems of Balance Laws with a Convex Extension

Tommaso Ruggeri

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We give a survey of the consequences of an entropy principle associated with a general system of hyperbolic balance laws. We discuss, in particular, the importance of the main field - for which the original system assumes the symmetric form - in order to recognize the nesting theories, the equilibrium manifold and the asymptotic behaviour of the solutions for large time. Some applications are presented with particular attention to the Extended Thermodynamics.

Effect of Density Gradients of a Binary Solution on its Phase Diagrams

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For a solution or alloy under phase transition, a large number of phase regions can exist. The densities of the components of the mixture are approximately constant within each region and are generally different in different regions. As a result, the densities will change drastically near the interface of two-phase regions. Refering back to van der Waals, one may take the interface energy into account by adding the terms related to the density gradients, $|\nabla\rho_\alpha|^2$, into the total energy. Such gradient terms will affect not only the dynamic behaviour of the phase transition process of a solution, as considered in phase field models, but also the phase equilibrium. Thus they will change the phase diagrams.

Consider a binary solution in a container with height H and identical cross sections, the total Helmholtz free energy of the mixture is assumed to be given as

$$E = \int_0^H \left\{ w(\rho_1,\rho_2) + \frac{\varepsilon_1^2}{2}|\nabla\rho_1|^2 + \frac{\varepsilon_2^2}{2}|\nabla\rho_2|^2 + \frac{\gamma_1^2}{2}|u_1 - u_1^\circ|^2 + \frac{\gamma_2^2}{2}|u_2 - u_2^\circ|^2 \right\} dh.$$

$w(\rho_1,\rho_2)$ is a double well potential with ρ_1 and ρ_2 as mole densities of the two constituents of the solution. $u_{1,2}(h) := \int_0^h \rho_{1,2}(h)dh$ and $u_{1,2}^\circ := \int_0^h \rho_{1,2}^\circ(h)dh$ are the mole numbers of the two constituents in $[0,h]$. $\rho_{1,2}^\circ = n_{1,2}/H$ are the homogeneous distributions of the constituents with $n_{1,2}$ total mole numbers in the container.

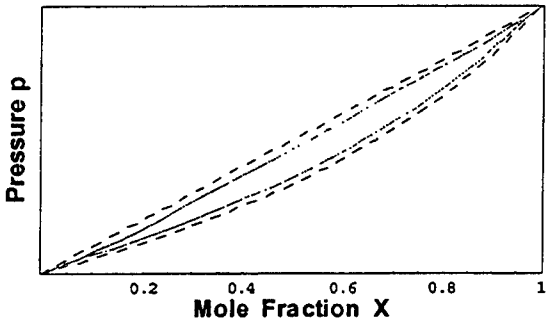
Minimization of the total energy E under the constraints: $\int_0^H \rho_{1,2}(h)dh = n_{1,2}$ for small values of the coefficients $\varepsilon_{1,2}$ and $\gamma_{1,2}$ leads to the following phase equi-

librium conditions between phase A and B:

$$N = N_0[z(1-z)]^{2/3},$$
$$p^A = p + \tfrac{2}{3}A[1-z)^2/z]^{1/3},$$
$$p^B = p + \tfrac{2}{3}A[z^2/(1-z)]^{1/3},$$
$$\frac{\partial g^A(T,p^A,X_A)}{\partial X_A} = \frac{\partial g^B(T,p^B,X_B)}{\partial X_B} = \frac{g^A(T,p^A,X_A) - g^B(T,p^B,X_B)}{X_A - X_B}.$$

z is the volume fraction of the phase A. N is the number of interfaces. p is the external pressure and T is the absolute temperature. $g^{A,B}$ are the Gibbs free energy of the mixture in phase A and B, respectively with $p^{A,B}$ the effective pressures and $X_{A,B}$ the mole fractions.

Phase diagrams can be constructed from the above phase equilibrium conditions, as shown in the following figure. The dashed lines represent the $p - X$ phase diagram without the interface energy and the solid lines are the phase equilibrium lines with interface energy.



Keywords: Phase diagram, Interface energy, Solutions, Energy minmization

Distance to Blow-up of Acceleration Waves in Random Media

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Effects of material spatial randomness on the behavior of acceleration waves were studied in [1,2]. The medium's randomness was introduced by taking two material coefficients mu and beta - that represent the dissipation and elastic nonlinearity, respectively, in the governing Bernoulli equation - as a stochastic vector process. Several types of such processes were considered. While the previous studies analyzed the effects of randomness on the critical amplitude, in the present paper we look at the distance to blow-up of acceleration waves, x*, in random media. The analysis involves a stochastic Bernoulli equation driven by mu and beta. Quantitative results are obtained by the method of moments in special simple cases, and otherwise by the method of maximum entropy. We find that the effect of even very weak random perturbation in mu and beta may be very significant on x*. In particular, the full negative cross-correlation between mu and beta results in the strongest scatter of x* and hence, in the largest probability of shock formation in a given distance x.

[1] M. Ostoja-Starzewski, "On the critical amplitudes of acceleration wave to shock wave transition in white-noise random media," *J. Appl. Math. Phys.* (ZAMP), 44, 865-879, 1993.

[2] M. Ostoja-Starzewski and J. Trebicki, "On the growth and decay of acceleration waves in random media," *Proc. R. Soc. Lond.* A 455, 2577-2614, 1999.

Modeling of Temperature Effects in Macro Fiber Composite Actuators

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Macro Fiber Composites (MFC) form a relatively new actuation device consisting of fibers of piezoceramic material embedded in a polymer and arranged with interdigitated electrodes. Such actuators offer distinct advantages over conventional monolithic actuators in both flexibility and electromechanical coupling. Here we report on the manufacturing, and mechanics modeling of such devices and in particular focus on extending our modeling to include temperature effects. The composition of piezoceramic, metallic leads and polymer matrix are smeared into a single temperature effect. Results will focus on the effect of temperature changes in the actuation properties of an MFC actuator.

CONTINUUM MECHANICS AND THERMODYNAMICS

In Honor Of Professor Dr. Ingo Müller

SESSION F2B
Shape Meomry Alloys II - Applications

Optimal Control of Microscale SMA Actuators

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Standard engineering control techniques fail for materials exhibiting non-linear hysteretic behavior. A typical application is encountered with, e.g., microscale SMA actuators, allowing for extremely high driving frequencies. The problem can be overcome by introducing a model-based control algorithm, which is able to compensate for the non-linear effects. The paper studies the application of an optimal control method employing an extended version of the SMA model originally developed by Mueller and Achenbach. This method allows for optimality criteria such as maximal adjustment speed and minimal energy consumption to be taken into account, while at the same time compensating for the material non-linearities. Several cases of different set points for the actuator stroke are treated.

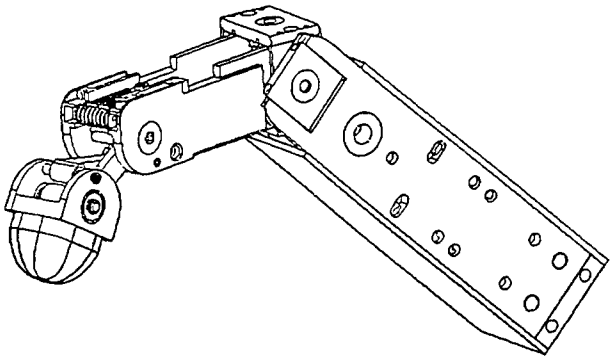
Development of an Artificial Finger Powered by Shape Memory Alloys

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Prestrained shape memory alloys change their length when heated above their transformation temperature. This effect can be used to generate high forces in a small workspace, which has particular advantages in actuator design. By now, there exist comparably few actuators based on shape memory alloys (SMA). Most of the publications deal with simple setups. The aim of the work is to examine the capabilities of shape memory alloys. A finger in the size of a human one has been chosen as an example for a comparably compact setup. All actuators are based on commercial shape memory alloy wires.

Different designs have been developed, which account for the restriction of a compact setup. Parallel to this, experiments have been performed to proof the functionality and to improve specific elements like the fixation of the shape memory alloys. The optimization and control of the actuator are based on a comprehensive simulation of the material behavior as the main element of the actuator model. Therefore, a material model for shape memory alloys from Seelecke (1999) is examined. This model describes the behavior of a one-dimensional infinite shape memory alloy, which is heated by electric current. It is employed in a simulation program to investigate and design an actuator based on shape memory alloys.



CAD-model of the robotic finger

In order to verify the model and to identify the material parameters an experimental setup has been developed, which allows to measure relevant material characteristics like temperature-deformation diagrams. The parameters of the simulation are fitted to the experimental results. Furthermore, two wires with different shapes are compared to each other. Finally, experimental results with the realized robotic finger are presented.

[1] S. Seelecke: Simulation and Control of SMA Actuators, Proceedings of the 6th SPIE Conference on Smart Structures and Materials, 3667, Newport Beach, USA, 1-5 March 1999

Keywords: Finger, Shape memory alloy, Actuator, Robotic

New Applications for Shape Memory Alloys in the Conservation of Cultural Heritage

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In the last years an increasing interest for the conservation of the cultural heritage has produced a growing demand of reliable tools for restoration. In this paper we want to describe the first results of a research project having the goal to realize new types of anchorages by means of shape memory alloys, for applications in the field of restoration of art works as mosaics, frescoes and statues.

In the first part, a brief description will be given about the principal real problems a restorer comes across as, for example, the frequent presence under the surface of a parietal mosaic of several detachments between the layers of plaster coats.

Then, it will be summarized the preparation of some different prototypes of devices with shape memory alloys, constituted by suitable spikes and working in particular temperature ranges.

Finally, the principal tests until now realized, both in laboratory and on the field, will be discussed, in order to verify the advantages of this new device with respect to other usual anchorages and set up a clear procedure that a trained restorer can easily apply.

Instabilities of a Two-bar System with Shape Memory Alloys

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The behavior of a von Mises two-bar truss provides an interesting area of study due to its nonlinear kinematics. Coupling this system with the highly nonlinear and hysteretic constitutive behavior of shape memory alloy bars deepens the richness of the study. A previous investigation of such a system assumed a polynomial constitutive model based on Landau's theory to represent the shape memory alloy [Savi et al., "Chaos in a Shape Memory Two-Bar Truss," International Journal of Non-Linear Mechanics, in press]. However, under deformation control, which is the relevant case in a dynamic application, this model does not predict the hysteresis-induced damping correctly. The current study uses a more realistic and physically meaningful model to describe the stress-strain relation for the shape memory alloy bars. This model implicitly provides damping from hysteresis loops traversed during straining or vibration. Results of both a quasi-static analysis and simulations of dynamic behavior are presented and explained.

On the Use of the Equilibrium Configuration in the Modeling and Simulation of Phase Transformations in Shape Memory Alloys

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Recent advances in the arena of quasi-convex analysis have made possible a more precise characterization of the equilibrium con.guration in phase transforming shape memory alloys through the introduction of accurate bounds on the macroscopic free energy functions as derived from microstructural considerations. Remarkably, one particular lower bound is available in closed form and has been shown to be exact for a significant region in the lattice correspondence variant phase space; this allows one to compute the limit state via an inequality constrained optimization problem. In the present work we examine a constitutive model explicitly based on this equilibrium state.

In the first part the continuum model is described and shown to have an interesting relation to the earliest models regarding shape memory alloys. This is followed by a discussion of issues related to implementation in a finite element setting including differences which arise based on the particular symmetry transformation under consideration. The third item is an assessment of the appropriateness of the theory for simulating the complex and often unexpected behavior exhibited by systems comprised of such materials. This final task is ccomplished via comparison with experimental data.

CONTINUUM MECHANICS AND THERMODYNAMICS

In Honor Of Professor Dr. Ingo Müller

Session F3B
Solids I

Non-Homogeneous Bars with Cohesive Energy

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A theory of elastic bars with cohesive energy was proposed recently by L. Truskinovsky and the present author (3), (4). It is based on the separation of the elastic energy into two parts, bulk and cohesive, and its purpose is to show that many aspects of material response which are usually considered as inelastic effects can, in fact, be described within the domain of elasticity.

A mathematical setting of the model and its characterization as the Gamma-limit of energies of finite-dimensional chains of atoms connected by non-linear elastic springs are given in (1) and (2). Specifically, (1) deals with the modeling of fracture-like phenomena, while (2) also considers the possibility of a "fragmentation of fracture" leading to the formation of microstructures.

The theory developed in (3) and (4) includes an explicit identification of some types of microstructure with the disarrangements usually described in plasticity or damage theories. In (4), special emphasis is given to the study of local energy minimizers, since metastable equilibrium branches seem to be frequently preferred in equilibrium paths generated by the evolution of applied forces or of Dirichlet boundary data.

For reasons of simplicity, the analysis in (3), (4) was restricted to one-dimensional bars with homogeneous bulk energy density, free of external loads and subject to prescribed displacements at the ends. In this contribution, I present an extension to bars with bulk energy density depending on the point and subject to non-null prescribed body forces.

With respect to the nonhomogeneous problem treated in (1), there are some non-trivial questions concerning the extension of the decomposition of the minimum problem introduced in (4), of crucial importance for obtaining both necessary and sufficient conditions for the existence of global energy minimizers. Also non-trivial is the extension of a sufficient condition, proved in (4), for the existence of metastable equilibrium branches with a constant number of discontinuities.

(1) Braides, A., G. Dal Maso and A. Garroni, Variational formulation of softening phenomena in fracture mechanics: the one-dimensional case, Arch. Rational Mech. Anal. 146, 23-58, 1999

(2) Braides, A., and M. S. Gelli, Limits of discrete systems without convexity hypotheses, Pre-print SISSA, Trieste 1999

(3) Del Piero, G., and L. Truskinovsky, Macro and micro cracking in one-dimensional elasticity, Int. J. Sol. Structures 38, 1135-1148, 2001

(4) Del Piero, G., and L. Truskinovsky, Elastic bars with cohesive energy, forthcoming

A Free-Energy Based Model for Hysteresis and Nonlinearities in Piezoceramic Materials

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An inherent property of piezoceramic materials is the presence of hysteresis in the relation between the applied electric field and the resulting polarization. While the deleterious effects of the hysteresis can be minimized through feedback mechanisms for a number of applications, for other applications, including high precision placement, the hysteresis must be accurately characterized and mitigated to achieve design criteria. For example, a limiting factor in achieving high speed nanopositioning in certain atomic force microscope applications is the presence of hysteresis in the piezoceramic positioning mechanisms.

In this talk, we consider the development of an evolution model for quantifying hysteresis in piezoelectric materials. This approach is based on an extension of the Müller-Achenbach-Seelecke model for shape memory alloys. The combination of thermodynamic principles, the theory of thermally activated processes, and the consideration of effective field distributions yields a low-order ordinary differential equation which quantifies hysteresis losses due to pinning sites in the material. Aspects of the model will be validated through comparison with experimental data. This is joint work with Stefan Seelecke, North Carolina State University, and Zoubeida Ounaies, Virginia Commonwealth University.

A Unified Model for Shape Memory Alloys and Piezoceramics

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North Carolina State University
Raleigh, NC

In another paper presented at this symposium (R.C. Smith, 2002), a model for piezoceramic behavior has been developed which is based on a free energy formulation and ideas from statistical thermodynamics and the theory of thermally activated processes. This model is capable of describing the non-linear and hysteretic effects exhibited by piezoceramics, when poled through the full range. The model is derived from an extended version of the original Mueller-Achenbach model for shape memory alloys; and it is the focus of this paper to highlight the common roots of both approaches and to illustrate the analogies between the two materials. It is also indicated how the approach can be extended to other active materials.

A Mechanism of Transformational Plasticity

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In order to understand the phenomenon of reversible plasticity exhibited by shape memory alloys and other smart materials, we study an elementary prototypical model. Building on an original idea of I. Müller and P. Villaggio, we consider an inhomogeneous ensemble of bistable elements connected in series and loaded in a soft device. To interpret the fine structure of the hysteresis loops observed experimentally, we assume that the dynamics is maximally dissipative and investigate different evolutionary strategies for a "driven" system with external force changing quasi-statically. Our main result is that the inhomogeneity of the elastic properties leads to a distinctive hardening with serrations of a Portevin-Le Chatelier type and produces a realistic memory structure characterized by the "congruency" and "return point memory" properties.

Discretization and Energy Landscapes

Bob Rogers

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In this talk I will discuss the relationships between the "energy landscapes" of related discrete and continuum models of mechanical problems. Discrete modes such as chains of "snap springs" have been shown to have a very "rough" energy landscape exhibiting hysteresis through local minimizers. Analogous continuum models can exhibit a much smoother landscape with no local minimizers (other than the global minimum) and thus no hysteresis. We examine this dichotomy and its implications for numerical calculations.

CONTINUUM MECHANICS AND THERMODYNAMICS

In Honor Of Professor Dr. Ingo Müller

SESSION F4B
Solids II

On the Precipitates Induced Hardening in Crystal Plasticity

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A material description for the elasto-plastic deformation of crystals with non-shearable precipitates at finite strains is presented in this article. On the basis of the elastic inclusion model of Bate et al. 1981 the constitutive equations are formulated in a crystal plasticity setting. The dependencies of the kinematic hardening of a slip system on shape, size, and orientation of the precipitates within the deformation process are discussed. The anisotropic kinematic hardening for the actual yield condition of a slip system is described by the averaged accommodation tensor incorporating precipitate rotations to describe the evolution of back stress terms within the deformation process.

Keywords: crystal plasticity, kinematic hardening, precipitated metals

Asymptotic Behavior of the Solutions in Nesting Theories of Symmetric Hyperbolic Systems with a Convex Extension

Francesca Brini

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It is well-known that starting from the Boltzmann equation it is possible to construct an infinite hierarchy of moment equations. Such a hierarchy is usually truncated and closed through then procedures of Extended Thermodynamics and it is possible to obtain different theories depending on the number of moments that are taken into account. In this manner we obtain nesting theories characterized by a symmetric and hyperbolic structure of the corresponding systems. The formal relation between theories truncated at different number of moments is clarified trough the principal subsystem properties, but the relation between the corresponding solutions is still an open question and will be investigated in the present work. In particular, we will construct some "toy models" which present the main peculiarities of the Extended Thermodynamics theories and we will numerically investigate the behavior of the solution for large time scales, in order to verify the conjecture that each solution tends to the stationary equilibrium one, narrowing the solutions corresponding to lower truncation order.

Thermodynamics and Kinetic Theory in 2-D Cosmological models

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The combination of general relativity with the kinetic theory of gases is remarkably useful to construct cosmological models. In these formulations the cosmic sources of gravitational interactions are represented by the energy-momentum tensor of a fluid; in addition we have the hypothesis of homogeneity and isotropy in the form of the well-known Robertson-Walker metric. Although these theories have explained several important features of our universe fundamental questions still remain to be answered.

Models in lower dimensions offer interesting results that, if properly analyzed, can be used to gain insight in the realistic formulations. Two-dimensional (2-D) gravity models have been under intensive investigation during the last two decades. The old problem of quantum gravity, black holes physics and string dynamics were tested in these theories. In particular Teiteboim and Jackiw proposed a consistent model in two dimensions analogous of general relativity.

For cosmological applications, a refinement in the construction of these models can be obtained by considering a non-equilibrium scenario, including a bulk viscosity term in the energy-momentum tensor. In the four-dimensional case the inclusion of this term to analyze the evolution of the cosmic scale factor with the time was done by Murphy who has found a solution that corresponds only to an expansion. Other models were based on the coupling of the Einstein field equations with the balance equations of extended thermodynamics (also known as causal or second-order thermodynamic theory) and among others we cite the works of Belinskii et al, Zimdahl and Di Prisco et al. In this work we develop a kinetic theory of relativistic gases in a two-dimensional space. The balance laws for the particle flow, energy-momentum tensor and entropy flow are obtained from a transfer equation that follows from Boltzmann equation. We find also the equilibrium distribution function and the expressions for the fields of energy per particle, pressure, entropy per particle, enthalpy per particle and heat capacities in equilibrium in a two-dimensional space. Moreover, by using the method of Chapman and Enskog for the kinetic model of the Boltzmann equation proposed by Anderson and Witting we calculate the bulk viscosity and the entropy production rate. We apply the ideas of Murphy to the 2-D gravitational field equations and we show that opposed to the four-dimensional case the cosmic scale factor attains a maximum value at a finite time decreasing to a "big crunch" and that there exists a solution of the gravitational field equations corresponding to a "false vacuum". The difference between the solutions in the four- and two-dimensional cases is due to the fact that the relationship between the metric tensor and the sources in the 2-D case is modified because the Einstein field equations give no dynamics for the 2-D case. The evolution of the fields of pressure, energy density and entropy production rate with the time is also discussed.

Physical Analogy between Continuum Thermodynamics and Classical Mechanics

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The main focus of the present paper is a profound physical analogy between a classical mechanical system of a few interacting particles moving with dissipation in a possibly time-dependent nonconservative external field and

a one-dimensional continuum thermo-dynamical system with relaxation. This thermomechanical analogy stems from the validity of variational methods in mechanics and thermodynamics. A physical analogy always improves our understanding of the subject on both ends and allows for possible extensions into untested areas.

Effective Properties of a Piezocomposite Containing Shape Memory Alloy and Inert Inclusions

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We use the energy equivalence principle and the Mori-Tanaka method of considering the interaction among inclusions to derive the effective thermo-electro-mechanical properties of a 4-phase composite consisting of an elastic matrix and shape memory alloy, piezoelectric and inert (nonpiezoelectric) inclusions. It is shown that the shapes and the volume fraction of inert (e.g. air) inclusions significantly influence the effective properties of the composite, and the addition of soft inert inclusions decreases the axial stress required to initiate the phase transformation in the SMA inclusions, and increases the electromechanical coupling constant. The 4-phase composite makes a very good sensor to measure low values of the applied axial stress since the axial strain induced by an axial stress of 80 MPa is 2sensor is improved by the addition of soft spherical inert inclusions. With a suitable choice of the matrix material, its compliance can be adjusted and its shape made to conform to that of the host structure.

Keywords: smart composite, effective moduli, Eshelby tensors, static deformations, ellipsoidal inclusions

Symposium on

Advances in Computational Mechanics

In Honor Of
Professor J. T. Oden

Organizer:
Professor L. Demkowicz
(University of Texas at Austin)

ADVANCES IN COMPUTATIONAL MECHANICS

In Honor Of Professor J. T. Oden

SESSION M3R

A Posteriori Finie Element Error Estimation for Hyperbolic Partial Differential Equations

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The discontinuous Galerkin method (DGM) is an appealing approach to address problems having discontinuities, such as those that arise in hyperbolic conservation laws. Originally developed for neutron transport problems, the DGM has been used to solve ordinary differential equations and hyperbolic, parabolic, and elliptic partial differential equations. The DGM may be regarded as a way of extending finite volume methods to arbitrarily high orders of accuracy. The basis is piecewise continuous relative to a structured or unstructured mesh. As such, it can sharply capture discontinuities in the solution. Regardless of order, the DGM has a simple communication pattern to elements with a common face that makes it useful for parallel computation. In order for the DGM to be useful in an adaptive setting with h-refinement (mesh refinement and coarsening) or p-refinement (method order variation), techniques for estimating the discretization errors should be available both to guide adaptive enrichment and to provide a stopping criteria for the solution process. We will show that the DGM discretization finite element solution of hyperbolic conservation laws with degree p exhibit superconvergence at Radau points of degree $p+1$ with the fixed endpoint selected at the downwind boundary of each element. We use this superconvergence result to construct asymptotically exact a posteriori error estimates for hyperbolic systems of partial differential equations. Finally, we present numerical results for several computational examples with both continuous and discontinuous solutions that show the efficiency of our a posteriori error estimator.

Shape Function Selection in the Meshless Method

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The meshless method relates to the approximation problem by the linear combination of shape functions with compact support. They are constructed in various ways, for example by the Reproducing Kernel Particle (RKP) method, Moving Least Square (MLSK) method etc.

The talk will address the problem of comparing their performance by the theoretical and computational tools.

Accuracy and Stability in CFD: Numerical vs. Artificial Dissipation

A.J. Baker, A. Kolesnikov, M.B. Taylor and S. Ericson

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University of Tennessee

The linear elliptic "optimal" Galerkin weak statement (GWS), implemented via finite element, finite volume or finite difference discretizations, yields an unstable Navier-Stokes algorithm for realistic Reynolds number. An incredible variety of theoretical approaches for stabilization have been developed in seeking stable essentially non-oscillatory CFD schemes. The "Taylor weak statement (TWS)" was derived in the 1980s as a weak form adaptation of Lax-Wendroff finite difference truncation error annihilation. The TWS has matured to providing an incisive uniform theory generating tensor-invariant modified Navier-Stokes conservation law forms for which the resultant GWS yields stable, higher-order algorithms devoid of strictly "artificial: diffusion. This paper documents the utility of the TWS theory for Navier-Stokes applications including illustrations.

Nonlinear Micromechanical Analyses of Composites by BEM

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The paper details elastoplastic analyses of a large number of cylindrical fibers embedded in a three dimensional elastoplastic solid. The cylindrical fibers are modelled using a semi-analytic BEM which allow them to be modelled as curvilinear line elements. Similar semi-analytical procedure is also adopted for the holes and the sorrounding elastoplastic region. These are then assembled to provide the BEM formulation for the system.

Multiscale Methods in Turbulence: A Variational Approach to Large Eddy Simulation

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Calculating turbulent flows requires solution of the Navier-Stokes equations at high Reynolds numbers. This is referred to as Direct Numerical Simulation (DNS). However, it is currently not feasible to perform DNS for all but the simplest turbulent flows due to prohibitive computational requirements. Even if current rates of increase of computational power continue, it is unlikely DNS will become an everyday engineering tool in this century! The problem stems from the fact that turbulence is characterized by a very broad spectrum of spatial and temporal scales and although engineering interest is focused on the behavior of the larger scales their dynamics is influenced by the presence of small scales due to nonlinear interactions.

Large Eddy Simulation (LES) is a procedure in which only larger scales are resolved numerically, and effects of smaller scales are modeled. This reduces computational requirements significantly and currently enables solution of many physically interesting flows. Recently, LES has become an important engineering tool. Even with LES, turbulent calculations still require enormous computational resources but there is hope that through continued improvements in computer performance and modeling concepts LES will emerge as the standard technology for computing flows of engineering interest.

The devil is in the details: There is still no general agreement as to best modeling procedures within LES, and even the proper theoretical framework of LES is debated. The presentation begins with a brief overview of traditional LES concepts and identifies points of concern. Elementary modeling ideas are review ed and examined from numerical analysis and "spectral eddy viscosity" points of view. The variational multiscale formulation of the Navier-Stokes equations is proposed. It has features which obviate some of the criticisms of the classical LES formulation and provides a framework with potential for improved modeling. Computations employing the

simplest instantiations of the ideas are presented for homogeneous isotropic flows and channel flows, and in all cases very good results are obtained. Particular accuracy is noted for non-equilibrium flows.

ADVANCES IN COMPUTATIONAL MECHANICS

In Honor Of Professor J. T. Oden

SESSION M4R

Eulerian Finite Element Methods for Mechanochemical Simulations

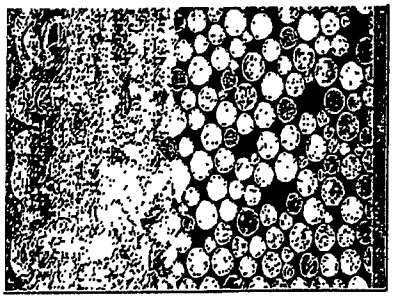
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Computational fluid mechanics has successfully addressed a wide range of problems in engineering in science. Most of them are associated with a single fluid or miscible multiphase fluids. There is, however, an interesting class of problems in materials synthesis that have been largely ignored, namely shock initiated chemical reactions (SICR). In this process, a well-mixed powder of two or more materials is shock compressed. The localized heating of the shock compression initiates an exothermic chemical reaction that propagates through the powder until the reaction has exhausted one or more of the starting materials. This process is characterized by

1. The initial materials are solid.
2. The materials are immiscible (the reaction occurs at the material interface).

The present work represents an initial attempt to model the process at the mesoscale. Substantial improvements in the computational methods are expected in the future. The objective of this talk is to present the difficulties in modeling this process, the current approach to their solution, and the direction of future research in this area.



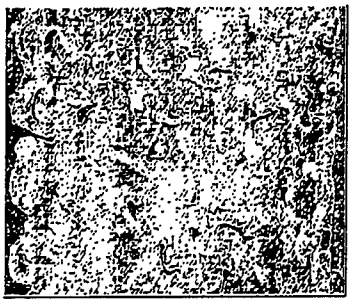


Figure 1. The SICR of niobium silicide: a) the sharp front indicates that the reaction occurs very quickly, b) the final state showing the final product surrounding the excess niobium.

Keywords: Eulerian, mesoscale, finite element, chemistry

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Some Results on the Numerical Analysis of Piezoelectric Thin Shells

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An active structure is generally realized by assembling:

- a thin structure made of a "classical" material which has purely mechanical behaviour;
- some patches made of smart materials (piezoelectric, magnetostrictive, e lectrostrictive, shape memory alloys...), which are bonded upon the external surface of the structure and act as sensors or actuators.

In this talk, we present some results concerning the numerical analysis of piezoelectric thin shells:

- Firstly, we consider the modelization of a general three dimensional piezoelectric material by using general curvilinear coordinates and we study the associated existence of a solution;
- Next, by specializing these equations to the case of a piezoelectric thin shell, we derive an approximate two-dimensional variational formulation on the middle surface of the shell. We discuss the existence and uniqueness of the solution and its approximation by conforming finite element methods.
- Finally, previous results are used to modelize piezoelectric patches which are bonded upon thin shell structures made of a "classical" material. Once again, we obtain the associated existence of a solution and we study its approx imation by conforming finite element methods.

These theoretical results are illustrated by numerical experiments.

Keywords: piezoelectric thin shell; patch actuator; active thin shell; existence and approximation by FEM; numerical experiments.

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Symmetric Variational Boundary Element Methods for Interface Problems in Acoustics

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In this paper we present a variational framework for the solution of the interior acoustics problem in multiply-connected domains comprising a host homogeneous material and multiple homogeneous inclusions of different material properties.

The variational setting avoids the explicit imposition of the interface Neumann continuity conditions, which arise as natural conditions, and endows with symmetry and block-sparsity the algebraic systems resulting from the discrete forms. The approach extends earlier developments by the authors in the coupling of finite element and boundary element methods to a pure integral equation approach for multi-domain problems. Here integral representations of the solution on each subdomain are included in the variational statement via Lagrange multipliers. As in most Galerkin-type multi-domain integral equation approaches, here too, continuous, weakly-singular, and hypersingular integral operators arise from the variational statement. A characteristic of the method is the treatment of the hypersingular operator: whereas standard approaches are used to treat the single- and double-layer operators, the hypersingular terms are evaluated using Maue's identity, thus leading to integral forms that employ only weakly-singular single-layer type operators. Two formulations are considered, one where the usual integral representation appears explicitly in the Lagrangian functional, and a second one where the normal derivative of the integral representation is made part of the functional.

For the numerical implementation we favor the second formulation, for it entails inversion of the discrete form resulting from a double-layer operator that is numerically more stable than the single-layer. In all integral evaluations, three- or four-point Gauss quadrature rules are sufficient for accurate results. We present numerical experiments for two-dimensional multi-domain problems governed by the Helmholtz equation. Extensions of the approach to other elliptic operators, notably the elastostatic and elastodynamic cases, are straightforward.

Eigenvalue Evaluation of Symmetric Tridiagonal Matrices - a Unified Approach

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The implicit shift QR algorithm of Wilkinson is one of the most efficient methods available for the evaluation of eigenvalues of symmetric tridiagonal matrices. A traditional method of evaluation of eigenvalues proceeds from finding the zeroes of the characteristic polynomial. The basic idea of this paper is to show the imbedded characteristic polynomial in the implicit QR algorithm. This results in the definition a new parameter termed the characteristic angle. Convergence aspects are considered.

Keywords: tridiagonal matrices, eigenvalues, Wilkinson shift, characteristic polynomial

Discontinuous and Coupled Continuous/Discontinuous Galerkin Methods for Shallow Water Equations

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We consider the approximation of a simplified model of the depth-averaged two dimensional shallow water equations. The system consists of a first order hyperbolic continuity equation for the water elevation coupled to momentum equations for the horizontal depth-averaged velocities.

We consider three approaches to solving the system. In the first approach, the model domain is split into distinct subdomains with an internal interface Γ. A coupled formulation is obtained by discretizing the problem in one subdomain via a continuous Galerkin finite element method, and in the other subdomain via the local discontinuous Galerkin method (LDG)[1].

For the latter two approaches, a discontinuous Galerkin (DG) method is used to approximate the continuity equation within the entire domain. In the second approach, a continuous Galerkin method is used for the momentum equations. Thirdly, a particular DG method known as the nonsymmetric interior penalty Galerkin method (NIPG)[2] is used to approximate momentum. *A priori* error estimates are derived and numerical results are presented for each approach.

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This research was supported by NSF grants DMS-0107247 and DMS-9805491.

ADVANCES IN COMPUTATIONAL MECHANICS

In Honor Of Professor J. T. Oden

SESSION T3R

Incompressible Media Analysis Using the Method of Finite Spheres and Some Improvements in Efficiency

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Over the past few decades, the finite element method has emerged as a highly effective numerical technique for the solution of boundary value problems in Engineering. However, in this technique, a great deal of effort is associated with the generation of a good quality mesh. Hence there is much interest in the development of meshless techniques. The method of finite spheres [1] was introduced as a truly meshless technique with the goal of achieving computational efficiency. In the method of finite spheres interpolation is performed using functions that are compactly supported on n-dimensional spheres ($n = 1, 2$ or 3), which form a covering for the analysis domain [1]. It was observed that for incompressible or nearly incompressible media, the pure displacement-based formulation exhibits a degradation of convergence rate, a phenomenon known as "volumetric locking". In order to remedy this problem, we present a mixed formulation based on displacement and pressure interpolations [2]. However, a displacement/pressure mixed formulation may behave reasonably for certain problems and completely fail for certain others unless the displacement and pressure approximation spaces are properly chosen. To obtain a stable and optimal procedure for the selected interpolation, the mixed formulation should satisfy the ellipticity condition and the inf-sup condition. We have identified several displacement/pressure mixed interpolation schemes that pass the numerical inf-sup test. We also discuss several new integration schemes that have allowed us to reduce the computational cost substantially.

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Integration of hp-Adaptivity with a Multigrid Solver

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Dedicated to Prof. J. Tinsley Oden, on occasion of his 65-th birthday

In the presented work we will show our recent results on a fully automatic hp-adaptive strategy [1] that not only delivers predicted, optimal exponential convergence rates, but remains fully competitive with h-adaptive quadratic elements in the preasymptotic range. The method draws on our recent progress in the understanding of the idea of hp-interpolation [2], new hp data structures [3], and a full integration with two- and multi-grid solvers for hp meshes. The method delivers a sequence of 'coarse' meshes, with corresponding sequence of 'fine' meshes obtained from the coarse ones through a global hp-refinement. Construction of a next coarse mesh in the sequence is based on minimizing the hp-interpolation error of the fine mesh solution, with the fine mesh solution obtained using a two-grid or multi-grid solver.

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Some Properties of Kriging Based Meshfree Method

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A meshfree method based on Kriging is developed recently[1]. The meshfree method has been extensively popularized in literature in recent years, due to its flexibility and high convergence rate in solving boundary value problems. However, accurate imposition of essential boundary conditions method often presents difficulties because the Kronecker delta property, which is satisfied by finite element shape functions, does not necessarily hold for the meshfree shape functions. The proposed new formulation of meshfree method eliminates this shortcoming through the Kriging interpolation.

Kringing is a geostatistical method of spatial data interpolation. The mathematical model of Kriging is names after D. G. Krige, who first introduced a version of this spatial prediction process. Kriging has been extensively in the literature since Sacks et al[2] proposed the application of Kriging in computer experimental. Mathematical theory of Kriging is available[3].

A brief summary of Kriging and some basic formulas is given in this paper. We also introduce the idea of Moving Kriging (MK) and show how it can be used to formulate a new type of mesh-free method. Two major mathematical properties, interpolation and consistency, will be approved in the paper.

Kriging Approximation

Consider the function $u(x)$ which is defined in the domain Ω and the approximation be $u^h(x)$. Let the nodes defined by $s_1, \ldots, s_n$ Giving a set of function values $u_1, \ldots, u_n$. n is the total number of nodes in Ω. Kriging postulates a combination of linear regression model plus departures[2].

$$u^h(x) = p^T(x)\hat{\beta} + r^T(x)R^{-1}(u - P\hat{\beta}) \quad (1)$$

where

$$\hat{\beta} = (P^T R^{-1} P)^{-1} P^T R^{-1} u \quad (2)$$

or

$$u^h(x) = p^T(x)Au + r^T(x)Bu \quad (3)$$

where $A = (P^T R^{-1} P)^{-1} P^T R^{-1}$ and $B = R^{-1}(I - PA)$.

InterpolationProperty

One important property of the MK shape function is that the Kronecker delta property is satisfied. The value of shape function $\phi_I(x)$ at s_J is given by

$$\phi_I(S_J) = \sum_j^m P_j(S_J)A_{jI} + \sum_k^n r_k(S_j)B_{kI} \quad (4)$$

It can be written in the matrix form

$$[\phi_I(s_J)] = PA + RB = PA + RR^{-1}(I - PA) = I \quad (5)$$

Consistency Property

Another property of MK shape function is that the MK interpolation will reproduce any function in the basis exactly. In particular, if the basis includes all constants and

linear terms, it will reproduce a general linear polynomial exactly, i.e.

$$\sum_{I}^{n} \phi_I(x) = 1 \text{ and } \sum_{I}^{n} \phi_I(x) x_{Ii} = x_i \qquad (6)$$

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Towards Adaptive Multiscale-Multiphysics Computational Framework

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In this talk I will describe an adaptive multiscale-multiphysics based computational framework aimed at predicting the behavior of structural systems with strong spatial-temporal scale mixing and significant interaction of physical processes. The term multiscale-multiphysics based design framework is coined to emphasize that the behavior of the structure is assessed from the first principles, which are operative at smaller scales than currently resolved in simulations. A number of important applications fall into this category including: 3D woven architectures in aircraft engines, advanced airframes, tires, microelectronic devices, and porous engineering materials such as honeycombs and truss-like materials. In these structures the size of the microstructure is comparable to that of structural details or to the wavelength of a traveling signal often leading to strong dispersion effects. This is further complicated by the fact that various physical processes, such as deformation, heat conduction, oxidation, stress corrosion, fatigue and fracture are operating at different spatial and temporal scales.

A Flexible Parallel Adaptive Discontinuous Galerkin Procedure

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The discontinuous Galerkin method (DGM) provides an appealing approach to address problems having discontinuities, such as those that arise in hyperbolic conservation laws. The DGM may be regarded as a way of extending finite volume methods to arbitrarily high orders of accuracy. The solution space is a piecewise continuous (polynomial) function relative to a structured or unstructured mesh. As such, it can sharply capture solution discontinuities relative to the computational mesh. It maintains local conservation on an elemental basis. Regardless of order, the DGM has a simple communication pattern to elements with a common face that makes it useful for parallel computation. It can handle problems in complex geometries to high order. And, it is useful with adaptivity since interelement continuity is neither required for h-refinement (mesh refinement and coarsening) nor p-refinement (method order variation).

We describe several aspects of our development of an efficient adaptive DGM including basis construction, data structures and local time stepping. Emphasis is placed on its effective parallelization where the parallel data management system can handle high-order techniques and maintain a dynamic load balance. Results of unsteady compressible flow problems involving instabilities and other complex two- and three-dimensional phenomena will be presented. The results to be presented will demonstrate the ability to address adaptive simulations in which thousands of steps of mesh refinement and coarsening are needed.

Keywords: Discontinuous Galerkin methods, Parallel adaptive methods

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ADVANCES IN COMPUTATIONAL MECHANICS

In Honor of Professor J. T. Oden

SESSION T4R

Hyperelastodynamics, Hamilton's Principle, and Spacetime Discontinuous Galerkin Methods

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This paper presents a new spacetime formulation of hyperelastodynamics and a related stationary principle that provides the theoretical framework for a new class of spacetime discontinuous Galerkin methods. We begin with an integral statement of momentum balance in spacetime, and demonstrate its equivalence to a system of local balance equations and local jump conditions. Since only the complete local system is equivalent to the integral balance law, a dynamic analysis method must enforce the

equation of motion and the full set of jump conditions to ensure good performance for shock problems.

Mechanical fields that are distinct in traditional theory merge into unified entities in the spacetime theory. For example, stress and linear momentum density comprise the stress-momentum, while strain and velocity form the strain-velocity. The hyperelastodynamic theory describes the evolution of internal energy and kinetic energy in a unified fashion: the total energy density rate is simply the exterior product of the strain-velocity rate and the stress-momentum.

A Galerkin weighted residual scheme enforces the complete local system and generates a new stationary principle for dynamics. The principle is an analogue of Hamilton's Principle, but the spacetime Lagrangian involves a power density, rather than an energy density. Discrete versions of the stationary principle constitute a new class of spacetime discontinuous Galerkin methods. These are Bubnov-Galerkin methods; they do not rely on stabilization terms or tuning parameters. Nonetheless, they deliver solutions that are free of Gibbs oscillations for shock problems, they are high-order stable, and they exhibit optimal convergence in smooth regions.

Keywords: discontinuous Galerkin methods, spacetime, elastodynamics, Hamilton's principle

Recent Advances in the Finite Element Method for Incompressible Flow

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Recent availability of divergence-free finite elements permits computation of incompressible flow without the usual divergence constraint. Computations of flow in 2D with a solenoidal velocity element that is the curl of a sufficiently-continuous Hermite stream function element are presented. The governing equation for this flow does not involve the pressure.

The usual Navier-Stokes momentum equation is not the dynamic equation involvingpressure forces it would seem to be. It is two separate orthogonal equations: a pressure-free one for the velocity, and one for the pressure as a functional of the velocity field and any conservative body forces.

The weak form of this velocity equation follows from the inner product of the NS momentum equation with solenoidal test functions. From the Helmholtz decomposition theorem, the pressure gradient and conservative body forces vanish by orthogonality. An integro-differential equation form results from application of the solenoidal projection operator to the momentum equation. These can be understood as forms of a kinematic governing equation for the velocity, where the incompressibility constraint plays the role of a conservation law. Absence of the pressure gradient can be understood at an elementary level: a dynamic pressure gradient cannot be imposed on an infinitesimal fluid element as it would be instantly equilibrated due to the infinite speed of sound in an incompressible medium.

"Pressure-driven" flow would seem to present a dilemma for pressure-free computation, but net flow in these problems is governed by the stream function on the boundary. Hermite elements, with stream function and velocity degrees of freedom, seem to be essential to application of this approach.

Computational results will be shown as examples of different boundary conditions, including the lid-driven cavity, fully-developed and developing flow, flow over a backward-facing step and general Couette flow.

Keywords: Computational Mechanics, Incompressible Flow, Finite Element Method, Navier-Stokes

High Frequency Dispersive Modeling of Periodic Media

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In recent years, a new arena opened up in the area of composites technology where the emphasis is to have improved overall dynamic characteristics. Wave propagation and the physical phenomenon of geometric dispersion are of paramount importance in this context. This work focuses on the development of a computational tool for the accurate and efficient prediction of the dispersion curves corresponding to arbitrarily periodic composite materials. A recently developed high-order homogenization based method, referred to as the Assumed Strain Method [McDevitt et al., 2001], form the core of the analysis methodology being proposed. To extend the capabilities of current technology to high frequency ranges, eigenvalue analysis is carried out on the periodic microstructure problem and the resulting eigenvectors are used to enrich the projections undertaken in the Assumed Strain Method. Numerical results are presented for a one-dimensional model of a periodically laminated medium using the developed technique, and comparisons are made with the exact solution. The potential of using this type of computational tool for developing advanced design strategies in

composites engineering is highlighted and some examples are presented.

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The Mesoscale Simulation Grain Growth and its Consequences

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The simulation of curvature driven growth in grain boundary systems is becoming an important tool in understanding the behavior of microstructure evolution and there is much distinguished work in this subject. Here we address the mesoscale simulation of large systems of grain boundaries subject to the Mullins equation of curvature driven growth with the Herring force balance equation imposed at triple junctions. This will serve as a calibration for future work when experimentally derived energies and mobilities can be employed. What is the result of the simulation? This is a very pregnant question. We discuss what such a simulation is capable of predicting, taking as a prototype the histogram of relative area population as it changes through the simulation. We do not use this data to seek the best distribution, like Hillert, Rayleigh, or lognormal. Instead we treat the set of distributions as the solution of an inverse problem for a time varying function and determine the equation they satisfy. This results in a coarse graining of the complex simulation to simpler system governed by a Fokker-Planck Equation. Even so, fundamental questions concerning the predictability of simulations of large metastable systems arise from these considerations.

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Integral Representations of Contact Conditions in Computations of Interfacial Phenomena

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This talk has as its primary focus the successful implementation of mortar-based contact strategies in large deformation finite element analysis. As has been recognized by a number of authors, the use of traditional node-to-surface formulations in finite element analysis of contact has several difficulties, not the least of which are a lack of ability to trasmit spatially constant stress fields (i.e., contact patch tests); and a degradation of standard convergence rates expected for Galerkin formulations. These problems come to the fore in contact analysis because surfaces which undergo mechanical interaction are often naturally non-conforming. The use of mortar methods, popularized for domain decomposition applications, shows considerable promise for the spatial discretization of contact phenomena. Fundamentally, such techniques construct nonlocal, integral representations of contact conditions, in a manner that facilitates low order consistency of the approximation while preserving expected convergence characteristics.

Three issues pertaining to the generalization of mortar methods will be discussed. First, the issue of patch test passage over curved interfaces will be addressed. It will be shown that a generalization of the mortar projection method is required to pass patch tests in this instance. Second, issues relating to the exact numerical integration of the mortar projection integrals will be outlined. Third, the issue of mortar discretization will be critically examined, and some situations in which locking phenomena can be observed will be discussed and demonstrated.

Effects of Microscale Material Randomness on the Attainment of Optimal Structural Shapes

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Classical procedures of shape optimization of engineering structures implicitly assume existence of a hypothetical, perfectly homogeneous continuum - they do not recognize the presence of any microscale material randomness. The first study of this effect, conducted recently on the paradigm of the Michell truss [1], has shown that the random microstructure prevents attainment of the classically predicted optimal shape using the homogeneous continuum. The investigation was carried out under the assumption of fixed load and the search was conducted for a structure of optimal (i.e., minimal) weight. By contrast, the present study investigates this aspect on the paradigm of the Michell truss with minimum compliance, while having a prescribed weight. The problem involves a stochastic generalization of the topology optimization method [2] implemented in a commercial Altair's OptiStruct computer code. In particular, this generalization allows for the dependence of each finite element's stiffness matrix on the actual microstructure contained in the given element's domain. Contrary to the intuition, stochastic material properties may improve the compliance of optimal design. This is because the optimization is performed on a given random distribution, so that the design process has an opportunity to choose 'stiffer' cells and discard those with weaker material.

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Modeling of a Press-Fit Problem in Computational Biomechanics Using the Fictitious Domain Method

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In this paper we discuss an efficient approach to the modeling of a press-fit problem arising in the computational modeling of implantation processes in biomechanics. A fictitious domain approach is followed that allows for the ready and easy integration of the heterogeneous material properties that originate from computed tomography scans on regular grids.

The methodology is described in the context of a linear elasticity problem with Dirichlet boundaries and necessary conditions for optimal convergence rates are discussed. The approach bypasses the geometric reconstruction processes typically associated with surgical simulations (segmentation, boundary extraction, surface and/or volume reconstruction, surface and volume boolean operations, etc) and thus offers advantages over methods based on unstructured meshes.

Numerical results are presented for prototype problems as well as problems based on actual anatomical data.

A Perfectly Matched Layer Approach to the Nonlinear Shallow Water Equations Models

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A limited-area model of nonlinear shallow water equations (SWE) with the Coriolis term in a rectangular domain is considered. The rectangular domain is extended to include the so-called perfectly matched layer (PML).

Following the proponent of the original method, the equations are obtained in this layer by splitting the shallow water equations in the coordinate directions and introducing the damping terms. The efficacy of the PML boundary treatment is demonstrated in the case where a Gaussian pulse is initially introduced at the center of the rectangular physical domain.

A systematic study is carried out for different mean convection speeds, and various values of the PML width

and the damping coefficients. For the purpose of comparison, a reference solution is obtained on a fine grid on the extended domain with the characteristic boundary conditions. The L2 difference in the height field between the solution with the PML boundary treatment and the reference solution along a lineat a downstream position in the interior domain is computed.

The PML boundary treatment is found to yield better accuracy compared with both the characteristic boundary conditions and the Engquist-Majda absorbing boundary conditions on an identical grid.

Parallel Adaptive Lagrangian Discontinuous Galerkin Methods

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In this talk we will discuss the development of highly accurate parallel adaptive Lagrangian discontinuous Galerkin techniques that will be central to the development of high fidelity simulation tools for investigation of pediatric brain injury mechanisms and preventive strategies. Even on the most powerful massively parallel processors currently obtainable, using the currently available computational tools (parallel Lagrangian explicit dynamics codes e.g. ParaDyn and Pronto3D) it is estimated that many of these calculations would consume not hours but weeks or months and still fail to provide reasonable simulations due to the poor numerical accuracy of the low order finite element/finite difference schemes and explicit time integration schemes used.

The key element of the strategy proposed here is the use of new parallel adaptive Lagrangian discontinuous Galerkin schemes that provide the accuracy and computational efficiencies necessary for dealing with the complex geometric and material structure of the brain tissue, associated membranes and blood vessels. These schemes will enable the use of higher order approximations to obtain accuracies that are higher order in space and time. While the pediatric brain injury application will drive the research into this new class of parallel computational techniques, the codes and methodology should be useful for a much wider class of problems e.g. metal forming, vehicle crash simulations.

Keywords: Lagrangian, Discontinuous Galerkin formulations

Direct Numerical Simulation of Polycrystals

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A quantitative assessment of the effect of elastic and plastic inhomogeneities of grain deformation is critical for the determination of the aggregate response in polycrystals, an effect that is specially important at large deformations. To this end, a computational method is presented for the simulation of grain interactions in polycrystals including the accurate resolution of inhomogeneous anisotropic elastic and plastic fields at grain boundaries. The computational approach is based on a Lagrangian large-deformation finite-element formulation. The multiscale, atomistically-informed crystal plasticity model presented in [1], the shock capturing method presented in [3] and the equation of state and pressure-dependent elastic constants for Ta obtained in [2] from *ab initio* quantum mechanical calculations define the material model used in calculations. The considerable computing effort is distributed among processors *via* a parallel implementation based on mesh partitioning and message passing, following [4]. Each mesh partition represents a grain with a different orientation and is assigned to a different processor.

The versatility of this approach is demonstrated in large scale three-dimensional simulations of a strong shock propagating in a Ta cylinder. The simulations are performed on the ASCI super-computers on up to 1856 processors. The role of inhomogeneities of plastic deformation ensued as a result of grain boundary constraint in determining the macroscopic polycrystal response is assessed by comparison with averaging techniques. The scalability properties of the proposed ap-proach on up to thousands of processors are briefly discussed.

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ADVANCES IN COMPUTATIONAL MECHANICS

In Honor Of Professor J. T. Oden

SESSION W4R

Multi-Level Models for Multiple Scale Damage Analysis in Composite Materials

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In this work, a multiple scale computational model is developed to concurrently predict evolution of variables at the structural and microstructural scales, as well as to track the incidence and propagation of microstructural damage. The microscopic analysis is conducted with the Voronoi cell finite element model (VCFEM) while a conventional displacement based FEM code executes the macroscopic analysis.

Adaptive schemes and mesh refinement strategies are developed to create a hierarchy of computational subdomains with varying resolution. Such hierarchy allow for differentiation between non-critical and critical regions, and help in increasing the efficiency of computations through preferential 'zoom in' regions. Coupling between the scales for regions with periodic microstructure is accomplished through asymptotic homogenization, whereas regions of nonuniformity and non-periodicity are modeled by true microstructural analysis with VCFEM.

An adaptive Voronoi cell finite element model is also developed for micromechanical analysis. Microstructural damage initiation and propagation in the form of debonding and particle cracking are incorporated. Error measures, viz. a traction reciprocity error and an error in the kinematic relation, are formulated as indicators of the quality of VCFEM solutions. Based on a-posteriori evaluation of these error measures, element adaptation is executed by displacement function adaptations and enrichment of stress functions. The complete process improves convergence characteristics of the VCFEM solution.

An Unstructured Inverse Design Method for Blade Design

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An inverse design method for the blade design by using adaptive unstructured meshes has been developed. In this method, the pressure loading are prescribed. The design method then computes the blade shape that would accomplish the prescribed pressure loading. The method is implemented using a cell-centred finite volume method, which solves the Navier-Stokes equations on the unstructured mesh. An adaptive unstructured mesh method based on grid subdivision and local remeshing is used for increasing the accuracy.

In the inverse design method, blade geometry is updated at the end of each design iteration until final optimal geometry of the blade is reached. A remeshing strategy based on a modified version of spring method for geometric adaptation of grids to moving or deforming of blade is presented. The efficiency of the design method is demonstrated using several cases.

Keywords: Inverse design, adaptive unstructured mesh, Navier-Stokes, Finite volume

Large-Scale Simulations of Stokesian Emulsions

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We will discuss the development of a fast solution method for the accurate large scale modeling of fluid dynamics problems involving emulsions. The development combined boundary element methods with fast iterative solvers based on the fast multipole method. Our solution method required extending the fast multipole method to generalized electrostatics problems to periodic domains. In addition, we developed an efficient hierarchical time stepping scheme and adopted accurate integration

schemes, particularly useful in simulation of dense emulsions. Our solution method was implemented on parallel computers and used to model a creaming experiment of an emulsion.

Discontinuous Galerkin Methods for PDEs with Higher Order Spatial Derivatives

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In this talk we will describe our recent work on developing a local discontinuous Galerkin method to solve the KdV-like equations containing linear or nonlinear third derivatives, time dependent bi-harmonic type linear or nonlinear equations containing fourth derivatives, and linear or nonlinear equations containing fifth derivatives.

Discontinuous Galerkin method is a finite element method using totally discontinuous, piecewise polynomial basis functions and cleverly chosen interface numerical fluxes to enforce local conservativity and stability. The original discontinuous Galerkin method is designed for hyperbolic conservation laws, for which the upwinding principle, or the more sophisticated monotone fluxes or approximate Riemann solvers, are the basic guiding principles in designing those interface fluxes. The resulting scheme can be proven to satisfy a local cell entropy condition for the square entropy, which trivially implies an L^2 stability for nonlinear, multi-dimensional scalar hyperbolic conservation laws with arbitrary triangulations and any order of accuracy. This is by far the strongest stability result for such general cases in any types of schemes. The success of the discontinuous Galerkin method has been extended to the so-called "local discontinuous Galerkin" method, for solving the heat equations or other convection diffusion problems containing second derivative terms. A local variable representing the derivatives of the solution is introduced and the equation is rewritten into a first order system, then a discontinuous Galerkin method is directly applied. The key to the success is still the design of the interface fluxes, as upwinding is no longer a valid mechanism for such problems. Instead, a different guiding principle is developed by Cockburn and Shu, resulting in a class of interface fluxes which lead to a nonlinearly L^2 stable scheme for general multidimensional nonlinear convection diffusion equations in arbitrary triangulations.

This spirit has been recently extended by us to the design of a discontinuous Galerkin for PDEs containing higher order spatial derivative. We have developed a new class of interface fluxes such that the resulting scheme is nonlinearly L^2 stable for quite general multidimensional equations with certain types of nonlinearities in the third (KdV type), fourth (bi-harmonic type) and fifth derivative terms. Numerical experiments indicate that this class of methods have a good potential in solving such equations with good massive parallel efficiency and good h-p adaptive capability, especially for the so-called "convection dominated" case where the coefficients in front of the higher derivatives are small and the nonlinear first order derivative term dominates.

Keywords: local discontinuous Galerkin method, numerical fluxes, KdV equations, bi-harmonic equations

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The Time Dimension: A Unified Theory and Design of Computational Algorithms for Transient Problems

K.K. Tamma, X. Zhou, and R. Kanapady

A unified theory and design of computational algorithms for first-order transient systems is described leading to new avenues not explored to-date. The unified framework not only provides new avenues for designing computational algorithms for transient problems, but also explains the underlying relationships of a variety of time operators such as linear multi-step methods, sub-stepping methods, Runge-Kutta methods, higher-order methods, etc., and provides design critera for evaluatiing time operators.

Emanating under the umbrella of a generalized time weighted approach, and alternately via the notion of: 1) the size of the equation system involving the unknowns, and 2) the associated system solves, the resulting time discretized operators have been recently characterized as pertaining to three distinct Type 1 , Type 2, and Type 3 classifications. The Type 1 classification of algorithms are the exact integral operators and naturally inherit a single system size and representation. Since such a class of integral operators are computationally cumbersome, the so-called Type 2 classification of operators are consequently designed to preserve the representation of the Type 1 operators and systematically approach the exact response with increasing order of accuracy in the process of time integration; and obviously also inherit a single system size and a single solution step.

Alternately, from the viewpoint of computational considerations, the Type 3 classification of time discretized operators are designed and are all those representations which are spectrally equivalent to the Type 2 classification of operators but appear in various alternate forms

of representation. That is, the general Type 3 classifications have the representation of a multiple sytem size and/or multiple solves and encompass both time discontinuous/continuous operators. An underlying stability and accuracy limitation theorem in the context of the Type 2 classification of time operators serves to provide the limitations of the spectrally equivalent Type 3 classification counterparts. More noteworthy, the classical LMS methods we are mostly familiar with are a special limited case of the Type 3 classification and the Dahlquist theorem serves as a particular limited case.

Illustrative examples are particularly highlighted.

ADVANCES IN COMPUTATIONAL MECHANICS

In Honor Of Professor J. T. Oden

SESSION R3R

Some Basic Problems in Virtual Fabrication

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The conceptual and computational problems associated with the development of a virtual fabrication environment designed for cost-effective utilization of materials and manufacturing resources in the fabrication of complex metal aircraft components will be discussed. Specifically, the formulation and experimental validation of mathematical models that account for residual stresses in rolled aluminum plate stock will be described.

A properly designed virtual fabrication environment will make it possible to plan the fabrication processes so that the incidence of re-working and scrapping of partially or fully manufactured parts is substantially reduced. In addition, a virtual fabrication environment will serve the design process by providing information on the basis of which costs associated with alternative designs can be estimated.

An Inverse Finite Element Method for Application to Structural Health Monitoring

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Real-time structural health monitoring is commonly recognized as one of the key enabling technologies designed for the next generation of aerospace vehicles. The central problem is to monitor, in real time, the structural response that is determined from in-flight sensor measurements, e.g., surface strains. The structural deformations are reconstructed from the discrete measurements and *hot spots*, where various modes of material and/or structural failure may be initiated, are identified. The numerical treatment of such problems generally falls into the category of inverse, ill-posed problems.

In this paper, a computationally attractive and highly efficient *Inverse Finite Element Method (IFEM)* is developed that is perfectly suited for real-time structural health monitoring applications. The formulation is based upon the minimization of a smoothing functional that employs least-square-difference terms involving the interpolated element-level strains and the strains measured by sensors (gauges). The least-square enforcement of the strain-displacement relations is included in the smoothing functional. The physical domain is discretized by the *Deformation Reconstruction (DR)* finite elements that maintain C^0 continuity across their interfaces. The simplest and most efficient *DR* elements are developed for one- and two-dimensional problems and have, respectively, two- and three-node patterns. The inverse formulation results in the governing system of linear algebraic equations. Upon enforcing the requisite displacement boundary conditions, these equations are readily solved for the unknown displacements. Thus, the deformed structural shape is fully reconstructed from a set of discrete strain measurements. Subsequently, complete strain and stress fields are computed using customary procedures.

The paper describes the mathematical foundation of the method and presents numerical examples pertaining to shear-deformable beam and plate deformations.

Keywords: Inverse Problem, Finite Element Method, Least Squares, Ill-Posed Problem

Goal-Oriented Adaptive Modeling in Computational Mechanics

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The choice of a mathematical model of a mechanical event, while perhaps the most important step in a simulation of that event, is often based on heuristic arguments or the analyst's intuition. In some cases, a less accurate model is chosen because of its computational simplicity, even if the resulting solution is known to be inaccurate. In [1] and [2], Oden and Vemaganti put forward an adaptive mechanism for choosing the most appropriate mathematical model based on the goals of the simulation. This goal-oriented approach relies on a posteriori estimates of modeling error: the error introduced by the use of a simplified mathematical model (compared to the most sophisticated model available). In this work, we present some recent theoretical and computational results based on this approach. Applications to plate- and shell-shaped structures will be discussed.

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On Accuracy Of Explicit Finite Element Analysis For Structural Dynamics

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Dedicated to Prof. J. Tinsley Oden, on occasion of his 65-th birthday

Structural dynamics plays an important role in various engineering applications. Explicit finite element analysis is now frequently employed to solve impact related problems, a type of nonlinear transient dynamics. However, if the analysis tool is devised for nonlinear applications, it is expected to be able to deliver accurate solutions to linear problems as well. This paper is devoted to the evaluation on accuracy and convergence of the explicit finite element method for linear structural dynamics applications.

The axial free vibration of an elastic rod excited by initial velocity was studied. The numerical solution of natural frequencies and vibration motion by explicit finite element analysis are compared to the analytical solutions. Here, the time history of nodal displacement was obtained using an incremental procedure. The natural frequencies were extracted from the displacement history by using fast Fourier transform instead of the eigenvalue matrix solver used in implicit algorithms. For uniformly refined meshes with linear interpolation, the finite element convergence rate of frequencies matches the theoretical results by Babuska [1]. Cases of flexural free vibrations of beam and rectangular plate were studied in a similar way.

The studies are extended to forced vibrations of rod, beam and rectangular plate driven by given displacement boundary conditions. The numerical results are presented and compared to the analytical solutions by Wu [2], which are decomposed into the superposition of a transformation part and a homogeneous harmonic vibration part. As a general observation, the explicit finite element analysis method can deliver solutions to these linear elastic problems with desired accuracy if the mesh is fine enough.

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Study Of Adaptive Explicit Finite Element For Crashworthiness

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Dedicated to Prof. J. Tinsley Oden, on occasion of his 65-th birthday

Adaptive methods of finite element analysis are considered powerful tools for many engineering applications. Explicit finite element analysis is effectively used for various problems related to crashworthiness and impact engineering, a type of nonlinear transient structural dynamics. The adaptivity of explicit finite element analysis will be

of interest to both research and engineering applications if it can efficiently deliver high accuracy solutions.

Examples of structural component crash simulations are used to illustrate the adaptive procedure of explicit finite element analysis and to examine the quality of adaptive refinement with comparisons to uniform refinement.

It was observed that solutions by adaptive method are comparable to those using a uniform mesh of the same level but use much less CPU time. For this type of transient dynamics problem, a backward loop to resume the analysis at an earlier time with a refined mesh is necessary to avoid or reduce error accumulation. A suitable time period of refinement is important for the engineering applications. The error indicator based on shell element normal rotation is found to be effective for the solutions of bending dominated crashworthiness applications.

Opportunities of future development are also discussed.

Symposium on

Turbulence Structure and Flow Control

In Honor Of
Professor A. Roshko

Organizer:
Professor D. Papamoschou
(University of California - Irvine)

TURBULENCE STRUCTURE AND FLOW CONTROL

In Honor Of Professor Anatol Roshko

SESSION R1F
Coherent Structures

Is Viscous Dissipation Always Needed?

Anatol Roshko

California Institute of Technology

The usual assumption in describing asymptotic models of free turbulent shear flows is that the mean flow field is independent of Reynolds number because, for values greater than $10^3 \sim 10^4$, the viscous stresses are much smaller than the Reynolds stresses. This leads to the well known growth laws for wakes, jets, etc. On the other hand, viscosity is seen as having a central role in turbulence models which are based on the energy equation, for example the $k - \varepsilon$ model, in which

$$\varepsilon = \nu \overline{\frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j}}$$

is the viscous dissipation. Two possible interpretations of this apparent contradiction lead to quite different views of the underlying mechanics, as follows.

(1) For ε to be independent of Re the squares of the turbulent velocity gradients must increase linearly with increasing Re, i.e. decreasing ν. This would be similar to the situation in a gasdynamic shock wave, in which the thickness of the shockwave is regulated by the viscosity while the mean-flow changes across the shock are independent.

(2) Alternatively, the viscous dissipation does not control the growth of a turbulent free shear flow but simply disposes of energy being removed from the mean flow by mixing. In this case the situation is more like that in an inelastic collision, in which the momentum exchange requires that a defined amount of kinetic energy be "lost" but the details of that dissipation need not be prescribed.

The second alternative appears to be the correct one. This is suggested by the progress that has been made in relating the development of turbulent mixing layers to the inviscid instability properties of their large structures. In this case the growth is limited by nonlinear features of the instabilities.

Core Dynamics of Coherent Structures in Shear: A Prototypical Physical Space Cascade Mechanism

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Motivated by the prevelance in turbulent flows of coherent vortices with complex axial structure (nonuniform core area, axial inhomogeneity of core vorticity distribution, helical vortex lines), we study a rectilinear vortex with sinusoidal core size variation in the presence of an orthogonal uniform shear. A newly found instability – core dynamics instability (CDI) – of the vortex (absent without the shear) is shown to result from stretching by the shear of helically twisted vortex lines. CDI-induced strong axial flow generates a low-enstrophy 'bubble' (similar to axisymmetric vortex breakdown), surrounded by a thin sheath of vorticity. The sheath rolls up into fine

scale 'vortexlets' via a Kelvin-Helmholtz-type instability. Additionally, fine-scale vorticity is generated by the axial flow via the folding and reconnection of core vortex filaments. The vortexlets (similar to 'worms') have in turn their own CDI, and hence this transition scenario suggests a physical-space cascade process in fully developed turbulence (as well as a concomitant anti-cascade process during the bubble's collapse phase). We show that CDI, despite its weaker linear growth compared to bending waves, effects surprisingly much faster transfer of energy to fine scales, and hence is more effective than bending waves in vortex transition and turbulence cascade. As an example, we consider a plane mixing layer and show that CDI – triggered at a large amplitude via the helical pairing instability of spanwise vortex rolls – dominates transition even in the presence of the bending waves excited by well developed ribs.

The Largest Scales of Turbulent Wall Flows

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Evidence has accumulated for some time that there are very large anisotropic structures (VLAS) in the intermediate layer of wall-bounded shear flows, with streamwise lengths which may reach 20-30 times the boundary layer thickness. On the other hand, investigations of the small scales of the turbulent near-wall region have identified self-sustaining structures who survive in the absence of interactions with the external flow, suggesting that the near-wall region acts in wall-bounded flows as a turbulence-generating layer.

We will discuss in this talk two sets of numerical simulations to explore possible relations between these two phenomena. The first one is a direct numerical simulation of a turbulent channel at $Re_\tau = 550$, in a very large computational box ($8\pi \times 2 \times 4\pi$) which allows for the study of the VLAS. The associated grid is $1536 \times 257 \times 1537$ (6×10^8) collocation points, using a fully pseudospectral code. The second set of experiments investigates the possible large-scale organization of the near-wall structures by means of large simulations of 'autonomous' walls in which the outer flow is numerically masked above some particular wall height.

It is for example found that, in autonomous walls in which the flow is masked above $y^+ \approx 80$, the three velocity components have substantial energy in structures which are several thousand wall units long. It is interesting that the spectra of the wall-normal velocity are almost identical, below $y^+ \approx 50$, to those of full turbulent channels, even if the outer flow is completely missing in the autonomous case. This result strongly suggests that the organization of the wall is essentially independent of the outer flow, even at the largest scales. In the case of the streamwise velocity the structures of the autonomous wall are actually longer than those of the full channel, suggesting that the effect of the outer flow is to limit the length of the near-wall structures, instead of imposing on them their large-scale organization.

The velocity in the full channel has a near-wall spectral peak which scales in wall units, and an outer one which scales in outer units. The longest velocity component in the streamwise direction is the streamwise velocity, and peaks at a maximum length of about $x = 4h$ somewhere above the upper edge of the logarithmic layer. These long structures are also wide, following an apparent power relation $\lambda_z \sim \lambda_x^\alpha$, with an exponent between $\alpha = 1/2$ and 1/3. This suggests that their size is controlled by dissipation, probably through smaller-scale eddy viscosity. These transverse spectra are relatively novel, since little was known up to now about the spanwise organization of the outer flow.

Some structure identification work will also be described, related to the question of whether the large structures can be described as 'attached' eddies, as proposed by Townsend.

The computer time for the largest simulations was graciously donated by the CEPBA/IBM research centre of the U. Politécnica de Catalunya.

Coherent Structures and Turbulent Drag Reduction in Boundary Layers

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Significant insight into the structure of turbulent boundary layers has been gained from direct numerical simulations, DNS. The first DNS of wall bounded flows was performed in the early 1980's when the interest in coherent structures was at its peak among the research community largely due to the works of Roshko and co-workers in free-shear flows and Kline and co-workers in boundary layers. Although early numerical simulations focused on computing realistic laboratory flows, recently, more has been learned about turbulence physics from DNS of ide-

alized flows that can not be attained in the laboratory (e.g., Minimal Channel of Jimenez and Moin, JFM, 1991).

DNS studies have shown that the regions with large skin friction on the wall are associated with quasi-streamwise vortices in the buffer layer. Turbulent control strategies that aim at suppressing the flow due to these structures have led to significant drag reduction. Although many of these flow control strategies are not practical for engineering applications, they have demonstrated the feasibility of significant drag reduction in a fully developed turbulent flow by controlling its relevant coherent structures.

In laboratory and practical devices large drag reductions have been achieved by injection of minute traces of long chain polymers. Recent DNS studies are beginning to shed light on the mechanics of drag reduction by polymers. In these studies, which have become possible owing to the availability of large parallel computers, long chain polymer molecules with multiple beads are tracked in a Largrangian fashion in a DNS flow field. The effect of the near wall coherent structures on the polymers is being investigated. The results from these studies and the insight gained on the mechanisms of polymer drag reduction will be presented.

Large Reynolds Number Asymptotics of Mean Velocity Profiles in Turbulent Wall-Bounded Flows

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Controversy concerning the form of the mean velocity profile, in particular of the universal "law of the wall" in turbulent wall-bounded shear flows exists. A methodology based on matched asymptotic expansion techniques, in which the measured or computed mean velocity profiles are identified with composite expansions, is used to extract the limiting behavior at infinite Re_τ (Reynolds number based on friction velocity and channel half-width or pipe radius) as well as the corrections for finite Re_τ. Concentrating on streamwise homogeneous (parallel flow) cases, several data sets for the channel and the Princeton "Super-Pipe" data are used to fit suitable "outer" solutions near the channel or pipe center. This outer fit permits to extract the "inner" solution from the original data, including the presumably universal near-wall solution in terms of the inner coordinate y_+. As shown on the figure below, the inner behavior of the viscous shear stress normalized by the total stress $(1-\eta)$, where $\eta = y_+/Re_\tau$ is the "outer variable", is clearly proportional to $(y_+)^{-1}$ for $y_+ \to \infty$, corresponding to the classical "log-law" with a Kármán constant of 0.39. For finite Re_τ, the different correlations obtained from various experimental data are discussed within the proposed framework, including the scaling of the friction coefficient and of the location of maximum Reynolds stress with Re. Finally, the streamwise inhomogeneous case of the boundary layer is examined in the framework of the present methodolgy, leading to some observations on the self-similarity of the "inner" and "outer" parts of boundary layer profiles.

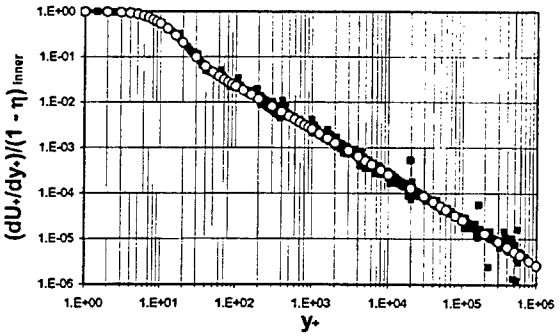


Fig. 1. The "inner" behavior of the normalized viscous stress in the limit of infinite Re, extracted from 12 channel and pipe data sets between $Re_\tau = 390$ and 528'000 (white circles represent a fit).

Keywords: Turbulence, channel and pipe flow, boundary layers, large-Re asymptotics

This work was supported by NSF, AFOSR & ERCOFTAC.

TURBULENCE STRUCTURE AND FLOW CONTROL

In Honor Of Professor Anatol Roshko

SESSION R2F
Bluff Body & Cavity Flows

Performance and Near Wake Flow Structure of Base Drag Reducing Devices

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In order to gain a better understanding of base drag, the near wake flow, base pressure and drag of a bluff body were measured with and without drag reducing devices

attached. The model is a rectangular box with sharp trailing edges, and rounded leading edges designed to produce attached flow over the length of the body. The drag reducing devices are attached to the base and do not interfere with the flow upstream of separation. The model was mounted near a ground board to simulate ground effects. Drag was measured in a large scale wind tunnel up to 2×10^6 Reynolds number based on model width. The velocity field in the near wake was measured using PIV in a smaller scale wind tunnel for Reynolds numbers of order 10^5. Mean and spectra of the base pressure fluctuation were measured in both tests. The results clearly demonstrate the large drag reduction that can be realized with relatively minor changes in the base flow, reminiscent of Roshko (1955) drag reduction concept of a "splitter plate" placed in the wake of a circular cylinder. However, in the present case several mechanisms of drag reduction appear to be at work. In analyzing these results basic ideas first introduced by Roshko and collaborators in the context of two dimensional bluff body wakes provide interesting new insights. In particular, th einterplay between drag, turbulent flow structure, base pressure coefficient, and the size of the recirculating flow region is reviewed.

Research sponsored by GM Corp.

The Limits of Drag Behavior for Two Bluff-Bodies in Tandem

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The drags of two rectangular parallelepipeds are examined with bodies arranged in tandem and close enough together to strongly influence one another. Each of the two bodies can either be perfectly blunt at both ends or can be fitted with an attachment that rounds the forward vertical edges. Simply rounding the vertical leading edges decreases the drag coefficient for the single body (body-in- isolation) from 0.92 to 0.46 for the edge radius (edge radius Reynolds number) utilized. Four tandem configurations are tested, depending upon the presence or absence of leading edge rounding-no attachment on either body, attachments on both bodies, attachment on the lead body only, and attachment on the trail body only. The most reliable experimental measurement is the value of the drag for either body-as a function of spacing between the bodies in tandem-relative to the drag of the same body in isolation. The body spacing is expressed as a multiple of (A, where A is the body cross-sectional area.

The drag of both bodies is decreased by the interaction for all body-spacings investigated from 0 - 3.5. The drag saving for the trail body is greatest at the smallest spacing, and decreases as spacing increases. Drag saving decreases by about a factor of two as spacing varies from 0 - 1.0, then decreases more slowly over a much longer length scale. Usually, the drag saving for the lead body is smaller than for the trail body, but not always. When both bodies have a low drag-in-isolation, there is a range of spacing for which the lead body has the lower drag. It is possible to understand these various behaviors by considering, separately, the drag contributions arising from the forebody and from the base of each body.

Another interesting feature of the interaction is the significant, unsteady cross-flow developed in the space between the two bodies. At spacings near unity, the cross flow often produces a local drag maximum and a concomitant fluctuating side-force (on both bodies) of magnitude approximately one-half the drag-in-isolation. Finally, it is demonstrated that drag savings for two tandem model trucks having wheels, cabs and trailers and drag coefficients in the range 0.5-0.65, are contained within the drag bounds established for the four parallelepiped tandem combinations discussed above. That is, the drag saving for the two model trucks is never as great as the saving for the parallelepiped arrangement of minimum drag, nor is it ever so poor as the saving for the parallelepiped arrangement of greatest drag.

Keywords: aerodynamics, experiments, bluff body, drag
The Limits of Drag Behavior for Two Bluff-Bodies in Tandem

Recent Advances in Hybrid Propulsion

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This presentation concerns rocket propulsion systems based on the burning of liquid or gaseous oxidizer with a solid evaporating fuel. The hybrid rocket has been known for over 50 years, but wasn't given serious attention until the 1960's. The primary interest was in the nonexplosive character of the fuel, which led to safety in both operation and manufacture. Additional advantages over a solid rocket are greatly reduced sensitivity to cracks and debonds in the propellant, better specific impulse, throttleability to optimize the trajectory during atmospheric launch and orbit injection and the ability to thrust terminate on demand. The main advantages of the hybrid over a liquid system are:

- The hybrid rocket presents a reduced explosion hazard compared to a liquid, since an intimate mixture of oxidizer and fuel is not possible.

- The hybrid rocket requires one rather than two liquid containment and delivery systems. The complexity is further reduced by omission of a regenerative cooling system for both the chamber and nozzle.
- Throttling control in a high regression rate single-port hybrid is simpler because it alleviates the requirement to match the momenta of the dual propellant streams during the throttling operation. Throttling ratios up to 10 have beencommon in hybrid motors.
- The fact that the fuel is in the solid phase makes it very easy to add performance enhancing materials such as aluminum. This enables the hybrid to gain an Isp advantage over a comparable hydrocarbon fueled liquid system.

The principal disadvantage of the hybrid rocket is the inherent low burning rate of conventional fuels due to the diffusive nature of the combustion process. However recent research in our laboratory at Stanford University has led to the identification of a class of solid fuels that burn at surface regression rates approximately 3 times that of conventional hybrid fuels. Our approach involves the use of materials that form a hydrodynamically unstable liquid layer on the melting surface of the fuel. Entrainment of droplets from the unstable liquid-gas interface can substantially increase the rate of fuel mass transfer leading to much higher surface regression rates than can be achieved with conventional polymeric fuels. The class of fuels we have identified provide Isp performance comparable to kerosene but are approximately 20% more dense than kerosene this permits the design of a high volumetric loading single-port hybrid system with a density impulse comparable to or greater than a hydrocarbon fueled liquid system. Initial design studies indicate that most applications up to large boosters can be satisfied with a single circular port configuration. The presentation will focus mainly on recent scale-up studies to motors with thrust levels over 2000 pounds.

Keywords: droplets, mixing, entrainment, stability

The Role of the Hemodynamic Stresses in the Etiology of Arterial Aneurysms

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Results of an ongoing study seeking to improve the understanding of the etiology of arterial aneurysms by quantifying the role that the mechanical stimuli on the arterial walls play in the aneurismal growth are discussed. DPIV measurements performed in prototypical arterial geometries as well as in anatomically correct models are presented and their role in the formation and growth of various types of aneurysms are discussed. High-resolution CAT scans are used to monitor the time evolution of the shape and size of Abdominal Aortic Aneurysms (AAA) as well as of intra-craneal aneurysms in patients that had elected to delay surgical treatment. At each observational time, an elastic silicone-based model of the arterial network is manufactured from casting molds obtained from the high-resolution CAT images using volume-rendering rapid-prototyping techniques. Detailed measurements of the distribution of wall shear stresses and pressures in the in-vitro laboratory models are then performed while simulating the hemodynamic conditions measured in the patient (cardiac output, cardiac pressure, pulse form, etc.). The clinically observed location and magnitude of the enlargement rate of the aneurysms are then analyzed in light of the laboratory in-vitro measurements of the distribution of pressure and shear stresses on its wall.

TURBULENCE STRUCTURE AND FLOW CONTROL

In Honor Of Professor Anatol Roshko

SESSION R3F
Vortex Aerodynamics

Point Vortex Models of Shear Layers and Wakes

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The kind of modeling we have in mind goes back to von Krmn, Rosenhead, Dolaptschiew and many others. Their early work resolved a great many issues and provided a framework for thinking about this class of problems analytically. As might be expected, advances in the theory of dynamical systems and in our understanding of vortex dynamics allow us to see many of the early results in a new light, to arrive at their conclusions in somewhat different ways, and to extend the investigations in various directions. In the presentation I shall not attempt to derive much of anything but devote my time to re-stating what is known, what can today be done in a more comprehensive or more expedient way, and to pointing out new directions that seem worth pursuing. The analytical results suggest that many modes exist which do not at the present time have experimental support.

Vortex Persistence: When a Turbulent Flow Yields a Laminar Flux

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Boundary layers are known to exhibit either relatively low values of wall fluxes or else relatively high values. According to conventional wisdom, low fluxes are always associated with laminar flow and high fluxes with turbulent flow. However, there is a third possibility. A novel kind of hybrid turbulent flow has been demonstrated to yield a low, laminar-like flux.

According to a recent theory by Cotel, when a vortex is near a wall, the wall fluxes are proportional to the inverse square root of an eddy rotation period. There are only two distinguished eddies in a turbulent flow, the smallest and the largest. If the smallest eddy controls the fluxes, then the fluxes have high, "turbulent" values. This is the case when the vortex moves with respect to the wall, such as in the ordinary turbulent boundary layer. On the other hand, if the vortex is somehow made sufficiently stationary and strong, or "persistent," the largest eddy controls the fluxes, completely independent of any fine-scale turbulence. The fluxes then have "laminar" values, in spite of the turbulence.

Experimental measurements of heat flux are in accord with theory. A special wavy wall developed by Balle passively stabilizes streamwise vortices introduced from an upstream array of vortex generators. Measurements reveal that the heat flux declines to a laminar value even though the flow contains fine-scale turbulence. It is counterintuitive that when strong vortices are added, the heat flux decreases. Persistent turbulence yields laminar fluxes.

The Dilemma of an Optimal Vortex: A Study of Vortex Ring Formation in starting flows

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The unsteady formation of vortices is amazingly common in nature and is a regular source of intrigue in the laboratory. In the absence of density gradient, vortex formation is usually involves boundary layer separation and generation of unsteady shear layers. Vortex rings formation, wake of the impulsively moving objects as well as the vortex shedding process are among typical examples of flows that involve unsteady vortex formation. A common feature of vortex formation process in the abovementioned flows is the existence of a time scales with a narrow range of values that charactrizes the saturation of the formed vortices. This time scale (referred to as the formation number) is the time beyond which larger vortices are not possible. It has been shown that this narrow range for the formation number is a direct manifestation of the variational principle proposed by Kelvin and Benjamin for steady axis touching vortices.

The mere existence of the formation number is intriguing since it hints at the possibility that nature may use this time scale for some evolutionary incentives such as optimum ejection of blood from the left atrium to the heart's left ventricle or locomotion process where ejection of vortices might have been utilized for the purposes jet propulsion.

In this talk we will address the question of vortex optimization. We will present experimental and analytical result that point at "formation number" as the key parameter responsible for optimizing thrust and mixing augmentation in pulsatile fluidic devices as well as lift and drag saturation in impulsively moving objects.

Flow Induced Vibration: Ongoing Modeling Efforts

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Recent studies of flow-induced, transverse oscillations of a circular cylinder that is dynamically mounted have revealed somewhat unexpected behavior, especially at low values of the cylinder/displaced fluid mass ratio m^*. When the nondimensional elastic force k^* is also small, the fluid dynamics seems to pay little respect to the mechanical system and has a mind of its own. Lock-in to the mechanical frequency no longer holds and, in the limited case of no damping and $m^* = k^* = 0$, a nearly sinusoidal oscillation at amplitude to diameter ratio $A/D = 0.47$ and a frequency $fD/U_\infty = 0.156$ is produced in two-dimensional numerical simulations reported in Shiels et al 2001.

On the other hand efforts to model this flow usually start with a van der Pol type equation for the fluid force that has correct limit-cycle behavior when the cylinder is at rest and vortex shedding produces a fluctuating lift force at a known (Strouhal) frequency. Models of this type do moderately well at reproducing the behavior of high m^* configurations but are not at all successful at low m^*. In particular, in the limiting case mentioned above,

the fluid force is identically zero for all time yet substantial cylinder motion occurs.

Recent efforts to model such behavior will be discussed.

Keywords: Flow-induced vibration, unsteady vortical flows

Shiels, D., Leonard, A., and Roshko, A., 2001, "Flow-induced vibration of a circular cylinder at limiting structural parameters," *Journal of Fluids and Structures*, **15**, 3-21.

Resonance Forever!

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In this work, we shall show a rather surprising new result, which comes from studies of resonance in vortex-induced vibration problems. We study the transverse vibrations of an elastically-mounted rigid cylinder in a fluid flow, at extremely low mass and damping, and we use simultaneous force, displacement and vorticity measurements (using DPIV) for the first time in such a free vibration study.

For large mass ratios (for large relative density of the oscillating structure), $m^* = O(100)$, as employed in classical studies of vortex-induced vibration (going back to the work of Den Hartog (1936)), the oscillation frequency for synchronization (f) lies close to the natural frequency (f_N), so that the normalised frequency, $f^* = f/f_N \sim 1.0$. However, as we reducethestructural mass to $m^* = O(1)$, in our studies, we find that the oscillation frequency f^* can reach remarkably large values. Derivation of a simple frequency equation uncovers the existence of a *critical mass ratio*, where the oscillation frequency f^*, for one of the vibration response branches, becomes infinite. The critical mass is given as:

$$m^*_{CRITICAL} = 0.54$$

If the structure mass falls below this critical value, one of the modes of vibration can never physically be reached, although another high-amplitude vibration mode exhibits oscillations which start when the normalised velocity $U^* \sim 4$, (corresponding to the classical synchronisation, $f^* = 1$), and continue as a "resonant" vibration, no matter how high is the free stream velocity! The oscillation frequency continues to increase as flow velocity is increased, and we find "resonance", for example, when the vibration frequency is 200 times the natural frequency, which is very far from conventional results! By rather careful selection of parameters, we have completed further independent experiments at infinite velocity (U^*) within the physical confines of our laboratory, and confirm the existence of large-amplitude resonant vibrations under these conditions, so long as the mass is below critical.

Our discovery that resonance can persist "forever", so long as the structural mass falls below a critical value, is quite different from the general belief since the 1930's, that the forcing frequency must be close to the natural frequency to induce large amplitude resonant flow-induced vibration. These simple results are a paradigm for other bodies undergoing vortex-induced vibrations, and are apparently generic features for such flows.

Keywords: Vortex Dynamics; Vortex-induced Vibration; Resonance; Critical mass.

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TURBULENCE STRUCTURE AND FLOW CONTROL

In Honor of Professor Anatol Roshko

SESSION R4F
Mixing and Combustion

Progress in Turbulent Mixing and Combustion

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Turbulent combustion combines the complexities of turbulence and mixing, challenges not met in the twentieth century, with the complexity and subtlety of chemical kinetics, and flow-combustion coupling through heat release. Issues that arise in non-premixed chemically reacting flows include the distribution and composition of the mixed fluid, mixing time scales, their relation to chemical-reaction time scales (Damkohler number effects), effects of heat release, the dependence of these phenomena on molecular transport coefficients at high Reynolds numbers (post-mixing-transition flows), the geometry of the irregular level sets (isoscalar surfaces) of the scalar field that arise in turbulent flows, and many others. The discussion focuses on progress and issues stemming from experimental, modeling, and direct-numerical simulation (DNS) studies of shear layers, jets, and Rayleigh-Taylor

flows. Experiments in high-speed shear layers and turbulent jets involving reactants with known chemical-kinetic rates have helped elucidate mixing-reaction regimes expected in high-speed flows and shed light on Reynolds number effects. Issues involving molecular-transport coefficients will also be discussed.

Work supported by the Air Force office of Scientific Research, the U.S. Department of Energy, and the Caltech John K. Northrop Chair.

Mixing Layers: What Happens at Large Density Ratio?

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The seminal study of variable density mixing layers by Garry Brown and Anatol Roshko indicated growth rate is an increasing function of the density ratio s, (density of the slow stream to that of the fast stream). This trend was observed for density ratios from $1/7$ to 7. The prevailing viewpoint has been that this trend can be extended to larger and smaller density ratios. To study this effect, One-Dimensional Turbulence (ODT), a stochastic simulation of turbulent flow, has been generalized to variable density spatially developing flow. As a first step, results obtained using a variable density temporally developing formulation have been compared to direct numerical simulations (Pantano & Sarkar, JFM, 2002). Velocity and density profiles are generally well reproduced by ODT, considering that the present formulation omits compressibility effects that are in the DNS results. Both ODT and DNS indicate growth rate reduction as density contrast increases (in temporal flow, density ratios s and $1/s$ are equivalent.) For the spatial mixing layer, ODT results are compared with measurements at velocity ratio $r = 0.38$. Adjusting one parameter to match the measured velocity profile at constant density, the overall width and other features of velocity and density profiles for $s = 1/7$ and $s = 7$ are generally well predicted. Various growth rate metrics indicate that a maximum growth rate occurs in the range $1 < s < 100$, beyond which the growth rate diminishes. In ODT, growth rate reduction is associated with the formation of a sharp density interface on the high density side. This inhibits the entrainment of high density fluid into the lower density mixed zone due to its high inertia relative to the mixed region. This inertial barrier to entrainment is reminiscent of the potential energy barrier to entrainment at stably stratified density interfaces.

Keywords: Turbulence, Modelling, Shear, Variable Density

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Flame Liftoff and Blowout

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Anatol Roshko had an interest in jets and jet flame stability, resulting in the Ph.D. thesis of Hammer [1]. Here we report on the transition from flame liftoff to flame blowout of a non-premixed turbulent jet flame by comparing a stable lifted flame with a lifted flame near blowout [2]. The near-blowout condition is easily achieved by changing the coflow speed of a lifted flame in coflow. The velocity field at the flame base and the location of the flame surface are simultaneously obtained using particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF) of CH. Instantaneous images show the divergence and the deceleration of the flow at the flame base which is characteristic of a leading edge flame. The width of the flame base is found to be wider when the flame is near blowout. The velocity measurements at the flame base show that the flame base of a flame near blowout is exposed to a higher axial velocity (3.1SL) when compared to a stable lifted flame (2.3SL), yet both velocities remain low. These observations are consistent with numerical studies of the laminar triple flame. In addition, the axial velocity on the flame surface tends to stay at or near the stoichiometric velocity (US), which is determined by the stoichiometric mixture fraction (ZS), jet speed, and the coflow speed (UCF). Accepting the leading edge flame as the flame st abilization mechanism, a simple blowout mechanism is proposed.

[1] J. A. Hammer, "Lifted Turbulent Jet Flames", Ph.D. Thesis, Caltech (1993).

[2] Donghee Han, "Study of Nonpremixed Jet Flames Using Simultaneous Measurements of Velocity and CH Distribution", Ph.D. Thesis, Stanford University (2001).

TURBULENCE STRUCTURE AND FLOW CONTROL

In Honor Of Professor Anatol Roshko

SESSION F1F
Flow Control

Experiments on Boundary Layer Receptivity, Stability and Transition at Mach 3

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Recent results from an experimental study of receptivity, along with earlier measurements on stability and transition of the flat plate, laminar boundary layer, at Mach 3 are discussed. The most recent results involve acoustic forcing with oblique waves from two sources in the settling chamber. Spectra, growth rates and amplitude distributions of naturally occurring boundary layer waves were measured initially. These results are compared with the recent measurements of receptivity in the forced case. Comparisons between experiments and calculations for the growth rates of unstable high frequency waves based on a non-parallel, mode-averaging stability theory (Federov) are shown and good agreement is found. In contrast, naturally occurring low frequency disturbances were measured to grow in regions where according to linear stability theory they are expected to decay. A detailed investigation of the free-stream disturbance field provides some reasons for this discrepancy. It was found that a free-stream calibration of the hot wire gave a double peak boundary layer disturbance amplitude distribution, as has been found by previous investigators, which is not consistent with the predictions of linear stability theory. This was found to be an anomaly due to assumptions often made in the free-stream calibration procedure. Agreement between experimental and theoretical results was established only when the hot-wire voltage was calibrated against the mean boundary layer profile. Difficulties in the calibration of wires at conditions typical of a laminar compressible boundary layer are briefly mentioned. In the late stages of transition, calibrated amplitude levels are obtained at locations where non-linearities are first detected and where the mean boundary layer profile is first observed to depart from the laminar similarity solution. A qualitative discussion of the character of ensuing non-linearities is included.

Fluidic-Based Aerodynamic Flow Control

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Controlled modification of the global performance of aerodynamic surfaces is achieved by fluidic manipulation of their apparent aerodynamic shape that is effected by surface-mounted arrays of synthetic jet actuators. The interaction domain of the jets with the cross flow displaces the local streamlines near the surface and thereby induces an 'apparent' modification of the flow boundary. The actuation frequency is selected to be high enough so that the actuation period is at least an order of magnitude lower than the characteristic time scale of the flow. Hence, on the global time scale, the interaction domains between the actuator jets and the cross flow are quasi-steady and therefore the induced aerodynamic forces are virtually time-invariant.

The local displacement of the cross flow and consequently the alteration of the streamwise pressure gradient near the flow boundary enables the suppression of flow separation, the alteration of lift and form drag, and the manipulation of vortex flows on scales that are one to two orders of magnitude larger than the actuation length scale. An important attribute of active modification of the apparent shape of aerodynamic surfaces is that it may enable unconventional aerodynamic design approaches that are driven primarily by mission constraints (e.g., stealth, payload, volume, etc.). The reduced aerodynamic performance of such unconventional airfoil shapes (which may stall at small angles of attack) can be augmented by the use by fluidic control throughout their flight envelope.

The prescribed modification of the streamwise pressure distribution on aero-surfaces and the extent of separation suppression (including the controlled formation of closed recirculating flow bubbles) is affected by the streamwise location and the strength of the actuator jets. The excitation is effective over a broad streamwise domain that extends well upstream of where the flow separates in the absence of actuation and even downstream of the front stagnation point on the pressure side of the airfoil. At low angles of attack (when the baseline flow is fully attached), the interaction of the actuator jets with cross-flow can result in substantial reduction of pressure drag with minimal or no penalty in lift. Furthermore, the quasi-steady lift coefficient of the attached flow can be substantially augmented by exploiting a prescribed unsteadiness of the separated flow domain using a temporally-modulated control input and thereby controlling the rate of vorticity shedding into the wake. Finally, high-frequency excitation at Strouhal numbers that are at least an order of magnitude higher than the Strouhal number of the unforced flow

(based on the time of flight along the chord) can result in a narrower wake and weaker (less coherent) spanwise vortices.

Keywords: Synthetic Jets, Fluidic Actuators, Virtual AeroSurface Shaping, Separation

A Systems Control Theoretic Approach to Turbulence Control

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Control of turbulent boundary layers has been a subject of much interest because of its high potential payoffs. The control requires, however, a thorough understanding of the underlying physics of the turbulent flow and an efficient control algorithm, both of which have been less than satisfactory. Great strides on both fronts have been made through the recent advancement in computational fluid dynamics and control theories. New approaches to controller design are significantly different from existing approaches, which were mostly based on the investigator's physical insight into the flow, in that modern control theories are incorporated into the controller design. We have been developing controllers for boundary-layer control utilizing the systems control-theoretic approach.

Examples include linear quadratic regulator (LQR) control, linear quadratic Gaussian (LQG) synthesis, and the system identification approach for incompletely known dynamical systems. These approaches explicitly exploit certain linear mechanisms present in the wall-bounded shear flow, and their success suggests the importance of linear mechanisms in the turbulent (and hence, nonlinear) flow. Although all of these new approaches have been thus far based on numerical experiments (and yet to be verified in laboratory experiments), they have shown great promise and present a new approach to flow control.

Active Control of Separation

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Zero-mass Efflux Repetitive Oscillatory (ZERO) jets introduced from spanwise slots at various locations on the upper surface of steady and oscillating airfoil models are shown to be effective in controlling lift, moment and drag coefficients over the range of Mach numbers up to 0.42. This control is demonstrated over a wide range of mean angles of attack from light to deep stall conditions on several airfoil cross sections with or without flaps. Maintaining the non-dimensional frequency and amplitude of the forcing unchanged results in comparable modifications of the aerodynamic coefficients throughout this Mach number range. Near the higher end of this Mach number range, local supercritical conditions are experienced near the leading edge and shocks are present. Even in these cases the flow control was found to be effective with slot locations near the location of the shock. Therefore, it appears that this active-flow control technique is only limited by the ability to generate the adequate forcing conditions at the higher Mach numbers required for applications such as rotorcraft, and aircraft requiring high lift for short takeoff and landing or controllable drag for rapid maneuverability. The presentation will focus on the flow physics in the regions where the control is introduced and on the scaling of the control parameters.

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On the Dynamics of Controlled Separation and Reattachment of Turbulent Boundary Layer

I., Wygnanski

The controlled separation and reattachment of flow to an inclined flat surface was investigated experimentally, emphasizing the transient aspects of the process. A fully developed turbulent boundary layer separated from a flat surface, when it encountered a divergent corner simulating the flow over a deflected flap. The state of the flow was altered by the addition of periodic perturbations emanating from the flap hinge. Particle Image Velocimetry (PIV) and dynamic pressure measurements were made concurrently during the transient processes. The results from this investigation can help in controlling an airplane without physically deflecting a flap (a control surface) or controlling the dynamic stall on helicopter rotor blades.

TURBULENCE STRUCTURE AND FLOW CONTROL

In Honor Of Professor Anatol Roshko

SESSION F2F
Jet Noise

High Speed Jet Noise Reduction Using Microjets

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The dominant component of the mixing noise of high-speed jets is highly directional, peaking at smaller angles to the jet axis (or larger angles to the inlet axis), emanating from sources at the end of the potential core. The radiation field containing shock like wave structures is associated with the "crackle" that is peculiar to high-temperature and high-speed jets. The frequency of occurrence of these strong waves increases with increasing temperature. In this paper, using a novel technique, we will demonstrate the suppression of the far field sound associated with crackle. The technique uses injection of high-pressure (500 psia) air from micronozzles at the nozzle exit. The main converging nozzle has an exit diameter of 50.8mm. The micro nozzle has a diameter of 400μ. Eight micro nozzles are used to inject high-pressure air at the nozzle exit with the resulting mass flow being about 1% of the main jet. The far field narrow band frequency spectrum shows the effectiveness of the microjets in reducing the sound pressure levels in a wide frequency range. The corresponding OASPL shows a decrease of about 4.5 dB. It is believed that microjet injection eliminate the sources associated with the crackle generation.

Noise Generating Mechanisms Involving Large Scale Structure in High Speed Jets

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For a number of years we have been conducting experiments to develop an understanding of the noise generation mechanisms in high speed jets. The focus of the work has been on the large-scale structures that produce the largest component of noise radiated from the exhaust jets of turbojet engines. There is a good possibility that such noise generation will soon be amenable to computation that will require little empirical input to produce accurate predictions. The reported measurements were devised to provide guidance for, and to evaluate such developing computational methods.

A unique feature of the experiments has been operation of the jets over a broad Reynolds number range, including Re values that are so low that the jets have substantial portions of laminar flow. The low density jet flows used to obtain the low Reynolds numbers permitted hot-wire measurements in supersonic jets to as high as M=2.5. In our conventional high density jet experiments, optical deflectometry has provided a method of measuring some of the properties of large scale turbulence structures. Most recently, efforts are focusing on noise generated by heated jets and helium/air mixture simulation of heated jets. This presentation will highlight the major results of this body of work, and will discuss the unresolved issues that are currently being addressed in our laboratory.

Keywords: Instabilities, noise, turbulence, jets

The Role of Large-Scale Turbulent Structures in Jet Noise

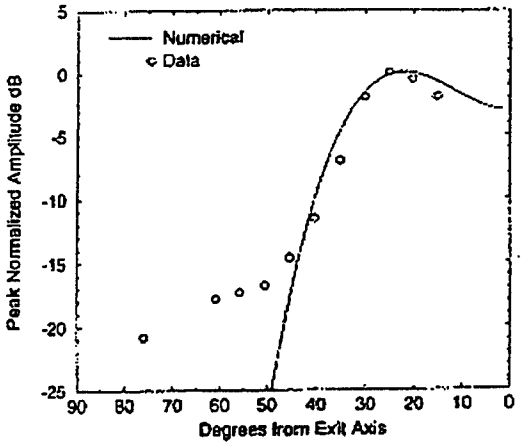
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The experimental observations by Brown and Roshko of large-scale structures in shear layers revolutionized the accepted view of turbulence in free shear flows. It became clear that these structures dominate the turbulent mixing process. It was also observed that the structures convect at approximately the average speed of the two freestreams and that they generate a traveling pressure disturbance at the edges of the shear layer. At sufficiently high speed, this disturbance travels supersonically with respect to the ambient speed of sound. By analogy with a supersonically moving wavy wall, the disturbances generate a wave field that propagates away from the shear layer. In a jet, this results in intense noise radiation at relatively small angles to the jet downstream axis. This has been termed Mach wave radiation or instability wave radiation. The latter name stems from the observation that the characteristics of the large structures are described very well if they are modeled as instability waves driven by the jet or shear layer mean flow. This paper reviews models for the large scale turbulence structures and their role in both turbulent mixing and noise generation. Examples are given for both free shear layers and jets. Predictions of turbulent mixing,

the effects of compressibility, Mach wave radiation and jet screech are presented.

Keywords: Turbulence, Free Shear Flows, Mixing, Noise



Comparison of Measured and Predicted Jet Noise Directivity for Supersonic Jet. Dahl and Morris, *J. Sound Vib.* **200** (1997)

Turbulence and Jet Noise[1]

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Noise from high-speed jets is generated by the turbulence of the flow. To predict jet noise or to reduce it, one must first find out how turbulence produces noise. Recently, Tam and Auriault [1] investigated the source of noise from high-speed turbulent jets. By using an analogy of how pressure is generated by the random motion of gas molecules in classical gas kinetic theory, they suggested that the dominant part of noise from the fine scale turbulence of the jet flow is produced by the unsteady fluctuations of the turbulence kinetic energy. In this talk, the basis of this suggestion is discussed. A theory, based on the suggested noise source mechanism, will be presented. The turbulence intensity, length and time scale of the theory are supplied by the k-e turbulence model. The model theory accounts for mean flow refraction effect through the use of an adjoint Green's function. The theory also incorporates source convection effect. Extensive comparisons between the predictions of the theory and experimental measurements over a wide range of jet Mach number and temperature ratio will be presented. It will be shown that there are excellent agreements. Noise data and predicted noise spectra for jets in simulated forward flight as well as for non-axisymmetric jets will also be presented. Again, it will be shown that there are good agreements. All these good agreements offer strong support for the validity of the model theory.

[1] AIAA Journal, vol. 37, pp. 145-153, 1999

[1] Work supported by NASA Langley Research Center Grant NAG 1-2145

Symposium on

Viscoelasticity in Composites

In Honor Of
Professor R. A. Schapery

Organizer:
Professor D. Allen
(Texas A&M University)

VISCOELASTICITY IN COMPOSITES

In Honor Of Prof. R. A. Schapery

SESSION M3I

Size Effect in Sea Ice Fracture and Triggering of Avalanches

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Based on the premise that large-scale failure of sea ice is governed by fracture mechanics, recently validated by Dempsey's in-situ tests of fracture specimens of a record-breaking size, the present study applies fracture mechanics and asymptotic approach to obtain approximate explicit formulae for the size effect in two fundamental problems. First, the load capacity of a floating ice plate subjected to vertical load is determined. Subsequently, the horizontal force exerted by an ice plate moving against a fixed structure is analyzed in a similar manner. The resulting formulae for vertical loading agree with previous sophisticated numerical fracture simulations as well with the limited field tests of vertical penetration that exist. The results contrast with the classical predictions of material strength or plasticity theories, which in general exhibit no size effect on the nominal strength of the structure.

A similar size effect model is formulated for dry slab snow avalanches. The ratio of the thickness of snow layer to the length is assumed to be small enough for one-dimensional analysis to be applicable. Equivalent linear elastic fracture mechanics (LEFM) is used to obtain a formula for the decrease of the nominal shear strength of the snow layer with an increasing thickness of snow. The formula is shown to closely agree with two-dimensional numerical solutions according to the cohesive crack model for mode II fracture with finite residual shear stress. By fitting these solutions for various snow thicknesses with the size effect law, an approximate one-to-one relationship between their fracture parameters is established. The effect of a pre-existing weak zone of small thickness and finite length is also studied. It is found that the pre-existing shear stress in this zone stress significantly affects the behavior. It causes that above a certain critical depth of snow depending on the pre-existing stress in the weak zone the size effect disappears.

References:
Bazant, Z.P., Scaling of Sea Ice Fracture: I. Vertical Penetration, and II. Horizontal Load from Moving Ice. ASME J. of Applied Mechanics — in press.

Keywords: Scaling, Sea Ice, Fracture, Size Effect.

The Viscoelastic Fracture and Indentation of Sea Ice

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The fracture of sea ice is modeled using a viscoelastic cohesive zone model. The sea ice is modeled as a linear viscoelastic material. The cohesive zone model is implemented via the weight function method. Viscoelastic behavior in the bulk is assumed. The model is applied to large scale in-situ sea ice fracture tests. Two coupled influences are back-calculated: the shape of the size-independent rate-independent stress separation curve, and the relevant creep compliance function. The basic knowledge thus gained is applied to ice-structure indentation and the high pressure zones that precede flaking, spalling and cleavage failure of the ice sheet. The influences of scale and indentation speed on the formation of these high pressure zones are explored. Line-like and localized high pressure contact zones are modeled via quasi-brittle hollow cylinder and hollow sphere approximations, respectively. For both simultaneous and non-simultaneous contact, the critical lengths of stable cracking that may occur prior to flaking and flexural failure are strongly linked to the current level of specific pressure parameters for both line-like and localized high pressure zones. The stability aspects of the in-plane cracking, and the link between the maximum possible crack lengths and the relative magnitudes of the local and far-field pressures help explain the transitions observed within the realms of ductile, intermittent, and brittle crushing.

Dynamic Fracture in a General Linear Viscoelastic Body

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Most dynamic fracture analyses for linear viscoelastic material bodies have assumed either anti-plane shear symmetry or isotropy with a constant viscoelastic Poisson's ratio. Recent progress by Maurizio Romeo (Rayleigh waves on a viscoelastic solid half-space, *J. Accoust. Soc. Am.*, **110**(1),2001,pp.59-67) on analyzing viscoelastic Rayleigh waves provides tools that allow one to treat the two dimensional opening mode steady-state dynamic fracture problem in a linear viscoelastic body for general isotropic material with non-constant Poisson's ratio and even for certain classes of anisotropic material behavior. This talk describes the connection between the viscoelastic Rayleigh wave and dynamic steady-state fracture problems, and how solving the former permits one to solve the latter.

Elastothermodynamic Analysis of a Griffith Crack

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When a homogeneous material is subjected to a nonuniform stress field, different regions undergo different temperature fluctuations due to the well-known thermoelastic effect. As a result irreversible heat conduction occurs, and entropy is produced which is manifested as a conversion of mechanical energy into heat. Moreover, the changes in temperature produce a thermal strain that is out of phase with the stress, thus converting mechanical energy into heat, i.e. work is lost. In this paper we present an approximate analysis of the entropy produced and work lost in

the neighborhood of a Griffith crack subjected to a time-harmonic loading in modes I, II, and III. In all three modes the temperature at the crack tip remains bounded. In mode I the entropy produced (per unit volume per cycle) is finite at the crack tip, whereas the work lost (per unit volume per cycle) goes to infinity as $1/\sqrt{r}$. Conversely, in mode II the entropy produced goes to infinity as $1/r$ as the crack tip is approached, whereas the work lost is finite. In mode III the thermoelastic effect disappears altogether and, therefore, both the entropy produced and the work lost are zero throughout the plate.

Analysis of Viscoelastic Microcracking in a Rubber-toughened Composite

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Time-dependent distributed microcracking is studied in a nonlinear viscoelastic rubber-toughened carbon/epoxy composite. A method of modal acoustic emission monitoring and waveform analysis is developed as a means for tracking the two primary cracking mechanisms, matrix-cracking and fiber/matrix debond. With direct monitoring, the extent of damage in the material does not need to be inferred from its effect on the stress-strain response. Unidirectional 30(, 45(and 90(coupons are monitored in this way for various loading histories. An interpretation of the AE data is proposed based on an initial population of existing flaws that grow dynamically upon failure, releasing a detectable acoustic wave, and subsequently arrest. Then a cumulative distribution function (CDF) of microcracking is defined and used to study effects of stress history. A single mixed-mode loading parameter, theoretically independent of loading history, is derived from viscoelastic fracture mechanics to serve as the distribution parameter. To account for microstructural relaxation observed in ramp-hold experiments, an idealized model of the material consisting of two viscoelastic phases is developed. Using the stresses on the nonlinear material phase to calculate the loading parameter, this parameter is found to collapse data from all samples and loading histories, thus supporting the theory.

Keywords: Viscoelasticity, fracture mechanics, composites, acoustic emission

VISCOELASTICITY IN COMPOSITES

In Honor Of Prof. R. A. Schapery

SESSION M4I

Stress Relaxation In Prestressed Composite Laminates

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Viscoelastic deformation caused in symmetric laminated plates by release of fiber prestress and by uniform thermomechanical loads is analyzed on the constituent, ply and overall laminate scales with the Transformation Field Analysis (TFA) method (G. J. Dvorak, Proc. R. Soc. Lond. A (1992) 437, 311-327). Fiber prestress is applied in individual plies prior to matrix cure and released after matrix consolidation. Linear or nonlinear viscoelastic constitutive relations are used to evaluate the inelastic deformation rates in terms of current constituent stress averages. The TFA method regards both thermal and inelastic strains as piecewise uniform eigenstrains acting in superposition with mechanical loads and fiber prestress release on an elastic laminate. Interactions between the eigenstrains at the three different size scales are described by certain influence functions derived from micromechanical analysis of the plies and laminates. Applications describe stress relaxation in two carbon/epoxy laminates after cooling from the curing temperature and release of optimized fiber prestress, that allows maximum tensile load application while keeping both interior and free edge stresses within prescribed strength limits. Subsequent viscoelastic deformation under constant rate loading, and stress relaxation caused by a sustained application of an elevated temperature to a laminate without prestress are also analyzed. Results are presented in the form of initial failure maps that identify overall stress states which may or may not initiate a specific damage mode in the laminate.

Time-Temperature Superposition of Strain Components in Asphalt Concrete

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Sophisticated material characterization models are essential for fully mechanistic predictions of the performance of asphalt concrete pavements. The Schapery continuum damage model (Park and Schapery, 1997; Ha and Schapery, 1998) with viscoplasticity extensions (Schapery, 1999) can model the important aspects of asphalt concrete behavior over the full range of temperatures, loading rates, and distress modes of interest in pavements. Key conceptual components of this model include the use of viscoelastic correspondence principles, thermodynamics-based microstructural damage relations in terms of internal state variables, and a strain hardening viscoplasticity formulation. A simplified form of the basic Schapery continuum damage model has been applied in the past by Park *et al.* (1996) and Lee and Kim (1998a, 1998b) to asphalt concrete under moderate temperature tension loading neglecting viscoplasticity.

The Schapery model explicitly separates the total strain ε_t into viscoelastic ε_{ve} and viscoplastic ε_{vp} components:

$$\varepsilon_t = \varepsilon_{ve} + \varepsilon_{vp}$$

in which both ε_{ve} and ε_{vp} can include contributions from microstructural damage. The strain components can be further separated in conceptual terms as:

$$\varepsilon_t = \varepsilon_e + \varepsilon_{jve} + \varepsilon_d + \varepsilon_{vp}$$

in which ε_e is the instantaneous elastic strain, ε_{lve} is the linear viscoelastic strain, ε_d is the strain due to microstructural damage. The v iscoplastic strain ε_{vp} may also include damage contributions.

Unfortunately, comprehensive constitutive models for asphalt concrete often demand extensive laboratory testing to characterize the model parameters over the full range of loading rates, temperatures, and stress conditions of interest in pavements. Time-temperature superposition principles can be used to reduce the testing factorial, however. A key question for the Schapery model is whether time-temperature superposition relationships exist for all of the strain components, i.e., whether $a_{Tlve}(T) = a_{Td}(T) = a_{Tvp}(T)$ in which the a_{Txx} are the temperature shift functions for linear viscoelastic, damage, and viscoplastic strains, respectively.

The objective of this study is to determine whether time-temperature superposition principles continue to apply to the behavior of asphalt concrete in compression at strain levels well beyond the commonly assumed small strain ($< 100\mu\varepsilon$) limits (i.e., into the peak and post-peak response regions). A companion study on time-temperature superposition behavior in tension is reported by Chelab *et al.* (2002). Small strain frequency sweep tests, constant crosshead displacement rate tests to failure, and sequential creep and recovery tests to failure are used to separate the strain components for a typical dense-graded asphalt concrete mixture. The test results suggest that asphalt concrete in compression is a thermorheologically simple material well into the post peak region–i.e., that time-temperature superposition is valid throughout the useful stress-strain response. Moreover, the temperature shift function a_T appears to be only a weak function of strain level–i.e., it is only slightly different for linear vs. nonlinear response. This finding can greatly simply the laboratory testing program required to characterize the material constants for the constitutive model.

Keywords: asphalt concrete; pavements; viscoelasticity; viscoplasticity; damage.

Multiscale Representations of Lattice Materials

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Existing homogenization theories have to distinguish between microscopic and macroscopic scales. This distinction is purely artificial, and it often leads to ambiguous notions, like the one of representative volume element. In this talk, a radically different view of homogenization is presented. Our approach is based on hierarchy of scales and does not require any additional scales other than those naturally set by the microstructure. We present our ideas using lattice materials as the model.

The Time-Dependent Torque and Normal Force Responses of Polymer Glasses

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When a material is subjected to a torsion at fixed length, there is a twisting moment and a normal force response.

In prior studies we have found that while polycarbonate and poly(methyl methacrylate) at room temperature exhibit similar torsional moduli at moderate deformations, the normal force response for the PMMA can be up to a factor of three greater. In the work presented here we provide new data for poly(methyl methacrylate) and for poly(ethyl methacrylate) in which we explore the relative roles of the glass transition (alpha process) and the subglass transition (beta process) on the torqe and normal force responses of these materials. Single step stress relaxation experiments have been performed as functions of deformation and of temperature in order that the relative magnitudes of T and N can be compared at different distances from the alpha and beta transitions for each of the PEMA and PMMA materials.

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The Non-Linear and Time-Dependent Behavior of Graphite Fiber Strand/Urethane Resin Composite

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Graphite fiber strand/urethane resin composites are candidate materials for automotive applications. In view of their rapid processing method, these composites contain multitudes of initial flaws that cause a substantial scatter in their mechanical behavior. This scatter increases with both stress and temperature levels. The material exhibits creep under sustained loading with a certain amount of non-recoverable deformation.

Despite the aforementioned scatter, it was possible to reduce the data by means of empirical expressions that correspond to both viscoelastic and viscoplastic components of creep. Subsequently, it was possible to employ the resulting expressions to predict the behavior of several laminate lay-ups. It is interesting to note that the stress-strain behavior of quasi-isotropic laminates became orientation dependent within the high stress range. This observation could be explained by means of resin plasticity.

Static and Dynamic Measurements of the Bulk Material Properties of Elastomers and Gels

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Elastomers and gels are widely used as dampers, sealants, biocompatible sensors and actuators or structural elements such as adhesives or propellant binders. These materials often come with different fillers or additives, or may be processed differently to change their cross-link density or other material parameters. All these factors may greatly alter their bulk material properties. Material characterizations of elastomers and gels including static bulk and shear moduli and their associated dynamic moduli and loss tangents are essential for static and dynamic applications of such materials, especially in constrained configurations. Determination of bulk modulus or Poisson's ratio, however, is difficult for elastomeric or gel-like polymers. Often, five or more significant digits of Poisson's ratio are needed to calculate reliable bulk modulus data. We propose an indirect method to measure the force transmission within a polymer cylinder under compression so as to determine its Poisson's ratio or the bulk modulus, if the shear modulus is known. Theoretical prediction shows that the pressure attenuation is very sensitive to changes of Poisson's ratio as well as the aspect ratio of the constrained cylinder. Extended from the elastic solution, we also propose a technique to measure the dynamic viscoelastic bulk properties of elastomers and gels using the correspondence principle. We find that the pressure response of the elastomeric or gel cylinder is very sensitive to the ratio of shear modulus to bulk modulus and the difference between their tan deltas, which can be frequency dependent. Through this analysis, we propose using such geometries to measure the complex material moduli and Poisson's ratio over the applied frequency domain. The experimental technique proposed here will provide crucial experimental data for designers and engineers, in addition to the fundamental measurements and understanding of elastomers and polymeric gels.

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Micromechanical Models for the Nonlinear Viscoelastic Behavior of Pultruded Composites

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This study introduces a new three-dimensional (3D) micromechanical modeling approach for the nonlinear viscoelastic response of pultruded composites. The pultruded fiber reinforced plastic (FRP) composites under consideration include combinations of roving and continuous filament mat (CFM) reinforcements. The proposed framework can be easily integrated with a finite element

(FE) software for the analysis of pultruded structures. The proposed 3D framework consists of three nested and independent models for the roving layers, CFM layers, and a sublaminate model used to generate the overall 3D effective continuum response. The roving layer consists of unidirectional fibers embedded in the matrix; it is idealized as doubly periodic array of fiber with rectangular cross sections. The CFM layer consists of long, swirl, and in-plane randomly oriented filaments. This system is idealized using the average response of two alternating layers with limiting fiber orientations. A 3D nonlinear multi-axial viscoelastic constitutive behavior is formulated using Schapery's integral form. This model is implemented only for the isotropic matrix at the lower level of the nested modeling framework. The fiber medium is considered as transversely isotropic and linear elastic. Stress-update algorithms are needed at all levels of the framework in order to satisfy the nonlinear constitutive and micromechanical relations between the average stresses and strains in the subcells. New iterative numerical algorithms with predictor-corrector type steps are derived to achieve the correct stress and strain states. Experimental tests are performed to calibrate and predict the nonlinear viscoelastic response. These tests include creep and recovery at different loading levels.

This study was sponsored by NSF under grant award No. 9876080.

VISCOELASTICITY IN COMPOSITES

In Honor Of Prof. R. A. Schapery

SESSION T3I

Strain Rate Effect on Compressive and Shear Strengths of Polymeric Composites

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Strain rate effects on the compressive and in-plane shear strengths of S2/8552 glass-epoxy composite were studied. Off-axis brick composite specimens were tested to failure at various strain rates to investigate strain rate effect. For strain rates below 1/sec, compression tests were conducted on an MTS machine, while higher strain rate tests were carried out using a Split Hopkinson Pressure Bar (SHPB). There were several failure modes observed depending on the off-axis angle and strain rates. In the range of 5° to 10° off-axis angles, fiber microbukling (compressive failure) was found to be the dominant failure mode at strain rates up to 1100/s. A fiber microbuckling model derived using micromechanics based on the nonlinear rate dependent behavior of the matrix was extended to include the strain rate effect. The model prediction and the experimental data corresponding to different strain rates are shown in Figure1. It is clear that the compressive strength increases as the strain rate does and that the microbuckling model can predict the rate dependent compressive strength quite well.

For 30° and 45° off-axis specimens, the in-plane shear failure was the main failure mode at the tested strain rates. By using the coordinate transformation law, the critical in-plane shear stress were extracted. Figure 2 shows the in-plane shear strength of S2/8552 glass/epoxy composite with respect to different strain rates. An empirical formula is used to fit the rate dependent behavior.

Keyword: Strain Rate, Split Hopkinson Pressure Bar (SHPB), Shear Strength, Microbuckling

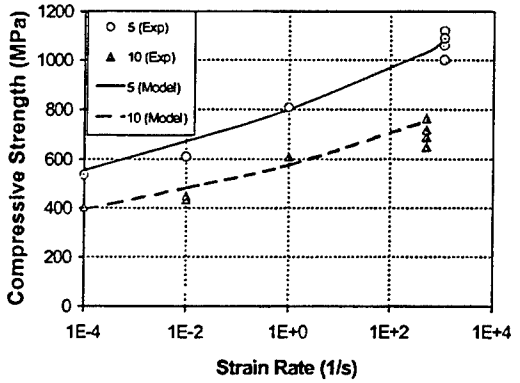


Fig. 1: Strain rate effect on compressive strength of 5° and 10° off-axis S2/8552 composites.

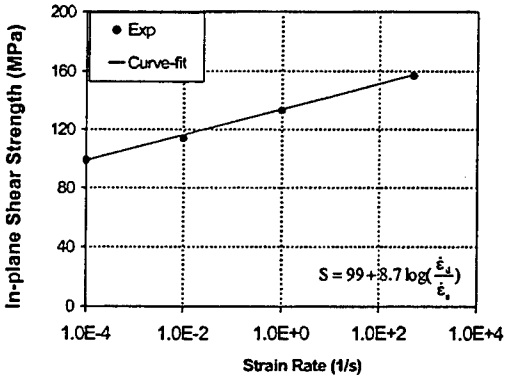


Fig. 2: Figure 2 Strain rate effect on in-pane shear strength of S2/8552 composites.

High-Temperature Mechanics of Thermal Oxidation, Degradation and Damage in Polymer-Matrix Composites

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Recent advances in high-temperature polymers and polymer-matrix composites have led to significant interest in their use in advanced engineering systems, such as high-performance propulsion systems, high-speed aircraft structures and advanced microelectronics. In many of these systems, the temperature in the load-bearing composite could reach 500°F to 800°F for a sustained period of time. Advanced polymer composite materials used in these systems must be capable of withstanding the extreme-temperature environment and still maintain their thermomechanical properties and load-bearing structural integrity. In this paper recent advances in high-temperature mechanics on thermal oxidation, and associated damage and degradation in polymer-matrix composites are presented. Specifically, the following high-temperature (up to 800° F) mechanics issues with internal and external thermally induced damage are addressed: (1). Thermal oxidation r eaction and stability at elevated temperatures; (2). Oxidation-induced damage mechanisms in extreme temperature environments; (3). Irreversible thermodynamic modeling of coupled oxidation reaction and microstructural damage; and (4). Computational micromechanics of associated thermomechanical degradation with the thermal oxidation damage evolution in the composites at elevated temperatures. Of particular interest is the important subject of interaction and coupling among oxidation reactions, thermal damage evolution and high-temperature thermomechanical degradation. The influences of the fiber-matrix interface and composite microstructure evolution during oxidation on the complex high-temperature mechanics and thermodynamics problems will be discussed. Fundamental irreversible thermodynamic dissipation and associated micromechanics formulations, based on high-temperature reaction kinetics for multi-component material systems will be presented. The analytical solutions are discussed in conjunction with the high-temperature experimental results obtained from a polyimide composite system with thermally stable high-modulus carbon fibers.

Characterization of Asphalt-Aggregate Mixtures in Tension Using Visco-Elasto-Plastic Continuum Damage Model

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This paper presents the recent research effort in Task F Advanced Material Characterization in the NCHRP 9-19 project. Previous work by Kim and his students applies the elastic-viscoelastic correspondence principle and continuum damage mechanics to the constitutive and fatigue performance modeling of asphalt concrete in tension with growing damage. The resulting uniaxial model was found to be accurate in predicting the material's hysteretic behavior under different modes of loading (controlled-strain versus controlled-stress), different loading types (cyclic versus monotonic), varying rates or frequencies of loading, strain amplitudes, and rest periods. This previous work is extended in this research to incorporate viscoplasticity to account for permanent deformation growth at high temperatures and low rates of loading. The strain decomposition concept serves as the basis for the model; that is, the total strain is decomposed into elastic strain, viscoelastic strain, viscoplastic strain, and the strain caused by damage. The triaxial frequency sweep and creep and recovery tests were used in measuring viscoelastic material property and for determining the viscoplastic strain as a function of the stress state and loading time, respectively. Included in this model are the effects of the stress state (confining and/or shear stress), temperature, loading rate and time, and rest period.

Modeling of Debond Growth Along a Viscoelastic Adhesive Interface Exposed to Aggressive Environments

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In this paper, the combined effects of nonlinear viscoelasticity, temperature variations, and moisture permeation and/or diffusion in the adhesive layer and their influence on crack-growth rates are simulated using the finite element method. Specifically, the focus is on modeling debond growth along the interface between an epoxy adhesive and a concrete substrate at different temperatures and humidity levels. The particular values of the parameters of the traction-separation law are determined through comparison with crack opening displacement data from test specimens following an iterative procedure previously established. The effect of crack length on mode mix and the existence of asymmetric shielding mechanisms can be accurately assessed using this procedure.

A Multiscale Continuum Mechanics Model for Predicting Damage Evolution in Laminated Composites

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Damage in laminated composites is almost impossible to avoid altogether due to material mismatches and geometric features that cause unavoidable stress concentrations. Indeed, in many cases the development of damage can be so widespread as to lead to ultimate failure of structural components under both monotonic and cyclic loading conditions. The accurate prediction of this damage has in all but a few simplified scenarios eluded the scientific community, so that design tools for predicting composite life have not yet reached a state of maturity.

This paper presents a methodology for predicting the development of multiple cracks of differing types during both monotonic and cyclic loading. This methodology is based in continuum mechanics and thermodynamics for modeling this evolution of damage in elastic, viscoplastic, and viscoelastic media. The method takes advantage of the fact that damage occurs on multiple length scales in laminated composites. In particular, it is observed that microscale damage occurs ahead of delaminations (microscale), matrix cracks occur in plies (mesoscale), delaminations occurs between plies (local scale), and these interact in the structural part (global scale). Each of these scales is treated separately, and crack growth in each scale is accounted fro be employing ductile fracture mechanics concepts. The results of each scale are linked to the next larger scale by utilizing damage dependent homogenization theorems, thus accurately accounting for the energy dissipation at each length scale. A computational algorithm is utilized to link the various scales and perform simulations of structural part response.

Two and three dimensional simulations of damage accumulation in laminated composite plates are presented herein to demonstrate the methodology. Examples are given for both elastic and linear viscoelastic laminated composite beams and plates subjected to both monotonic and cyclic loading. It is shown that the methodology can be utilized to predict the evolution of multiple interacting cracks.

Symposium on

Advances in Modeling of Deformation and Instabilities in Solids

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ADVANCES IN MODELING OF DEFORMATION AND INSTABILITIES IN SOLIDS

SESSION T4I

Material Instability in Multi-mode Inelastic Solids

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In this paper, conditions for material instability are examined for a class of time-independent materials whose inelastic deformation is due to activity of a number of

internal mechanisms. This includes plasticity of crystals and polycrystals, damage, micro-cracking, phase transformation, etc., incorporated in a unified theoretical framework.

Four distinct conditions imposed on the matrix of interaction moduli of internal mechanisms are presented. Two of them are related to constitutive uniqueness and stability under strain control, the third excludes quasi-static bifurcation in a band from homogeneous deformation, and another rules out dynamic formation of shear bands induced by infinitesimal disturbances. In contrast to the widely applied, linearized condition of ellipticity for tangent stiffness moduli, any possible unloading is taken here into account. Lower and upper bounds for the onset of shear band formation have been established along a smooth straining path.

If the matrix of interaction moduli is symmetric and the internal mechanisms obey the normality flow rule then the energy criterion of instability of a uniform straining path is applicable. The distinction between path instability and instability of equilibrium, and the consequences for the post-critical behaviour of the material, are demonstrated for material models with an infinite number of internal mechanisms of plastic deformation, corresponding to polycrystalline metals. It is shown that the loss of ellipticity for tangent moduli in incrementally nonlinear solids should not be identified with the immediate localization of deformation within a vanishingly small volume fraction of the material. Rather, a post-critical deformation path can start with a well-defined, finite value of the volume fraction occupied by the initially formed bands.

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Shear Band Initiation Criterion for Materials with Incrementally Nonlinear Constitutive Response

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A theoretical analysis for the onset of a particular form of material instability that corresponds to a spatially localized bifurcation mode is given for a class of time-independent materials with incrementally nonlinear constitutive equation. The theoretical framework for the analysis of bifurcation of deformation into a highly localized pattern -a shear band- is well established for a standard case of incrementally linear constitutive equation where at a given state of stress and deformation the relationship between stress rates and strain rates is defined by the corresponding tangent operator. If the constitutive relation is nonlinear, we can still follow the similar line of analysis as in incrementally linear case, but the derivation of the shear band initiation criterion becomes much more demanding, since the structure of the resulting criterion depends directly on the chosen form of incremental nonlinearity. Such a criterion appears to be non-universal, and differs from the corresponding instability criterion of the incrementally linear case. Nevertheless, it can still be perceived as a bifurcation criterion, but with much more complicated structure. Strict derivation of the resulting shear band initiation criterion shows that incremental nonlinearity induces a nonlinear relation for the amplitude jumps of the velocity gradient across the shear band. This is in contrast to the classical case with incrementally linear constitutive relation where a derived universal bifurcation criterion yields a linear dependence in jumps of the velocity gradient, and thus makes the problem linearly solvable in the corresponding amplitude jumps. The derivation is illustrated for a subclass of constitutive equations of hypoplastic type that can be used to describe the behavior of granular materials. For this class of materials, the shear band initiation criterion is given in an explicit form.

Keywords: material instability, shear bands, bifurcation, hypoplasticity

Computational Prediction of Change in Mechanical Function of Bone-Porous Scaffold Structure in Tissue Regeneration Process

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In bone tissue regeneration using a biodegradable scaffold, geometry of porous scaffold microstructure is a key factor to control mechanical properties of regenerated bone as well as mechanical function of bone-scaffold system. In this study, computational simulation was conducted for degradation of porous scaffold and formation of new bone in the bone regeneration process, and a

framework to design the porous scaffold microstructure was proposed. Degradation of the scaffold was mainly assumed to be due to hydrolysis, which results in a decrease in polymer molecular weight. Thus, a rate of degradation was modeled affected by the water content diffused from the surface into the bulk of the polymer governed by the diffusion equation. Stiffness of the scaffold was assumed to decrease with the molecular weight. Assuming that new bone is formed on the surfaces of bone and scaffold, a rate equation of trabecular surface remodeling was used to express new bone formation. Pixel/voxel finite element method was applied to simulate the bone regeneration process in bone-scaffold system. Mechanical function in the regeneration process was quantitatively evaluated by measuring change in strain energy of a bone-scaffold system. A method to design an optimum scaffold microstructure that provides the desired mechanical function during and after the bone regeneration process was proposed. From case studies, it was demonstrated that the proposed simulation method could be applicable for the design of porous scaffold microstructure. In addition, it was found that the regeneration process was very complicated because of the coupling effects between scaffold degradation and new bone formation, even if the simple rate equations were used.

Keywords: Computational biomechanics, Bone tissue regeneration, Porous scaffold microstructure, Pixel/voxel finite element method

An Engineering Model for Damage due to Adiabatic Shear Bands

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Scaling laws for adiabatic shear bands are used to parameterize a model that is suitable for introducing shear damage within engineering calculations. One-dimensional solutions to the governing equations for a single shear band have provided these laws that connect the driving deformation, the imperfections, and the physical characteristics of the material to the process of stress collapse [1,2]. The current model uses homogenous material response and the scaling laws to anticipate the correct timing beyond the maximum stress at which stress collapse should occur. The model is implemented into a finite element code for wave propagation and used to examine a series of dynamic experiments where differing geometries provide a variety of driving imperfections. Such experiments involve non-homogenous deformation by design, and thus, require detailed finite element analysis in order yield meaningful interpretation. Finally, implications of the model on simulations of target-penetrator interaction are discussed.

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Computational Simulation of Impact Deformation Behavior of TRIP Steel by Dynamic Explicit FEM

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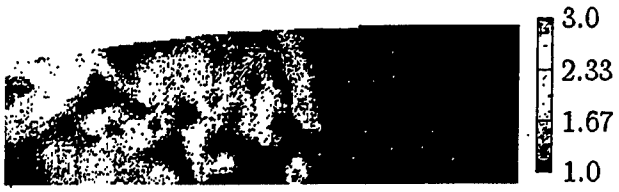
Due to the strain-induced martensitic transformation (SIMT), the strength, ductility and toughness of TRIP steel are enhanced. The deformation behavior of TRIP steel is mainly yielded on this SIMT behavior and the deformation behaviors of the austenitic and martensitic phases. TRIP steel possesses such favorable mechanical properties due to the appropriate combination of these behaviors. However, the desired mechanical properties are realized under fairly restricted temperature and strain rate range.

Recently, a low-alloyed high strength steel based on TRIP steel is under development and its application to an impact absorption member is being investigated. According to some experimental studies, the impact energy absorption of TRIP steel is higher than other steels, and its high impact absorption energy depends on the SIMT behavior along with volumetric and shear transformation strain. However, not only the impact deformation behavior of TRIP steel but also the mechanism of its high impact energy absorption are still unclear.

Here, the impact tensile deformation behavior of TRIP steels and the austenitic material without SIMT are simulated under plane strain condition by dynamic explicit FEM along with the constitutive equation proposed by Iwamoto et al. [1998]. This figure shows the equivalent plastic strain rate of each material normalized by a given nominal strain rate. The tensile nominal strain rate of $2.5 \times 10^4 [1/s]$ is applied horizontally at left end. From Fig. (a), the shear band is formed near the left end in the case of austenitic material without SIMT. On the other hand, no shear band formation can be observed in the case of TRIP steel as shown in Fig. (b). Thus, the shear band formation can be suppressed by the SIMT in TRIP steel.



(a) Austenitic material



(b) TRIP steel

Fig. Distribution of normalized equivalent plastic strain rate for austenite and TRIP steel

Keywords: TRIP Steel, Strain-induced Martensitic Transformation, Dynamic Explicit FEM, Impact Deformation Behavior

ADVANCES IN MODELING OF DEFORMATION AND INSTABILITIES IN SOLIDS

SESSION W3I

Material Instability at Non-local Continua

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Material instability problems like strain localization, shear banding etc. are of great importance in the catastrophic damage of machines and engineering structures. In the last three decades several papers studied the problem in linear case. Linearization can be performed in the kinematics (small deformations) or in the material modeling. Firstly, a simple linear material and kinematics was studied. Then in the numerical investigation of post-localization exhibited a kind of numerical instability: the mesh dependence. It was eliminated by using strain rate or gradient dependent (non-local) material models.

In our previous work material instability was studied as the loss of Lyapunov stability of a dynamical system formed by the set of fundamental equations of the solid continua. We could find mathematical background for mesh dependence, because then at the loss of stability the critical eigenspace is of infinite dimensions. By adding second strain gradient dependent (non-local) terms into the constitutive equation this dimension is finite.

On the other hand small deformation theory can also be considered a local one: it concentrates on the small neighborhood of the no deformation state. When we would like to study what happens beyond such small domain, finite deformations are necessary. In this paper we use a quasi-linear second order constitutive equation and "non-local" kinematics. The aim is to study what happens at the loss of stability and to compare finite deformation and small deformation cases. We remain at uniaxial case for the sake of simplicity then the field variables are scalars instead of tensor functions.

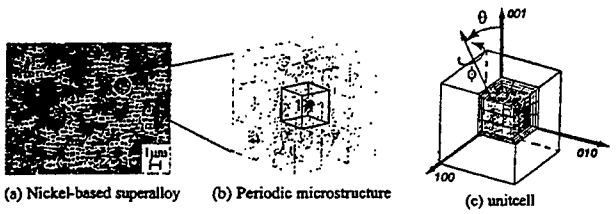
Computational Simulation of Characteristic Length Dependent Deformation Behavior of Nickel-based Superalloy using Homogenization Method

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In order to clarify the characteristic feature of nickel-based superalloy in which fine and hard (gamma-prime-phase) precipitates are embedded in a soft (gamma-phase) matrix, the asymptotic homogenization method for the materials obeying the constitutive equation based on the dislocation densities dependent strain gradient crystal plasticity theory taking into account for elasto-plastic anisotropy caused by the heterogeneity of the precipitated microstructure has been developed. Then, assuming that the gamma-prime-phase precipitates with different morphologies are ordered and periodically distributed in gamma-phase matrix, a unit cell model consists of two phases is established as shown in Fig. 1.



(a) Nickel-based superalloy (b) Periodic microstructure (c) unitcell

Fig. 1. Computational model for Ni-based Superalloy.

A series of computational simulations have been performed for the alloy with characteristic length scales such as volume fraction, spatial distribution of precipitates and crystallographic orientations, the macroscopic mechanical behavior of the alloy with a complex dependence on the microscopic morphologies and loading directions have been elucidated.

Keywords: Nickel-based Superalloy, Homogenization Method, Strain Gradient Crystal Plasticity, Length Scale

A Model for Nonlocal Crystal Plasticity

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A nonlocal crystal plasticity model is presented. The crystal kinematics is based on the usual multiplicative decomposition of the deformation gradient, $\mathbf{F} = \mathbf{F}^e\mathbf{F}^p$, but extended to include the incompatibility condition of $\mathbf{F}^e$ and $\mathbf{F}^p$ [1]. This condition, physically associated with the formation of geometrically necessary dislocations (GNDs), is characterized by a dislocation density tensor expressed in the intermediate configuration in terms of either the material gradient of $\mathbf{F}^p$ or the spatial gradient of $\mathbf{F}^e$. These gradients introduce a length scale into the model. In a thermodynamic framework, this dislocation density tensor is recognized as a state variable related to the elastic lattice curvature. The thermodynamic conjugate stress to this lattice strain is identified as a backstress, an internal stress field induced by the presence of GNDs. This stress field acts in addition to the normal mechanical resistance that is proportional to the square root of the statistically stored dislocations (SSDs). The formulation incorporates this backstress field into the crystal constitutive equations.

The proposed gradient-dependent crystal plasticity model has been implemented in an implicit finite element code. The integration scheme used is an extension of the implicit time-integration procedure presented in [2], where the primary unknowns are the components of $\mathbf{F}^p$. The tangent modulus consistent with this integration scheme is also derived. The resulting integrated equations and the consistent modulus include nonlocal (gradient) terms which, as a first approximation, are not considered in the numerical implementation. A number of examples are then solved with this implementation to demonstrate the predictive capabilities of the model.

Keywords: Crystal plasticity, Nonlocal model, Dislocation tensor, Constitutive integration scheme.

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Polycrystal Modeling of Unstable Unstable Plastic Flow Patterns in Aluminum Alloys

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Spatial characteristics of unstable plastic flows in polycrystalline aluminum alloys are investigated both experimentally and theoretically. Macroscopically, the unstable plastic flows often manifest as hopping or propagative deformation bands in a plastically deforming structure. It is observed that the pattern of localized deformation bands associated with dynamic strain aging (the PLC effect) depends on the deformation stage of the uniaxial tension of polycrystalline aluminum alloys. At the early stage of the tensile loading of thin polycrystalline aluminum alloys, localized deformation bands crossing the whole width of the specimen are oblique to the loading axis, and the propagation of the bands is discontinuous along the elongation axis. At the later stage, however, symmetric double bands form to make seemingly perpendicular bands to the tensile axis, and the bands move more continuously. This character of the localized deformation bands of polycrystalline alloys has been analyzed by a perturbation method. A rate-dependent constitutive equation is used to account for the interaction between dislocations and solute atoms in dynamic strain aging. Plane-strain and plane-stress cases are considered. Unconstrained and constrained models are used to impose appropriate loading conditions at the early and later deformation stages of polycrystalline metals, respectively. It has been shown that the unstable plastic flow patterns are closely related to the microscopic grain deformation mechanisms.

ADVANCES IN MODELING OF DEFORMATION AND INSTABILITIES IN SOLIDS

SESSION W4I

Modeling of Dislocation Patterning based on Field Theory of Plasticity

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Recently a new theoretical framework called "field theory of plasticity" has been adovocated to cope with dislocation patterning problems. This theory makes use of several updated concepts like "gauge field theory of dislocations", "non-Riemannian plasticity" and "method of quantum field theory". Based on this theory a governing equation for the dislocation patterning has been successfully derived with respect to a macroscopic order parameter which has the form of Ginzburg-Landau equation. This paper proposes a model especially for the cell formation process based on the field theory of plasticity. Annihilation process of pair dislocations due to dynamic recovery is considered to be most important elementary process and the annihilated field is taken as the macroscopic order parameter defined as the energy expectation value of the process. Also the long range internal stress is taken into account based on "elastic misfit-like" effect caused by piled-up redundant dislocations at cell wall-cell interior interface. This effect is modeled as apparent variations of elastic constants with dislocation density. The model is numerically solved under several conditions and necessary conditions for obtaining the cellular pattern is extensively discussed. It is demonstrated that the "elastic misfit-like" effect producing long rang stress field plays an essential roll in the cellular patterning: without this effect we merely obtain modulated structures far from cell. Relationship between a parameter expressing the "elastic misfit-like" effect and the inverse of the resultant cell size is discussed and a linear relationship is found between the two implying a possible origin of the so-called "similitude law".

Formation of Prismatic Dislocation Loops by Dilatation of Precipitates

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Lattice defects formed near phase boundaries in the microstructure of multiphase metal materials play important roles in the microstructural evolution, nonlinear deformation and fracture process. When small particles of secondary phase precipitate during material processing and their lattice constant is different from that of the matrix, a dilatational strain field is formed around the particles and generation of prismatic dislocation loops often accompany to it. Also, when the precipitate-matrix system experience temperature change, prismatic dislocations are generated due to the possible mismatch of the thermal expansion coefficients of the two phases.

Emission of prismatic dislocation loops from precipitates has been studied experimentally and theoretically and it was shown that dislocation half loops are formed from the phase boundary at the first stage of slip process and then, the screw segments of the loops cross slip to form the prismatic ones.

In this paper, we employ a simple model of two-phase material where spherical shaped precipitate of SiO2 is embedded in nickel matrix. Plastic slip in the model due to a temperature decrease is analyzed by a finite element technique and the density distribution of the geometrically necessary (GN) dislocations is evaluated from the numerical data for the shear strain on twelve slip systems. Numerical data for the GN dislocations are used to construct the three dimensional images for the dislocation structure.

Results show that high density of dislocations on pairs of slip systems, where slip planes differ each other while slip direction is common, form a rhombus shaped dislocation structure. Examination shows that the obtained structure has a close relation to that of the prismatic dislocation loops.

Keywords: geometrically necessary dislocations, crystal plasticity analysis, precipitate-matrix system, prismatic dislocation loop.

Acknowledgement: This research is supported by ACT-JST*.

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Modeling the Behavior of FCC Single Crystals under Shock Loading: Dislocation Dynamics Analysis

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Understanding the dynamic response of materials under the effect of very high strain-rate shock loading, such as explosive deformation and high speed machining, is very important. However, current experimental capabilities cannot address the response of the materials at pressures larger than 1.0 Mbar. The aim of this work is to investigate using a multiscale model, which includes discrete dislocation dynamics analysis, the materials response under the effect of high strain-rate shock loadings. Computer simulation analyses were carried out to characterize the mechanical behavior and the response of copper and aluminum single crystals to various types of extremely high strain rate shock loadings ranging from 106 to 108/s, yielding pressures as high as 10 Mbar. The effect of material properties, loading conditions, shock plus duration and peak pressure on the dynamic deformation and the failure modes were studied. Relaxed configurations using dislocation dynamics show formation of different types of dislocation and deformation patterns like dislocation cells and adiabatic shear bands.

Keywords: High Strain Rate, Dislocation, Computer Simulations, FCC materials.

Molecular Dynamics Simulation on Dislocation Motion in γ/γ' Microstructure of Ni-based Superalloy

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The mechanism of dislocations at γ/γ' interface of nickel-based superalloys, e.g. dislocation pinning by γ' precipitates and nucleation of superdislocation in precipitates, is of great interest in understanding the mechanical behavior of the superalloys. The necessity of atomic study arises for the phenomena since the scale of the interfaces is less than sub-micrometer and in nanoscale. Numerous atomistic studies have been made on the dislocation in intermetallic compounds from the viewpoint of the anomalous harddening at high temperature, however, only few attempts have so far been made at atomic simulation of the dislocation behavior at the γ/γ' interface. In the present study several molecular dynamics simulations are conducted on the behavior of edge dislocations nucleated from a free surface and proceeded in pure Ni matrix (γ) toward cuboidal Ni_3Al precipitates (γ') by shear force. All simulations are based on the EAM interatomic potential and implemented with more than one million atoms by MPI parallel computing. Fig. 1 indicates one of the simulation condition adopted, of which γ channel has 0.04 μm width close to real superalloys. The dislocations are pinned by γ' precipitates and bowed-out in γ channel and they begin to break into the precipitates from the edge when dislocations are piled up as shown in Fig. 2. The local shear stress for the nucleation of the "super-partial" is evaluated as about 3GPa. It is also suggested by the other simulations that a dislocation line branches at an atomistically sharp edge of γ' precipitate to have its end on the γ/γ' interface nearly normal to the line.

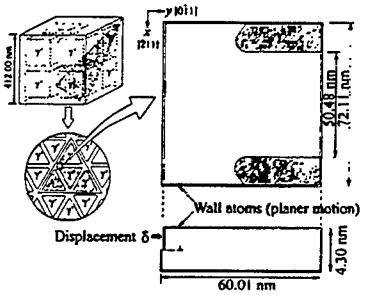


Fig. 1 Simulation cell

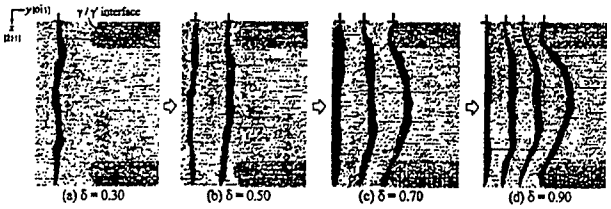


Fig. 2 Dislocation motion near the edges of adjacent γ' precipitates

Keywords: Molecular Dynamics, Dislocation, γ/γ' microstructure, Embedded Atom Method

Microscopic Bifurcation Condition of Periodic Materials Based on a Homogenization Theory

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In this paper, microscopic bifurcation in periodic materials subjected to macroscopically uniform stress and strain is studied in general by using the homogenization theory of finite deformation in the up-dated Lagrangian form. Thus, a necessary and sufficient condition of microscopic bifurcation is established for periodic materials as follows: An eigen solution exists in the boundary value problem governing microscopic velocity in unit cells, and the eigen solution, which represents spontaneous velocity, satisfies orthogonality with the field of microscopic stiffness. Furthermore, the following symmetry of microscopic bifurcation, which was assumed in our previous paper [1], is shown to always prevail in periodic materials: A change in the sign of spontaneous velocity has no influence on the variation in macroscopic states at the onset of microscopic bifurcation. The condition and the symmetry are confirmed by analyzing microscopic buckling of a periodic lattice material, which has no geometrical symmetry with respect to the axis of loading.

Keywords: Bifurcation, Periodic Materials, Microstructures, Homogenization Theory

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ADVANCES IN MODELING OF DEFORMATION AND INSTABILITIES IN SOLIDS

SESSION R3I

Modelling of Polymer Failure by Crazing

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Fracture of many polymer glasses occurs by the formation of 'crazes', which are crack-like defects with their faces bridged by numerous fibrils. On application of stresses, the crazes widen until the fibrils break down and a crack has formed. In this work, we attempt to model the process of fracture in polymers through the nucleation, widening and eventual breakdown of crazes.

The first step is to model the crack tip fields in a glassy polymer, incorporating characteristic features, like yield drop and network hardening. Because of these, the crack-tip fields in polymers are distinctly different than in metals. Once these fields are obtained, a stress-dependent craze initiation criterion can be used to determine where crazes are likely to initiate and to obtain a conservative estimate of the fracture toughness. A feature common to all craze-initiation criteria is the strong dependence on the hydrostatic stress. The first part of this paper will focus on this approach and will discuss effects of strain rate and temperature on fracture toughness.

The next part will address a more refined approach, which involves embedding cohesive zones ahead of the crack tip in order to model the propagation of the crack by crazing. The traction-separation law adopted in the cohesive zone model should effectively mimic the actual process of craze widening and breakdown. In order to be able to design a realistic traction-separation law, we have developed a separate unit-cell model involving a single craze fibril. This model includes the effect of disentanglement taking place at the craze-bulk interface. Various well-known experimental facts about craze widening behaviour have been verified with this model. The overall response predicted by this model gives insight in the nature of appropriate cohesive laws for crazing.

An Engineering Approach to Identify Stress-Strain Relationship for High Energy Absorbing Engineering Plastics

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Finite element analyses for structure/structural components, which are made of engineering plastics, are being paid more and more attentions. For example, many automobile interior structures/parts are made of plastics and they directly interact with passengers in the event of crash. Deformation and energy absorption characteristics are of concern from a viewpoint of passenger protection.

As seen in G'Sell and Jonas (1979), a class of engineering plastic materials such as polyvinylchlorid (PVC) and high density polyethylene (HDPE) exhibit peculiar stress-strain relationships such that the deformation is initially elastic and, after yielding, nearly ideally plastic deformation and, at large strain regime, strong strain hardening behavior are observed (Figure 1, left). When tensile tests are performed for such materials, a phenomenon known as "neck propagation" occurs. In neck propagation phenomenon, applied force reaches its maximum value, decreases and approaches to a nearly constant value. Correspondingly, after the maximum load point is passed by, diffused necking develops and the neck starts propagating. Hutchinson and Naele (1983) presented a theory characterizing stress-strain relationship that allows the formation of neck propagation. Finite element simulations have been carried out by Neale and Togcu (1985), and Fager and Bassani (1985) and Tomita and Hayashi (1992).

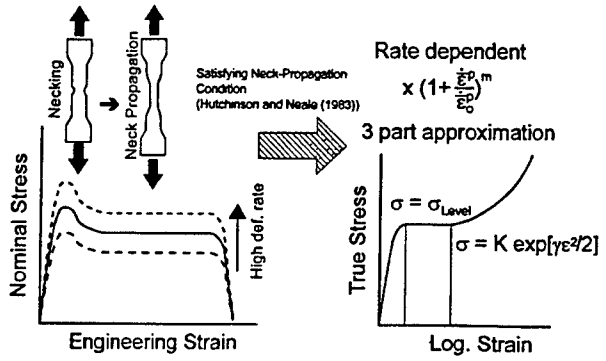


Fig. 1 Experimentally measured engineering strain-nominal stress relationship (left) and three part approximation for logarithmic strain-true stress relationship (right).

In present investigation, we aim at a development of analytical strategy, whic h can be used with many of major commercial finite element packages. To this end, we must use a widely available constitutive model to perform the computational analyses. We adopt the rate dependent J2-Flow constitutive model and develop a way to determine the hardening behavior and strain rate sensitivity from experimentally measured data. Tomita et al. (1997) have established an inverse analysis strategy. However, it requires a certain amount of efforts to develop an in-house computational code. We propose a simpler way to extract the stress-strain relationship from the experimental data by adopting a three part approximation, as shown in Figure 1 (right).

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Mechanical Properties of Single Trabeculae Measured by Micro-Three-Point Bending Test

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INTRODUCTION

Cancellous bone adapts its mechanical properties to changing mechanical environment by remodeling. The mechanical properties of the cancellous bone are determined by two major factors. One is morphological property of trabecular structure that has been shown to correspond to its mechanical environment by experimental and computational approaches [1,3,4]. The other is material property of the trabecula itself [2]. In this study, the relationships between the mechanical environment and the material properties at single-trabecular level were investigated using micromechanical testing by three-point bending [2,5].

METHODS

Rectangular beam specimens of single trabeculae were prepared from bovine coccygeal vertebra. Assuming trabecular mechanical environment was affected by the trabecular orientation, each five trabecular specimen for axial and transverse directions were created by using miniature milling machine. Specimen size measured by micrometer was 18023.2 μm (means.d.) in width and 18623.1 μm in height.

Load-displacement curve of trabecular specimens was measured by micro-three-point bending apparatus, as shown in Fig. 1. Bending load and displacement at the center of the specimen was measured by load cell under the bending block and LVDT placed between the loading head and the bending block, respectively. Span of the bending block was set to 1 mm. A rate of displacement of the loading head was set constant as 0.5 μm/sec in the mechanical testing. Displacement of the loading head was controlled by stepper motor. Elastic modulus was calculated from measured load and displacement by beam theory [6].

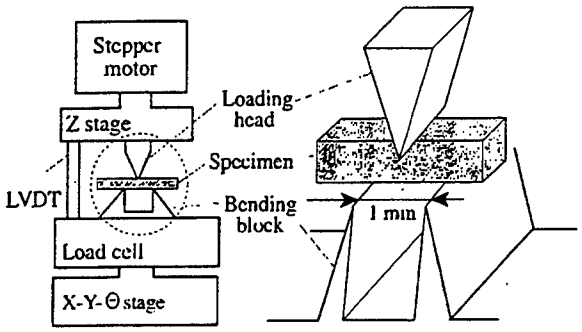


Figure 1: Micro-three-point bending apparatus for trabecular beam specimen.

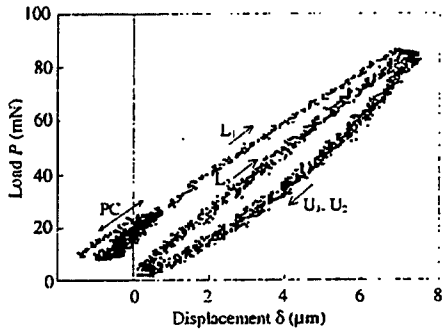


Figure 2: Load-displacement curve obtained by micro-three-point bending test.

RESULTS AND DISCUSSION

As a result of micro-three-point bending, load-displacement curve was obtained as shown in Fig. 2. In the mechanical testing, maximum displacement of 25 μm was applied to the loading head twice (indicated by arrows L_1, U_1, L_2, U_2 in Fig. 2) after preconditioning (indicated by arrow PC in Fig. 2) in which maximum displacement of 5 μm was applied. Elastic modulus was calculated from linear part of load-displacement curve. Elastic modulus was 2.910.29 GPa (means.d., $n = 5$) for the axial direction, and 3.150.31 GPa ($n = 5$) for the transverse direction. There was no significant difference in elastic moduli between axial and transverse directions ($p > 0.05$). The results indicated that the mechanical properties of trabeculae were not affected by its mechanical environment, and that mechanical adaptation in the cancellous bone was mainly accomplished by the morphological changes of trabeculae [1].

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Keywords: Micro-three-point bending, Single trabecula, Mechanical properties, Bone adaptive remodeling

Hyperelasticity of Magnetostrictive Particle-filled Elastomers

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An effective hyperelastic constitutive model is developed for particle-filled elastomer composites based on the microstructural deformation and physical mechanism of the magnetostrictive particles embedded in the hyperelastic elastomer matrix. Two types of loading conditions are considered - magnetic field and mechanical load. Magnetic eigenstrains are prescribed on the particles due to effect of magnetostriction. The effective constitutive relation of the composites during infinitesimal deformation can be established based on Eshelby's micromechanics approach. Since the elastomers normally exhibit finite hyperelastic deformation, the corresponding hyperelastic constitutive law of the composites is constructed in terms of the strain energy densities of the constituents.

On the Speed of an Unconstrained Shear Band in a Perfectly Plastic Material

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The speed of an adiabatic shear band may be estimated from its physical and constitutive properties within a constant. The constant must be obtained from the complete boundary value problem, but the functional dependence on the other properties is well defined from the known form of the similarity solution for the fields surrounding the tip of a propagating band, Wright and Walter (1996) and Chen and Batra (1999).

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ADVANCES IN MODELING OF DEFORMATION AND INSTABILITIES IN SOLIDS

SESSION R4I

Multiscale Modeling of Plastic Deformation in Void Growth and Fracture

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The nucleation and growth of voids in dynamic fracture is strongly linked to the concomitant plastic deformation that occurs around the voids. The nanoscopic mechanisms of this high strain-rate plasticity have not been studied previously in detail. In this talk we focus on FCC materials such as copper using molecular dynamics with an embedded atom model potential. Multi-million atom molecular dynamics models have been run to simulate systems consisting of a periodic box, filled with atoms initially in a single crystal or a polycrystal with a few grains. [1] These models are extended, where appropriate, with concurrent multiscale modeling techniques which embed the atomistic model in a finite element model which runs concurrently to capture the long range elastic fields. This minimizes the finite size effects associated with dislocations interacting with the periodic image of the deformed material. The atomistic simulations are used to characterize the dislocation activity in the plastic zone surrounding voids growing under tensile loading. A dilatational strain is applied that induces void growth. We have studied the nucleation of dislocations that effect the transfer of material associated with void growth. [2] The dislocations are naturally split into partials, and often appear in prismatic dislocation loops, which facilitate outward transport of material to accommodate the growing void. We further identify the character of the most numerous dislocations and their associated glide planes. The results are in agreement with experiment when account is taken of the strain rate difference.

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Modeling of Void Growth and Coalescence in Ductile Solids

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Mechanism-based concepts provide key insights to support development of predictive fracture models for assessment of structural components. Ductile fracture in metals follows a multistep failure process involving void nucleation, growth and coalescence. Due to huge differences between the dimensions of an actual structural component and the characteristic length scales involved in the material failure process, continuum damage models are often used in numerical simulation of ductile crack growth in structural components. It is crucial to ensure that these material models capture the material behavior in the failure process. In this study, we perform finite element analyses of a representative material volume (RMV) containing a spherical void. The effects of stress triaxiality and initial void volume fraction on void growth and coalescence are studied in detail. We then calibrate the micromechanics parameters (q1 and q2) in the Gurson-Tvergaard porous material model by requiring that the GT model predicts the same rate of void evolution, macroscopic peak stress and work of fracture process as the finite element results of the RMV. For materials with given yield strength and strain hardening, we obtain q1 and q2 as functions of the stress triaxiality and the initial void volume fraction. The finite element results of RMV also give us the variation of the critical void volume fraction for onset of void coalescence with stress triaxiality and initial void volume fraction. Finally the calibrated GT model and the critical porosity function are incorporated into the recently developed computational cell approach to predict details of the load-deformation records, crack growth profiles and crack growth resistance of fracture specimens under a wide variety of macroscopic geometries and loading conditions.

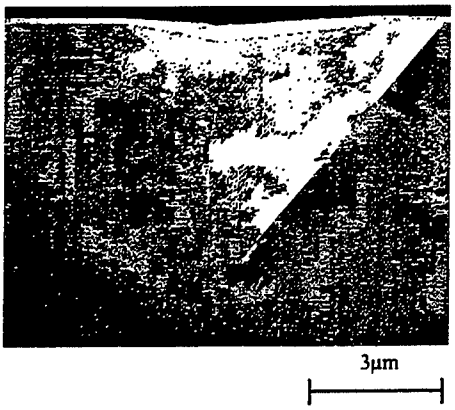
Support from the Faculty Research Grant of the University of Akron is gratefully acknowledged.

FIB-TEM Observations of Cross Sections of Indent-induced Plastic Zone

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Cross sections of the indent-induced plastic zones in single crystalline silicon and aluminum are observed by the transmission electron microscopy (TEM) in order to know their internal structural changes under indentation. A tiny piece involving the indented region is cut from the sample and thinned until a few hundred nanometer thickness by means of the Focus Ion Beam (FIB) technique. At the case of silicon (Fig.1 (a)), the hydrostatic pressure-induced phase transition recovers to the diamond structure with the different crystallographic orientation from the bulk after unloading, being compared with the sample having received the heat treatment for recrystallization. Perfect dislocations consisting of the 60 degree dislocations and screw dislocations may be emitted from the boundary between the phase transition and the diamond bulk. Emission and movement mechanism of the dislocation are also investigated with help of the molecular dynamics simulations. On the other hand, it is found at the case of single crystalline aluminum (Fig.1 (b)) that the subgrains less than one micron are organized at the maximum shear stress region. It seems to be one of the self-organization of dislocation network as a result of the collective mechanical behaviors.



(a) Silicon



(b) Aluminum

Fig. 1 Cross sections of indent-induced plastic zones.

Keywords: Indentation, FIB-TEM, Silicon, Aluminum

Localization Conditions for High Porosity Sandstone Using a Two-Yield Surface Constitutive Model

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A two-yield surface constitutive model is used to examine localization conditions for compacting high porosity sandstones. Localized deformation in these materials occurs in the form of shear bands and/or compaction bands (planar zones of pure compressional deformation, perpendicular to the direction of maximum compressive stress). The proposed model, motivated in part by observations of two microstructural damage mechanisms, consists of a shear yield surface (dilatant, frictional mechanism), combined with a cap (compactant mechanism). When the "bulk" hardening modulus, k, is approximately zero, corresponding to the shelf observed in the mean stress - volume strain curve, both observed band types (compaction bands and shear bands) are permitted for probable values of key material parameters. The predicted value of the plastic hardening modulus, h (slope of the shear stress - inelastic shear strain curve at constant mean stress) at the inception of localization is positive. For normality (associated flow) on the cap, only compaction bands are predicted for a critical plastic hardening modulus equal to zero. Some sandstones exhibit a slightly sloping shelf during compaction band formation, corresponding to $0 < k << G$. In thiscase, when normality is assumed for the cap, the critical plastic hardening modulus at the inception of localization is negative for probable values of key material parameters, thus inhibiting localization.

Financial support provided by the National Science Foundation, Directorate for Geosciences, Division of Earth Sciences, grant EAR-0106932 to Clarkson University.

Initiation and Propagation of Adiabatic Shear Bands in Different Materials Deformed in Plane Strain Tension

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We have analyzed numerically plane strain thermomechanical deformations of heat conducting microporous thermoviscoplastic materials. Strain hardening, strain rate hardening and thermal softening of materials have been accounted for. The balance of internal energy has been modified so that thermal disturbances like mechanical discontinuities propagate at finite speeds. A shear band is assum ed to initiate at a point when the maximum shear stress there has dropped to 90% of its peak value at that point. The shear banded region is delineated at different times. The speed of propagation of the shear band is computed from locations at two successive instants of the shear band tip. These materials are also ranked according to their susceptibility to shear banding and this ranking is compared with that found earlier by Batra et al. in simple shearing deformations. The computed asymptotic variation of the effective plastic strain, the temperature rise and the effective stress ahead of the shear band tip is compared with that found earlier by Chen and Batra.

Symposium on

Impact on Composites 2002

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IMPACT ON COMPOSITES 2002

SESSION M3K
Low Velocity Impacts I

Low-Speed Impact Damage Tolerance of Anisotropic Composite Plates

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The need to develop efficient composite structures for advanced aerospace applications requires allowance for structural damage tolerance requirements. Some of these advanced vehicle concepts require that the structures be elastically tailored to effectively operate at multiple flight regimes and the corresponding loading conditions. Elastic tailoring requires unbalanced and even unsymmetric laminate ply stacking sequences. These ply stacking sequences result in different degrees of laminate anisotropy and, consequently, coupling of deformations to either soften or stiffen the structure. This behavioral characteristic may also be accentuated in the presence of in-plane loading during an impact event. The influence of laminate anisotropy, curvature and pre-loading conditions on the response and damage modes of structures needs to be understood to fully characterize elastically tailored structures for damage tolerance. Such a comprehensive assessment will contribute significantly to the design of weight-efficient structures.

The proposed paper summarizes a study conducted to assess the damage tolerance of anisotropic curved plates with and without in-plane pre-loading. Development of an analytical method for predicting the contact force and out-of-plane deformation of curved anisotropic laminates with arbitrary boundary conditions will be presented and validated using both finite element analyses and experiments. Results for contact forces, displacements, damage states, and residual strength will be presented and discussed for plates with different radii of curvature and degrees of anisotropy.

Influence of the Laminate Thickness in Low Velocity Impact Behavior of Composite Material Plate

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In a previous paper [1] we have considered the low velocity impact behavior of glass fiber-epoxy matrix laminates, both with unidirectional layers and with woven layers staking, with different layers orientations.

That research has been extended to carbon fiber-epoxy matrix laminates. In this case not only different layers stacking and orientations have been considered but also different thickness of the laminate.

Experimental tests are performed according to ASTM standards using a free-fall drop dart testing machine. The specimen are plates completely constrained on a circular edge by the clamping apparatus.

Attention is focused on two points particularly relevant for the intended application in vehicular structure: the energy absorption capability of the material and the sensibility of the material mechanical characteristic to the strain rate effect.

In order to deal with the first point the two energy absorption parameters defined in [1], namely *saturation impact energy* and *damage degree*, are evaluated and results are shown in a graphical form emphasising some typical features of the material.

In order to deal with the second point a number of impact test with different impact velocity have been performed, the superposition of the measured curves allow to evaluate the sensibility of the considered materials, under the considered loading conditions, to the strain rate effect.

In the proposed paper the effect of the different value of the plate thickness is particularly investigated, it will be pointed out

- the changes in the force-displacement and absorbed energy-displacement diagrams,
- the progressive transition from bending to membrane stiffness of the plate deflection characteristics with the increase of displacement,
- the changes in the damage evolution.

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Single and Repeated Low Velocity Studies on Stitched Woven S2-Glass/SC15 Epoxy Composites

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Though composites have excellent mechanical properties over conventional metallic materials, their use in

advanced technological applications has been limited due to their poor translaminar properties. Conventional laminates are made with unidirectional prepregs using autoclave-molding process. Prepregs as well as autoclave molding method are expensive. However, with the advent of low-cost liquid molding processes like vacuum assisted resin infusion molding (VARIM), the cost of production has been drastically reduced. Hence, it is being increasingly considered for manufacturing primary composite structures. In addition, woven fabrics, due to their ease of handling and greater drapeability have become excellent candidate reinforcement materials for VARIM process. Due to the interlacing of fibers in two mutually perpendicular directions, woven fabric composites offer excellent resistance to impact damage. Stitching the dry fabric with high strength Kevlar threads can enhance the damage resistance further. Studies on woven fabric composites manufactured using VARIM process under low velocity impact loading are limited.

In the current investigations, five layers of stitched and unstitched plain weave S2-glass fabrics were manufactured using toughened SC15 epoxy resin system. For stitching, two configurations: one with 25.4 mm grid and other with 12.7 mm grid, were used with the pitch of stitch at 6 mm. Damage resistance was evaluated by subjecting the laminates of size 100 × 100 mm to low velocity impact loading at energy levels ranging 10-80 J using DYNATUP Model 8210, an instrumented impact test system. Three samples were tested at each energy. The extent of damage was evaluated using ultrasonic C-scan. Results of the study indicate that stitching confined the damage size. As the damage was seen to be very low over most of the energy range, the study was further extended to determine the effect of repeated impact loading. Under this study, it was decided to impact the laminates 40 times at the same energy as that of initial impact energy. The damage size was evaluated at regular intervals through ultrasonic c-scan. All the laminates sustained repeated impact at lower energy levels (10-40 J). At higher energy levels (70 and 80J), the laminates could not sustain more than 20 - 25 repeated impacts and failed catastrophically.

Simulation of Structure Submitted to Drop-Test

Volnei Tita and Jonas de Carvalho

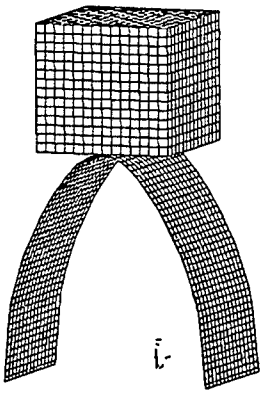
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INTRODUCTION

More recently, some works have carried out numerical analyses and proposed methodologies to predict composite structure behavior under impact loads, for example, Pérez Galán et al [1] as well as Vicente et al [2] made simulations to reproduce accurately the non-linear dynamic response and complex collapse mechanisms of composite frames using a commercial explicit finite element code. In this work, a composite aeronautical structure under crash loads was analyzed, using a commercial explicit finite element code (ANSYS/LS-DYNA).

CASE STUDY

The case study is based on drop-test experiments where a cube with edge equal to 15.6 cm and mass equal to 18.6 kg which impacts a composite aeronautical structure with five different stacking sequence (Figure 1).



E_{11}=286.21GPa;
$E_{22}=E_{33}$=5.86GPa;
$G_{12}=G_{13}$=2.23GPa;
G_{23}=1.9GPa;
$\nu_{12}=\nu_{13}$=0.30;
ν_{13}=0.43;
ρ = 1730 kgm^{-3}
X_{1T}=584 MPa;
X_{2T}=45 MPa;
X_{1C}=741 MPa;
X_{2C}=239 MPa;
X_{12}=71 MPa

Fig. 1 - Finite Element Model; Orthotropic Material Properties and Strength Values [3]

Levy Neto and Al-Quereshi adopted elastic behavior with Tsai-Hill Criterion to evaluate the failure process. In this work, Chang-Chang Criterion [4] was adopted in order to consider nonlinear behavior due shear stress.

RESULTS

t [mm]	V_0 [m/s]	Stacking Sequence	F_{max}[3] [N]	F_{max}[*] [N]
2.6	5.4	$[(90/0)_3]_s$	4036	4427
2.7	5.2	$[(90/0)_4]_s$	3191	4469
2.3	4.4	$[(90/0)_2(\pm45]_s$	2060	2922
2.4	4.7	$[(90/90/0)_2(\pm45)]_s$	2469	2588
2.4	4.9	$[(90/90/0)_3]_s$	3008	3118

t is thickness; v_0 is impact velocity of steel box; F_{max} is maximum impact force) -[*] present work

Finite element models did not include damping effects, which can have a large influence on the structure behavior. However, the damping phenomenon is rather difficult to model because information about viscoelastic phenomena associated with the matrix are quite scarce.

ACKNOWLEDGEMENTS

The authors thank FAPESP that is supporting this research and the CAD/CAE Laboratory (University of S. Paulo) for the support in the use of the package ANSYS/LS-DYNA.

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Keywords: composite materials, impact loads, failure criteria, finite element analysis.

IMPACT ON COMPOSITES 2002

SESSION M4K

Low Velocity Impacts II

Modelling Soft Body Impact on Composite Structures

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The paper describes recent progress on materials modelling and numerical simulation of soft body impact on fibre reinforced composite structures. To reduce certification and development costs, computational methods are required by the aircraft industry which are able to predict structural integrity of composite structures under impact from soft bodies such as birds, hailstones and tyre rubber. Key issues are the development of suitable constitutive laws for modelling composites in-ply and delamination failures, determination of composites parameters from high rate materials tests, materials laws for soft body impactors, and the efficient implementation of new materials models into FE codes.

The work is based on the application of explicit FE codes to simulate composite shell structures under impact from highly deformable impactors, which may flow over the structure spreading the impact load. These soft impactors are modelled by a smooth particle hydrodynamic (SPH) method, in which the FE mesh is replaced by interacting particles. Data from pressure pulses measured during gelatine impact on rigid plates are used to determine parameters for a gelatine material equation of state for use with the SPH method.

Improved composites ply damage and interply delamination models were developed based on a continuum damage mechanics (CDM) formulation and implemented in a commercial explicit FE code. The CDM ply failure model for fabric reinforced plies uses three scalar damage parameters representing modulus reductions under different loading conditions due to microdamage in the ply, and the delamination model requires two interface damage parameters. Damage evolution equations supported by a materials test programme are introduced which relate the damage parameters to strain energy release rates in the ply and interface. Code validation studies are presented in which numerical simulations are compared with high velocity impact test data of gelatine impactors on glass fabric/epoxy cylinders, showing good predictions of observed impactor flow and shell failure modes.

Carbon, Polyethylene and PBO Hybrid Fibre Composites for Structural Lightweight Armour

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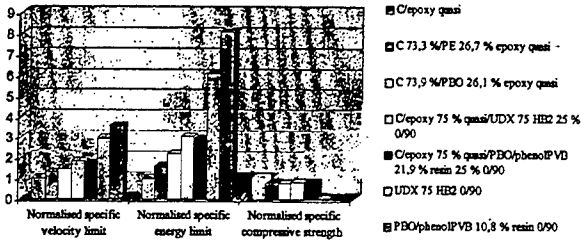
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Few investigations have been reported on the possibility of making structural lightweight armour out of polymer composites for application in for example armoured vehicles, combat aircraft and fighting ships. It should be feasible to produce such an armour using fibre hybridisation where one fibre is used to contribute structural properties and another fibre to give ballistic protection.

In this study the properties of different hybrid composite materials have been investigated. For structural properties carbon (Torayca T300) fibres were used and for ballistic properties polyethylene (Dyneema SK66) and PBO (Toyobo Zylon AS) fibres were used. Resin transfer moulding and press moulding were used for manufacturing composite panels. Besides using different fibres the effects of different lay-ups also were investigated.

The ballistic properties and compressive strength after impact were determined for the different laminates. The ballistic evaluation was carried out using fragment simulating projectiles (FSP, 1.1 gram) and steel spheres (0.88 gram). The impact and residual velocities were measured and the energy limits were calculated. Structural properties were evaluated using an compression after impact (CAI) test.

The investigation showed that separation of fibres with carbon fibres at the impact side is advantageous both for ballistic velocity limit and compression strength after impact. In order to utilise the inherent potential of the fibres a rigid matrix should be used for the carbon fibres and a weak matrix for the organic fibres. The figure shows normalised specific properties of selected laminates. As seen the reduction of specific compression strength can be more than compensated for by an increase of specific ballistic properties.



Keywords: Structural lightweight armour, ballistic properties, mechanical properties, hybrid fibre reinforcement

Initation and Propagation of Delamination in Thick-Section Composites under Dynamic Loading

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In a multi-layer ceramic faced composite armor, the arrest of a projectile is dependent on the energy absorption by composite backing plate through different damage mechanisms, e.g. fiber breakage, delamination, friction, fiber and matrix crushing etc. In the present paper, initiation and propagation of delamination in composite backing plate is investigated through model experiments and numerical simulation. The ceramic strike face deforms the projectile through its complex fracture mechanisms and distributes the dynamic load on the composite backing plate. In order to mimic this fact, a composite beam with an aluminum block is impacted with a 20-mm fragment simulating projectile (FSP) in the model experiment. Two different composite beam thickness with different impact velocities are considered. Composite beams and aluminum blocks are sectioned at the impact point to investigate the extent of delamination in composite and the depth of penetration of FSP in the aluminum block. A quarter-symmetric finite element model of the beam impact experiment is developed and solved using LS-DYNA 960. Johnson-Cook material model is used to model the FSP and aluminum block, while MAT_COMPOSITE_FAILURE_SOLID_MODEL and MAT_COMPOSITE_MSC is used for the composite backing plate. The composite backing plate is modeled with predetermined number of interfaces, where delamination can initiate and propagate. The CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK interface option of LS-DYNA 960 is used to model delamination and parametric study. The final delamination profile and penetration of FSP into aluminum block as obtained from the numerical simulation compared well with the experiment. It is shown that the initiation of delamination of composite backing plate is due to the stress wave propagation through the thickness and propagation of delamination is due to the flexural vibration. Initiation of delamination is a short duration event and propagation of delamination is a long duration event. Studying the stress-time history at different interfaces, the mechanics of dynamic deflection and delamination propagation is evaluated. The evolution of damage and different energy absorbing mechanisms are also investigated through parametric studies.

Impact Design of the Front Structure of a High Speed Train made by Composite Material

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The paper describes the development of the structural design of the front shield for a high speed train completely made by composite material.

The main requirement in the shield design is the impact behavior, as in the case of frontal impact it is the front shield that has to absorb the maximum possible amount of energy.

For the shield construction, a sandwich structure has been considered, made by two external composite laminates with a polymeric foam core. The external laminates are made of glass fibers in epoxy resin, with a different

reinforcement percentage and fiber orientation for the different layers. This type of structure should allow for a significant weight reduction in comparison with similar metallic shields, while the overall energy absorption is expected to satisfy the application requirements that, taking into account the train mass, are very severe.

The first phase of the research activity has been devoted to the experimental characterization of the proposed material, with particular attention to the interface between the composite layer and the foam. To this aim a number of quasi-static and impact tests have been run both on tensile and bending specimens of the composite laminates and on square plates of the whole sandwich.

The second phase of the research activity has been devoted to the finite element modeling of the characterization tests run in the first phase. The purpose of this second phase was to assess the capability of the FE code material model to simulate the experimental tests and to define the input data for the material constants required by the chosen material model. The third and final phase of the research activity has been dedicated to the study of the shield structure impact behavior by means of finite element analysis. The FEM simulation was performed with the explicit code PAM-Crash.

Delamination and Dynamic Response of Through-thickness Reinforced Delaminated Composites

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The paper deals with different aspects of the mechanical behavior of delaminated composites in the presence of bridging mechanisms such as those developed by a through-thickness reinforcement (stitching, z-pinning or weaving). We will present our recent work on the problems of mode I and mixed mode large scale bridging delamination and the dynamic response of through-thickness reinforced delaminated beams. The problem of mode I and mixed mode large scale bridging delamination is treated using the weight function method in terms of stress intensity factors at the crack tip. The model accounts for the orthotropy of the material and allows us to investigate problems characterized by very short cracks or bridging mechanisms acting close to the crack tip. The influence of the through-thickness reinforcement on the fracture behavior is investigated and unusual phenomena of crack arrests and crack propagation in the presence of regions of contact that have been observed in the experiments are predicted theoretically and explained [1]. A beam theory model has been formulated to analyze the role played by linear bridging mechanisms in reducing the delamination-induced degradation of the dynamic properties of laminated beams. The model follows the formulation proposed in [2] for

delaminated beams in the absence of bridging mechanisms. An application of the model to a typical stitched carbon epoxy-laminate shows that a low area fraction of through-thickness reinforcement can substantially reduce the degradation of the natural frequencies of the structure.

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Contact Between a Cylindrical Indenter and a Sandwich Beam with Functionally Graded Core

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In this paper we analyze the problem of indentation of a sandwich beam by a rigid cylindrical indentor. The core is assumed to be functionally graded with stiffness properties varying through the thickness. The contact problem is solved using the assumed contact stress distribution method. Relations are derived for load-contact length, load-indentation, and maximum stresses and strains in the core for functionally graded cores as well as homogeneous core. The results will be useful in answering the question if FG cores have an advantage over homogeneous cores when a sandwich panel is subjected to low-velocity impact.

The core/ face sheet delamination is a major concern in sandwich laminate construction. The stiffness discontinuity at the face sheet and core interface results in a large increase in shear stresses. While the core material itself

can withstand very high shear stresses, the bond (or adhesive layer) at the interface may be relatively weaker. The purpose of this research is to investigate the effect of functionally graded core on the stresses in the core and the interface. In particular we would like to consider the case of low-velocity impact and contact loads, wherein the load is applied over a small contact area.

The solution procedure for the sandwich beam problem follows that described in [1] and [2]. The assumed contact stress distribution method has been described in [3]. We combine the two solution procedures to obtain the relation between contact force and contact length from which the entire stress and strain fields in the sandwich beam can be determined.

A sandwich beam of length 0.2 m, core height 20×10^{-3} m and face-sheet thickness 0.3×10^{-3} m is considered as an example. The face-sheet Young's modulus was chosen as 50 GPa. The core Young' modulus varied from 50 MPa at the mid-plane to various values at the core/face-sheet interface. Poisson's ratios for the core and face-sheet, respectively, were 0.35 and 0.25. Detailed results will be presented at the meeting and also published elsewhere. The variation of maximum normal strain and maximum shear strain in the core for a given contact force are plotted in the figures below. One can note that the trend indicates that the maximum strains will be significantly lower when the core is graded as compared to homogeneous core.

Keywords: Functionally Graded Materials, Sandwich Beams, Contact problem, Low velocity impact

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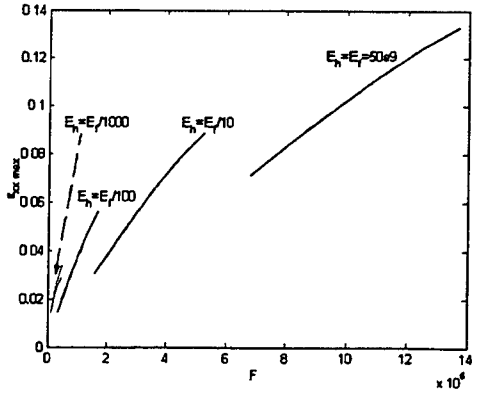


Fig. 1 Variation of maximum normal strain

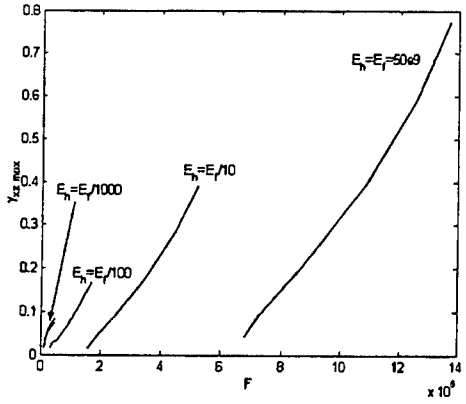


Fig. 2 Variation of maximum shear strain

IMPACT ON COMPOSITES 2002

SESSION T3K
Impacts on Sandwich Structures
and Fiber-metal Laminates

Impact Behaviour of Pre-Stressed Polymer Composite Sandwich Beams

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The paper describes an impact experimental and numerical study on the effect of pre-stress on the energy absorbing behaviour of polymer composite sandwich beams. The beam construction was carbon epoxy pre-preg laid up in a quasi-isotropic form for the skins, and Rohacell 51WF polymethacrylimide foam for the core.

A previous paper [1] has described experimental and numerical results for the static case. A 16mm diameter cylinder loads the panel, which is clamped but free to pull in at the ends. In-plane loads of 0kN, 5kN and 15kN are imposed on the beam prior to lateral loading by the cylinder. It was shown that the main mode of beam failure was core shear. The foam model in DYNA (Fu Chang) was enhanced to take account of tensile failure. The skin was modelled as an elastic plastic material. Good agreement was shown between experiment and simulation.

In the impact work, a mass of up to 5.6kg was dropped from a height of 2m, giving a maximum impact energy of 110J. The panels were pre-stressed to the same in-plane

loads as in the static case. The lateral displacement of the beam and the in-plane load were monitored during the test. High speed video was also taken. It was shown that the maximum lateral failure loads increase with in-plane load but that the maximum lateral failure displacements decrease with in-plane load.

As far as the numerical simulation of the impact tests was concerned, the main problem was modelling the dynamic in-plane load. Due to the inertia of the supports (4.5kg), the in-plane load varied from the pre-set value. The other main issue in the model was simulation of core failure. The simulation was adjusted to give good agreement with experiment, and a number of material modelling issues were highlighted.

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Numerical Modeling of Impact Damaged Sandwich Composites Subjected to Compression After Impact Loading

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Sandwich construction composites are used in a wide variety of structural applications largely because of their relative advantages over other structural materials in terms of improved stability, weight savings, and ease of manufacture and repair. While the initial design of sandwich structures is at a fairly mature stage of development, less progress has been made in understanding the effect of adverse in-service impact events on the structural integrity of sandwich composites. Foreign object impact damage in sandwich composites can be attributable to a number of fairly common discrete sources and may result in drastic reductions in composite strength, elastic moduli, and durability and damage tolerance characteristics.

In this study, physically motivated numerical models are developed for predicting the residual strength of impact damaged sandwich composites comprised of woven fabric graphite epoxy facesheets and Nomex honeycomb cores subjected to compression after impact loading. Results from non-destructive inspection and destructive sectioning of damaged sandwich panels are used to establish initial conditions for damage (residual facesheet indentation, core crush dimensions, etc.) in the numerical analyses. Honeycomb core crush test results are used to establish the non-linear constitutive behavior for the Nomex core. The influence of facesheet property degradation on the stress redistribution in damaged sandwich panels is examined. Facesheet strains from material and geometric non-linear finite element analyses correlate relatively well with experimentally determined values. Moreover, numerical predictions of residual strength and stable damage growth during the failure process are consistent with experimental observations. Similar calculations may prove useful in the development of a damage tolerance plan for sandwich composites that accounts for specific details of damage morphology and provide conservative estimates of residual strength.

A Study of Sandwich Plates Under Explosive Loading

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Sandwich plates play an important role in the design of lightweight structures. Current research has focused on developing continuum models for describing the performance of both solid plates and sandwich plates with truss cores under explosive loading. The coupled effects of both the material and structural length scales have been investigated. We have identified the response to an idealized impulse by assuming a uniform initial velocity applied to the plate (in the case of the sandwich construction, only applied to the outer face sheet). Furthermore, the response to general blasts, accounting for the time dependence of the pressure of the explosion, can be related to the response to idealized impulse load. The finite element method has been utilized to perform the parametric study and simulate the dynamic deformation history of the structure under conditions representative of blasts. The goal is to create lightweight core and face sheet systems with the maximum energy absorption or reflection per unit weight (mass).

Ballistic Impact of Fiber-Metal Laminates

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An analytical model to predict the ballistic energy absorption of GLARE, a fiber-metal laminate that consists

of alternating layers of 2024-T3 Al and S2-Glass/Epoxy laminates, is presented. The model is based on test results from the Ballistic Impact Lab at NASA Glenn. A blunt titanium cylinder with 0.5 in-diameter and 14.25 g-mass is used to perforate fully clamped GLARE panels, 6 in × 6 in and thickness ranging from 0.06-0.2 in. A section of the perforated GLARE panel suggests that the kinetic energy of the projectile can be dissipated in local transverse shear fracture on the frontal layers; bending, membrane stretching and petaling of the distal layers; and extensive delamination between the aluminum and glass/epoxy layers and within the glass/epoxy plies, respectively. A simple energy balance is thus given by

$$E_{tot} = E_{sh} + E_{bm} + E_p + E_{deb} + E_{del}$$

where energy components are as follows:

$E_{sh} = 2\pi R h_s \Gamma_f$: Frontal shear fracture

$$E_{bm} = P_o \Delta_{G/E} + \frac{K_b^{ep} \Delta_{G/E}^2}{2} + \frac{K_m^{ep} \Delta_{G/E}^4}{4} + P_o(\Delta_{A/} - \Delta_{G/E}) + \frac{K_b^p(\Delta_{Al}^2 - \Delta_{G/E}^2)}{2} + \frac{K_m^p(\Delta_{Al}^4 - \Delta_{G/E}^4)}{4}$$

: Distal bending and membrane stretching

$E_p = n_p \sigma_o \pi^2 R h_{Al}^2/4$: Petaling of Al layers

$E_{deb} = A_{deb} G_{IIC}^{G/E-Al} + A_{sp} G_{IC}^{G/E-Al}$: Debonding

$E_{del} = A_{del} G_{IIC}^{G/E}$: Delamination

and R is the projectile radius; h_s is the thickness of the sheared frontal layers; Γ_f is the transverse shear fracture energy per unit area; P_o is the rigid-plastic bending/membrane force; K_b and K_m are the laminate bending and membrane stiffness of the distal plies (ep and p denote elastic/rigid-plastic and rigid-plastic material behavior, respectively); $\Delta_{G/E}$ and Δ_{Al} are deflections when glass/epoxy and aluminum break, respectively; n_p is the number of layers undergoing petaling; σ_o is an average flow stress of the aluminum; A_{deb}, A_{sp} and A_{del} are the debond, spalling and delamination areas; $G_{IC}^{G/E-Al}$, $G_{IIC}^{G/E-Al}$ and $G_{IIC}^{G/E}$ are the Mode I and Mode II interlaminar fracture toughness between aluminum and glass/epoxy and within the glass/epoxy plies.

Table 1 shows that with the exception of the 0.076 in-thick GLARE, predicted total energy absorption are within 15% of test results. Roughly 40-60% of the total energy absorption is due to membrane stretching of distal plies, while delamination and debonding account for 20-40% of the total energy absorption.

Table 1 Energy partition during perforation

	GLARE 0.076 in	GLARE 0.1 in	GLARE 2*0.076 in	GLARE 2*0.1 in
$E_{sh}(J)$	0	0	0	9.4
$E_{bm}(j)$	59.1	116.9	136.4	171.0
$E_p(J)$	2.9	5.2	5.8	6.9
$E_{deb}(J)$	3.9	7.9	10.2	24.0
$E_{del}(J)$	34.6	68.5	72.2	106.7
$E_{tot}(J)$ (pred)	100.5	198.5	224.4	318.0
$E_{tot}(J)$ (test)	162.2	175.6	246.3	317.9

Modeling the Interfacial Fracture of a Sandwiched Structure due to Cavitation in a Ductile, Adhesive Layer

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The strength and durability of adhesively bonded, sandwiched structures often depend on the mechanisms of fracture which in turn depend on the properties of the adhesive and the microstructures of the interface. When the thin, adhesive layer is ductile, cavitation either within the layer or along the interface is often the dominant failure mechanism. In the present study, fracture due to cavity growth in a thin, ductile layer is analyzed. A new method utilizing fluid mechanics solutions is developed. Solutions of fluid flow field are used to approximate the plastic deformation field surrounding a growing cavity in the corresponding solid body. Cavity growth problems with very large deformation can be successfully dealt with using this method. Stress-separation curves due to cavitation in the thin layer can thus be obtained. Fracture resistance can therefore be obtained by integration of the stress-separation curve. The method has been validated by re-evaluating the 1-D problem of cavity growth in a sphere 3/4 a problem for which an exact, analytical solution exists. 2-D, plane strain cavitation problem and axisymmetric cavitation problem are analyzed using the new method. The stress-separation curves and the fracture resistance due to this mechanism are obtained. The results show that both the stress-separation curves and the fracture resistance are sensitive to the strain hardening exponent and the initial void size, but not to the yield strength of the material. The new method has clear advantages over numerical methods such as the finite element method for large plastic deformation when the last

stage of stress-separation curve is reached, especially for parametric studies involving several parameters.

IMPACT ON COMPOSITES 2002

SESSION T4K

Dynamic Properties of Composite Materials and Ceramics

Shock Response of a Glass-Fiber-Reinforced Polymer Composite

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This work presents the results of plane shock wave experiments conducted at Army Research Laboratory and Sandia National Laboratory to elucidate the nature of deformation of a Glass-Fiber-Reinforced Polymer composite (GRP) under shock compression, release, and tension through the use of different experimental configurations. The maximum stress attained in these experiments was 20 GPa. The principal results of this work may be summarized as follows: (i) The elastic wave velocity data indicate that the composite has tetragonal symmetry; (ii) the deformation of the composite normal to the lay-up direction is elastic to 1-3 GPa; (iii) its compression at higher stresses is represented by a linear relation between shock velocity (Us) and particle velocity (u_p) i.e., $U_s = 2.75 + 1.286\ u_p$; (iv) the release behavior suggests that the composite undergoes a permanent compaction when shocked compressed beyond 3 GPa; (v) The composite delaminates under rarefaction induced tension of magnitude 0.06 GPa; (vi) This delamination strength of the composite is reduced to 0.007 GPa with an increase in the shock-induced shear.

The Limits of the Classic Split Hopkinson Pressure Bar Data Reduction

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The classic split Hopkinson pressure bar (SHPB) data reduction methodology has been revisited. A complete one-dimensional analysis of SHPB system is presented for linear-elastic and visco-elastic specimens considering the specimen and bar diameter to be equal. In general, the assumptions in classic SHPB data reduction method are found to be inconsistent. However, the classic SHPB data reduction scheme is found meaningful in the case of acoustically very soft materials. These analyses are extended to explain major issues in the general non-linear elastic case. The situation with specimens having smaller diameter than the bar is briefly discussed.

Exact expressions for the average stress and strain in the specimen are formulated in terms of experimental parameters in the quasi-static limit. Dynamic adjustments associated with elastic and viscous relaxation processes are also derived. It has been shown that the deviation of specimen from mechanical equilibrium is proportional to the amplitude of the reflected pulse. Thus, either the specimen is in mechanical equilibrium and the reflected pulse is absent, or the reflected pulse is present and the specimen is not in mechanical equilibrium. The limits of SHPB experimental method are also investigated.

Non-equilibrium Dynamic Deformation and Energy Absorption of Metal Foams

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The ballistic impact of a massive, effectively 1-D plate on an initially stationary foam layer is considered. It is shown that four velocity regions must be separately considered. Two of these regions are of major interest for ballistic impact studies. The first region of major interest considers when the initial velocity of the plate is lower than the sound velocity of the constitutive material of the foam but higher than the linear sound velocity of foam (Regime 2). The second region of major interest considers when the initial plate velocity is lower than the linear sound velocity of the foam but remains higher than the effective sound velocity for a perturbation in which the amplitude lies in the so-called "plateau region" of the static stress-strain diagram (Regime 3).

Analytical solutions for dynamic deformation and energy absorption of foam materials under plate impact condition for Regime 2 and Regime 3 are developed. It has been shown that in both cases, a compressional shock wave appears. The physical difference between these two regimes entails not only the creation of a shock front associated with the collapsing foam, but also an acoustic precursor in the case of Region 3. As a result, the efficiency of energy absorption in Region 2 depends only on

the initial density of the foam, the density of the constitutive material of the foam and the areal density of the shocking plate, whereas the efficiency of energy absorption for Region 3 also depends on the Mach number and the critical stiffness of the foam.

Numerical plate impact experiments have also been carried out covering a wide range of impact velocities. Explicit finite element analysis is performed using LS-DYNA 960. Time history of dynamic deformation and energy of foam and impact plate is presented. The numerical predictiction is found to be in good agreement with the analytical results."

The Ballistic Damage Mechanisms and Their Sequence in Confined Alumina Tiles

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The basic ballistic damage mechanisms and their sequence occurring in dense alumina tiles during impact of armor piercing rounds were investigated. The alumina tiles were supported by semi infinite or finite thickness support blocks made of three different materials: steel, aluminum, and spectra composite. A special confinement frame capable of generating high biaxial compressive stresses confined the alumina tiles. We identified two major types of damage mechanisms. The first is the 'quasi-static' mechanisms resulting the propagation of the first pressure front: The formation of radial cracks followed by the propagation of a cone crack initiated at the periphery of the contact zone. The quasi-static damage mechanisms terminated by further crushing and erosion in the cone crack envelope. This damage sequence suggests the existence of three 'thresholds' in the development of damage. The first is that associated with the formation of the tensile radial cracks initiated at the back surface of the tile. The second governs the initiation of a shear dominated cone crack through the tile thickness to form a 'plug.' The third is responsible for the crushing and comminution of material within the cone envelope. Raising the first threshold may delay the onset of the other damage mechanisms.

The second major type is the so-called 'dynamic' damage in the form of spall cracks. When a significant impedance mismatch exists, as in a tile supported by an aluminum or spectra composite supports, the reflected stress waves are intense and spalling is the additional mode of damage, occurring in longer time scale.

Several parameters controlling the damage mechanisms were studied and will be reported, among them the tile thickness, the acoustic impedance mismatch and the level of confinement.

Experimental Studies using Hopkinson Tensile Bars of Damage Mechanisms in Reinforced Carbon Fiber used on Multihull Race Sailboats

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For severe sea conditions, impact loads with high pressure occur when the carbon fiber epoxy matrix composite sandwich hull of a ship strikes the water surface. These impulsive loads may generate local damages and delaminations phenomenon on the hull structure. Local ultimate fractures have also been observed as the result of severe slamming events. A multihull catamaran must endure very high loading because of it's ability to sail on one hull. Then the ability to better predict the structural response of the ship hulls made of carbon fiber epoxy matrix to slamming loads, both locally and globally, appears therefore necessary.

In order to take the main damage mechanisms into account, an initial step, which has been conducted in other studies, was to model the laminate as a stacking sequence of non-linear layers and non-linear interlaminar interfaces. The modeling of the single layer was identified by means of tensile tests performed on different stacking sequences.

In this study, we used Split Hopkinson Tensile Pressure Bar to identify the behavior of the GODT-1 carbon fiber epoxy resin material under high strain rate. GODT's name is a secret code in order to protected this material used for the building of race boats. Split Hopkinson Tensile Test were conducted in order to determine the proper-

ties as regards damage mechanisms. Each specimen test has strain gages. The SHPB technique is analyzed during the initial stage of loading by means of Finite Element simulations of tensile tests. The FE code Castem 2000 is used to predict the behavior of unidirectional GODT carbon fiber epoxy matrix specimens at different nominal strain. Finite element predictions are conducted with nonlinear geometric and material hypothesis.

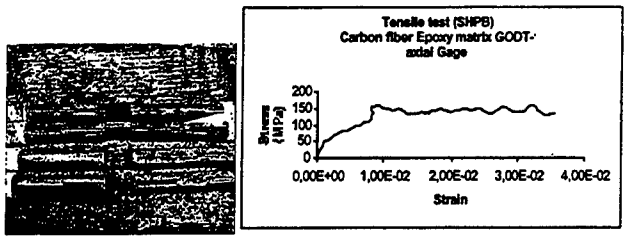


Figure 1. Specimens. Axial stress strain rate in the center of specimen

Low Temperature Effects on G30-500/EH-80 Graphite/epoxy Composite Material Properties at High Strain Rates

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Composite materials are used in a wide variety of low temperature applications because of their unique and highly tailorable properties. These low temperature applications of composites include their use in Arctic environments and most of them involve dynamic loads. For example, spacecraft applications where they use cryogenic engines, hypervelocity impact situations at very high altitudes, civil engineering applications in extreme cold regions, and offshore structures in cold regions. The U.S. Navy stated that under certain conditions naval vessels might encounter strain rate up to 1200/sec. Because the dynamic properties of composite materials may vary widely with strain rate it is important to use these dynamic properties when the loading conditions involve high strain rates.

Very few materials have been characterized at high strain rates even at room temperature. Still less effort has been spent in trying to model the high strain rate properties to develop a predictive capability at room temperature. It has been hoped that earlier modeling for metals, such as Johnson and Cook [1], and Zerilli and Armstrong [2] might be used for composite materials. The Johnson-Cook model was modified by Weeks and Sun [3] for composite materials. Other recent modeling research has been performed by Theruppukuzki and Sun [4], Hsiao, Daniel and Cordes [5] and Tsai and Sun [6]. Woldesenbet and Vinson [7] have characterized the high strain rate and fiber orientation effects on one typical graphite/epoxy composite. Most of these characterizations model ultimate strengths only.

Over the last several years a program has been conducted to experimentally determine the dynamic compressive material properties of various composite materials that are of interest to industry and to various government agencies. A Split Hopkinson Pressure Bar was used for all of the compression experiments. In all cases at least three replicate specimens were tested, and subsequently the data was analyzed to determine mean values, standard deviations, and coefficients of variation. Those experiments were conducted at room temperature and the results are presented in References 8 through 18. The mean values of those data [8-18] were presented recently in [19] in polynomial expressions for the ultimate strengths and moduli of elasticity of the materials tested over the range of strain rates that were tested. Only one paper has treated the effects of low temperature on high strain rate mechanical properties and that paper deals with an E-glass/Urethane composite material [20].

This study extends the experiments at high strain rate compressive testing from room temperature down to the liquid nitrogen temperature ($-196°(C)$ of a graphite/epoxy composite. The same equipment, and testing technique, and data reduction were employed for these tests as were used for the previous room temperature tests.

It is found that the effects of low temperature are significant on the G30-500/EH-80 unidirectional graphite epoxy for such properties as ultimate strength, strain energy density to failure, and modulus of elasticity. For instance, in the 1-direction, changes in ultimate compressive strength at liquid nitrogen temperature vary by 56.8% compared to the value at room temperature, and for strain energy density to failure, the difference is 152.4%!

Appreciation is expressed to the Office of Naval Research, which supported this research through Grant N000 14-93-1-1014, and to Dr. Yapa D.S. Rajapakse, the Project Manager.

Fracture Prediction of 3D C/C Material Under Impact

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In the study of composites, many scales can be defined, from the microscale to the macroscale. Moreover, when dealing with damage, scale has a very strong influence. Indeed, we know from the study of localization that a consistent damage model has to include a length scale to avoid such problems in calculations [1-4]. In static, a pragmatic way to answer this question is to seek a characteristic length of the main damage mechanisms. For 3D composites, there is a preferred modelling scale, between the macroscale (scale of the structure) and the microscale (scale of the single fibre), which is called the mesoscale. This scale is defined, as the scale where one can consider the damage as nearly uniform. This has led to the concept of a damage mesomodel [5-7], where the damage state is assumed to be uniform within each mesoconstituent. Its application to dynamics leads to specific difficulties.

The first one is the necessity to test or identify the mesoconstituents for representative loading cases. The second one is, of course, the modelling of rate effects, and, when dealing with shocks, the modelling and identification of compaction effect. In the following, we focussed on the previous difficulties in the case of a 3D C/C submitted to high velocity impact. The tests were conducted at the Centre d'Etude de Gramat [8]. Compared to other studies, we were abble to predict quite precisely the spalling plane The fracture results from an interaction of the compressive wave in the matrix blocks and of a release wave in the yarns.

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Time Dependent Fracture Processes in Composites: Modelling and Identification of Interface Behaviour

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Cohesive approaches to fracture have been highly successful in many numerical applications and are experiencing a great expansion in the scientific literature. In the composites field, interface models can be used for numerically capturing the fracture and separation processes related to the progressive damaging of adjacent components, either at the microscale (local separation between fiber and matrix) or at the macroscale (delamination).

Several interface (or cohesive) models have been recently proposed by different researchers. In between them, some seem to possess the characteristics to reproduce the progressive separation of composite components in static load conditions, in mode I or mixed mode. Numerous applicative examples demonstrate the efficiency and the versatility of such approach.

The experimental observation of polymer-matrix composites under dynamic loading (e.g. the delamination of polymeric composites subjected to impact) show that their

behavior is rate dependent, and the global response of the material is affected by the loading rate. A reliable and correct interface model should be able to account for this behavior.

In this research, we compare the possible ways to simulate time-dependent and rate-dependent decohesion and separation of composite components, referring to interface models proposed by the Authors or available in literature. We further discuss the possibility to calibrate the constitutive parameters of the interface models in a non-direct way, using parameter identification techniques. We support the discussion with significant examples of interlaminar fracture discretized through finite elements.

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Nonlinear Dynamic Behavior of Parachute Static Lines

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Static line deployed parachute jumping is the most efficient technique used by the United States Army Airborne Corp to deliver paratroopers to target drop-zones. The static line connects the parachute pack worn by the jumper to the anchor line of the jump aircraft. When the jumper exits the aircraft, slack in the static line is drawn tight as the jumper falls below and to the rear of the aircraft. The resulting tensile force generated in the static line achieves a magnitude of approximately 400 pounds before the parachute pack-closing loop is torn open thereby initiating canopy deployment. In some instances, the jumper becomes entangled in the line and prevents the appropriate tensile force from reaching the pack-closing loop. In most of these cases, the jumper remains entangled and is towed back into the aircraft by a high-speed winch connected to the onboard terminal of the anchor line. On rare occasions, the static line fails and the jumper is required to manually activate the reserve parachute to avoid fatal impact with the ground.

Static lines are complex fabric structures that exhibit highly nonlinear behavior while experiencing large deformations. Quasi-static tests were conducted to characterize the behavior of these materials. Drop weight tests simulating actual parachute jumps were also conducted. The forces applied to the test lines were recorded as functions of time. This data is used to determine the force-elongation behavior of the line during the dynamic tests. Results indicate that a significant amount of energy is dissipated during the loading-unloading process. The behavior during the loading phase is similar to that observed during static tests. The unloading phase is significantly different. A mathematical model for the predicting the dynamic response is presented.

The Lyapunov Exponents as a Quantitative Criterion for the Dynamic Buckling of Composite Plates

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The dynamic stability of infinitely wide composite plates subjected to suddenly applied thermal or in-plane mechanical loading is investigated. The Lyapunov exponents approach is offered as an efficient tool by which the dynamic buckling analysis can be performed. This approach is based on the determination of the sign of the largest Lyapunov exponent which characterizes the nature of the response. Thus, an unequivocal answer to the question whether the response of the plate due to a specific loading is stable or not is provided.

The results established by the Lyapunov exponents stability analysis are compared with those obtained by the application of other concepts of dynamic buckling to show good agreements and to demonstrate the advantages of the present approach.

Keywords: Dynamic stability; Lyapunov exponents; Thermal loading; Mechanical loading

Ballistic Impact on Brittle Composites: Shear-plugging Phenomenon

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During ballistic impact, the kinetic energy of the projectile is absorbed by various mechanisms. Impact on brittle composites, especially laminated composites made of unidirectional carbon layers, causes high stresses at the point of impact along the perimeter of the projectile. If this stress exceeds shear-plugging strength of the target, plug formation initiates in the top layers. As a result, impact energy of the projectile decreases. This plugging phenomenon continues until the impact energy of the projectile is low enough to be resisted by the remaining layers of the target. Shear-plugging thus, is the main energy absorbing mechanism in brittle composites.

Other possible energy absorbing mechanisms are: kinetic energy of the cone formed on the back face of the target, energy absorbed due to elastic deformation of secondary yarns, energy absorbed due to delamination, energy absorbed due to tensile failure of primary yarns and friction energy absorbed during penetration. In case of brittle composites, increase in failure strain at high strain rates is not considerable. So cone formation and hence other energy absorbing mechanisms are not prominent. As a part of the present work an analytical model has been presented for the prediction of the ballistic limit and the contact duration of brittle composite targets.

Energy absorbed due to shear plugging and possible other energy absorbing mechanisms is calculated at the end of each time interval and the remaining projectile energy is checked for further plugging. Calculations are continued until all layers fail or projectile comes to rest and rebounds. Initial velocity of the projectile, which gives zero exit velocity, when all layers fail, is the ballistic limit.

Numerical Modelling of the Impact Behaviour of New Particulate Loaded Composite Materials

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The main parameters of lightweight armours design are ballistic efficiency and cost. Metallic materials present disadvantages due to their high density. Mixed armours, made of monolithic ceramic tiles and a metallic plate, seem to be a very efficient shield against low and medium calibre projectiles since they combine the light weight and high resistance of a ceramic with the ductility of metallic materials. However, the use of ceramic tiles in mixed armours has the limitation of its high cost. The authors developed a new material made of ceramic particles and vinylester matrix. This material covers the gap between metallic and ceramic ones and could be interesting for applications where weight is not the primary concern and cost saving should be achieved. In this work, a model that considers damage in the ceramic material has been developed and implemented in a numerical code and compared with experimental results.

For the ceramic material fraction, the damage model proposed by Cortét al. (1992) was adopted. This model considers a damage variable η, that defines the fragmentation of the ceramic, $\eta = 0$ standing for intact material, and $\eta = 1$ for comminuted material. Due to the characteristics of the developed material, the ceramic fraction has an initial fragmentation degree before impact. This initial value depends on the different ceramic particle sizes in the composite tile and was determined by assigning a fragmentation level to each particle size and calculating an average initial damage for the tile.

The second material of the composite is the vinilester. For this resin, a Cowper-Symonds equation was used. The mechanical properties of the composite were calculated from the volume fraction of the ingredients of the composite material.

This model was implemented in a finite differences code. Two-dimensional axisymmetric numerical analysis of Depth of Penetration tests were performed. The numerical results agree with experimental values of full-scale fire tests.

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Ballistic Impact into Fabric and Compliant Laminates

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The introduction of high stiffness and strength fibers in the early 1960s and their corresponding use in fabrics and compliant composite laminates, has allowed the development of lightweight body armor systems that are effective against a variety of threats. Soft body armor systems that protect against threats such as the 9mm bullet typically consist of such fabrics; however, as the threat level increases, multiple component armor systems that include ceramic plates, fabrics and compliant laminates are required. Design of these multi-component systems involves a considerable amount of expertise, experience and experiments. In order to assist in the development of personnel protection, computational methods are being developed to simulate the ballistic impact into multi-component armor systems. As part of this effort, a material model for fabrics and compliant laminates has been developed. Based on the characteristic bi-linear qu asi-static response of the warp and weft direction of ballistic fabrics, the model was also formulated to account for the compaction of multiple plies and the very low shear resistance typical of fabrics. This material model was implemented as a user defined material in the explicit finite element program LS-DYNA. Computational simulations of a steel right circular cylinder impacting multiple plies of KM2 Kevlar fabric were performed and good agreement is found when compared with previously published experimental results. In summary, remarks will be made about further refinement to the model.

Ballistic Impact of VARTM Processed Carbon Epoxy Composites

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Recently cost-effective vacuum assisted resin infusion / transfer molding (VARTM) has received high interest for defense and large-scale commercial applications. Unlike autoclave molded composites, there is limited information and a need therefore for understanding the impact response of composites processed by VARTM. Recently the authors have conducted a series of ballistic impact studies on carbon epoxy composites with plain and eight harness (8H) satin weave fabric architectures. Initial studies indicated that the ballistic impact response for panels of equivalent areal densities was influenced significantly by the type of fabric architecture. In particular, satin weave architecture laminates were seen to exhibit higher energy absorption and enhanced ballistic limit in comparison to plain weave laminates. The studies have been extended to include hybrid panels comprising plain as well as satin weave architectures of three thickness values representative of thin laminates (2 mm thick) for aircraft application through thick laminates (12 mm thick) for marine applications. A systematic series of experiments has been performed for investigating the ballistic perforation, type and shape of projectile, variations in ply sequence in the hybrid panels, range of impact velocities and energy absorption characteristics. This paper will present the results on ballistic response of carbon/epoxy hybrid panels of satin and plain weave architectures of three thickness in light of the above parameters.

Ballistic Behaviour of Hemp Fabric Reinforced Polypropylene Composites

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While plenty of work has been published on ballistic properties of high performance fibres such as Spectra and aramids and their composites, literature on ballistic impact potential of natural fibre composites is non existent. In comparison to continuous filament synthetic fibre composites, the mechanical (and by extension ballistic) properties of discontinuous fibre (notably natural fibres) composites are much lower. However, changes in processing methods have been found to positively affect the mechanical and ballistic behaviour of natural fibre composites. In this work, the ballistic properties of hemp fabric reinforced polypropylene composites processed on a hot compression moulding are investigated. The composite's V_{50} was determined by subjecting the material to ballistic impact loading using a Block Cannon Interchange gun. Further tests were carried out on a composite-steel hybrid system prepared by gluing thin steel plates on the face side and then on the backside of the composite. It was found that the ballistic properties of the hemp reinforced polypropylene composite increased significantly when it is used as a backing to a steel plate. There was a large increase of the V_{50} in the hybrid system with thin steel plates glued on both sides of the composite, as opposed to only the front side.

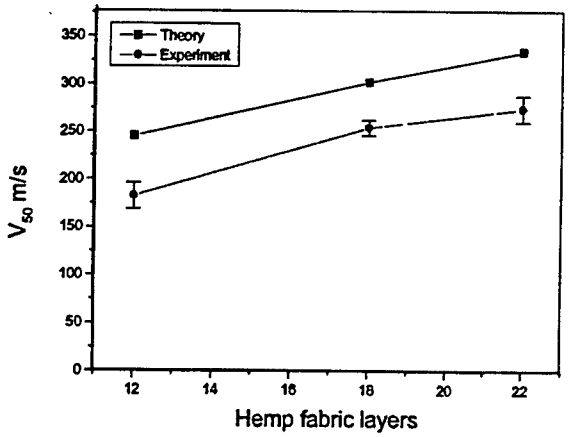


Fig. 1 Plain hemp composite V_{50}: Relationship between theory and experiment

Keywords: Ballistic, V50, Natural fibres, Hemp

Projectile Impact on FRP Laminates

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Introduction Projectile impact on FRP laminates can be generally categorized into two regimes, i.e. low velocity impact and wave-dominated response. In the former case global response as well as local deformations/failure are simultaneously present while in the latter case local deformations/failure dominate. Two semi-empirical modelling methods are described. One uses the dynamic enhancement factor to scale the quasi-static behaviour and encompass the whole range of perforation/ballistic data. The other (wave-dominated) model is based upon a local mechanism alone and incorporates inertial effects in a simplified manner.

Low Velocity Impact The ballistic limit, Vb, can be written as [1,2]

$$V_b = \left(\frac{2E_{pi}}{G}\right)^{\frac{1}{2}} \tag{1}$$

where $E_{pi} = \phi E_f$ is the dynamic perforation energy. ϕ and E_f are the dynamic enhancement factor and the quasi-static penetration energy, respectively [1-2].

Wave-Dominated Response The critical impact velocity or ballistic limit, V_c, can be written as [2,3]

$$V_b = \frac{\pi\Gamma\sqrt{\rho_t\sigma_e}D^2T}{4G}\left[1+\sqrt{1+\frac{8G}{\pi\Gamma^2\rho_t D^2T}}\right] \tag{4}$$

Critical Transition Condition The critical condition for the transition between low velocity impact and wave-dominated response may be expressed as

$$T/L_e = (\pi/2)(\rho_p V_0^2/\sigma_0) \tag{5}$$

where $\sigma_o = [1+\Gamma(\rho/\sigma_e)^{1/2}V_0]\sigma_e$ with V_o and σ_e being the transition velocity [1,2] and the elastic limit of theFR-Plaminates,respectively. L_e is the length of an equivalent flat-ended missile.

Conclusions Projectile/ballistic impact on FRP laminates can be generally categorized into two regimes, i.e. low velocity impact and wave-dominated response. Models have been developed to predict the conditions for the perforation of FRP laminates subjected to impact by missiles with different nose shapes. The critical conditions for the transition between the two different regimes have also been proposed and discussed. It has been shown that the model predictions are in good agreement with experimental observations.

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Correlation of Full-Scale Crash Simulations with Test Results

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The goals of the NASA Aviation Safety Program are: to significantly reduce the aircraft accident rate; and to reduce the fatality rate in survivable aircraft accidents. One element of this program is a multi-year project utilizing a *System's Approach to Crashworthiness*. The objective of this element is not only to reduce fatalities, but also to mitigate injuries through energy management, and maintaining the restraints and the occupiable volume. Current regulations specify requirements for occupant responses to various excitations for structural components consisting of the floor, seat and dummy. The current regulations do not enable utilization of the entire aircraft for impact energy attenuation. A major hurdle impeding the development of a *System's Approach* has been the lack of analytical tools to adequately model aircraft crashes and the relevant test data to validate the models. With the recent advances in computational technology, detailed crash simulations are now possible. However, with the use of detailed finite element models comes a need to develop new techniques for correlating results and an expected higher correlation level between the test data and the analytical results.

The presentation will describe recent advances in the correlation of test and analysis results for full-scale crashes. Examples will be drawn from three full-scale composite impact test and analysis correlation tasks performed at the Impact Dynamics Research Facility, NASA Langley Research Center. The targeted structures were: an innovative, composite fuselage section; a composite Lear Fan aircraft; and a general aviation aircraft prototype developed in conjunction with the Advanced General Aviation Transportation Experiment (AGATE) Program. Several types of both photographic and transducer data are correlated. For example, interior photographic data can provide valuable information with regard to failures and fuselage deformation. Commercial high quality, high-speed digital video system capabilities are now adequate to enable tracking of the external structure's gross motion, as well as identification of the timing of structural failures. Large numbers of strain gage, accelerometer, and load cell data are recorded. The advantages and disadvantages of using the various visual and transducer data for the correlation of full-scale aircraft testing with simulation results will be discussed. For example, the comparison of measured and predicted forces along the primary load paths is important to validate models for several applications. However, the use of load cells, strains gages, or accelerometers often does not completely characterize the structural response. These initial projects focused on utilizing recent technological advances and on identification of areas for improvement in both the testing and the analysis. The implementation of such improvements is imperative to enable the success of a *System's Approach to Crashworthiness*.

Finite Element Analysis of Crush in Carbon Fiber Composites for Vehicle Structures

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In this study the crush behavior of various carbon fiber structures were predicted using a newly developed material model within Radioss(tm). The structures consist of circular and hexagonal cross section tubes as well as conical tubes. The materials used in the study included aerospace grade carbon fiber at various fiber angles and thicknesses. The model takes into account the anisotropic material properties which include the 0° and 90° moduli and strengths. In addition, the failure strain is also

taken into account. The model simulates the microcracking within the crushing structure by determining the stress in each ply within the element, and deletes those plies that are at their failure strength using a Tsai-Wu failure criteria. Once all plies within the element are fractured, the element is deleted. As a result of this, progressive crushing within a structure can be modeled. Although the fracturing is modeled in a discrete fashion, by using an appropriate mesh size for a given structure progressive crushing can be modeled. A number of crush tests were conducted using the cross-sections mentioned with differing materials, orientations, and thicknesses. The results of this analysis proved to be within 15of the experiments.

An Embedded-Tow Shell Model for Crush Simulation of a Textile Composite Tube

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An embedded-tow model was developed to simulate the response of a circular triaxially-braided textile composite crush tube. The embedded-tow model was conceived from preliminary simulations of crush tube response using its parent model, the simplified discrete-tow model. Unlike the discrete-tow model, which represents the fiber tows and resin as beam and shell finite elements respectively, the embedded-tow model incorporates the fiber tows and resin into shell finite elements. Progressive failure of individual tow and resin is accounted for separately. The composite micro-constituent contribution to the overall composite macro-mechanical properties is represented using a micro-mechanical approach similar to the one adopted in the discrete-tow model. With a FORTRAN algorithm to model the composite non-linear material properties and the use of ABAQUS/EXPLICIT software code for simulation in the present study, the embedded-tow model is able to simulate crush tube behavior under compression with adequate computational accuracy and efficiency. The model has the potential to predict general triaxially-braided composite structure response.

Modeling and Analysis of Transient Transient Dellamination in a Layered Composite Laminate Panel Subjected to Explosive Blast

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Advanced lightweight fiber-reinforced polymer (FRP) composites are increasingly being used in armored combat vehicles due to advantages in strength-to-weight ratio and spall reduction capability. However, failure mechanisms governing these materials under highly dynamic loads are rather complex. The design is further complicated by the non-isotropic high strain rate structural properties inherent in use of FRP composites. One of the principal ways in which composite components fail is by delamination of multi-ply constructions which consists of multiple layers of fabric bonded together by typical resin compounds. Conventional finite element models are incapable of simulating delamination failure since multiple layers in a continuum model share common nodes at the interface. As a result, nodes and elements at the interface cannot separate and discontinuity between layers cannot develop. These types of models preclude start and propagation of delamination.

In order for finite element models to predict reliably the response of composites subjected to transient loads, these damage mechanisms must be included in the models in a realistic manner. In multi-layered composite laminate panels subjected to high strain transient loads, experiments indicate that delamination occurs in times that are consistent with propagation of the shock wave induced in the thickness direction and reflected as a rarefaction wave at the interface. This causes separation of layers at the interface to start. This process proceeds very rapidly with damage occurring in tens of microseconds. This is in sharp contrast to the global structural deformation which typically occurs in milliseconds. Finite Element models must replicate this damage in a correct temporal manner if the resulting response predictions are to match what is observed in experiments.

In the current study, the surface-to-surface node tiebreak capability available in the LS-DYNA finite element code has been employed at the interface between two layers of a 15 ply glass/epoxy panel to simulate the occurrence and propagation of delamination. The panel with two opposite edges hinged is subjected to a blast load from a 2.27 kg explosive located 45 cm above ground at 152 cm standoff. The node tiebreak elements between layers were allowed to fail when a delamination failure criterion based on normal and shear failure strengths of the interface bonding resin was exceeded. The results indicate initiation of delamination between 12-14 microseconds which approximately equals the duration of shock propagation from the near panel surface until it is reflected as a rarefaction wave from the interface causing layers to separate.

Characterization of Air Blast-Loaded FRP-Composites

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A major goal for future combat systems is reduced weight without loss of lethality or survivability. Fiber-reinforced polymer (FRP) composites offer advantages over convention metal construction both in strength-to-weight ratio and spall reduction. These advantages are attractive for application to ground vehicles as well as ships and aircraft.

A combined experimental and analytical program is currently being conducted in which FRP panels that are approximately 1 m square are being subjected to air-blast loading. In the program a variety of FRP constructions are being exposed to a variety of air blasts. Beyond characterizing the ability of FRP composites to resist air-blast loading, we intend to develop accurate finite element models of panel response with the long-range goal of improved survivability predictions for vehicles and other Army systems.

Earlier work on blast-loaded aluminum and steel panels with subsequent finite element modeling has been used to resolve several issues in the development of appropriate finite element models for the FRP panels, without the additional complications of composite material behavior. FRP structural elements present an additional challenge because of their anisotropic properties and the way in which they fail under highly dynamic loads. One of these failure modes is delamination of multi-ply constructions.

To develop data for validating finite element model response, a major effort focused on the detection and measurement of the delamination process as it occurs in real time. In experiments conducted with impact excitation, the delamination occurs in times that are consistent with the passage of the shock wave in the thickness direction. Results from the delamination detection work, the air-blast testing, and the finite element modeling effort will be presented.

IMPACT ON COMPOSITES 2002

SESSION R4K
Impact on Composites and graded materials

Damage Mechanisms and Energy Absorption of Plain Weave S-2 Glass/SC-15 Composites under Quasi-Static Punch-Shear and Low Velocity Impact Loading

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Quasi-static punch-shear and low velocity impact tests are carried out on plain weave S-2 glass/SC-15 epoxy composite laminates with blunt and hemispherical impactor. Energy absorbed by composites at different impact energies are plotted to find out different damage mechanisms and energy required to initiate such damage. Different thickness to span ratios and impactor diameter to span ratio are considered to isolate interlaminar shear and flexure dominated damages. The damage mechanisms investigated are delamination, fiber breakage, and matrix cracking. Energy absorbed by different damage mechanisms and elastic energy are isolated and added up to give total absorbed energy. Load-displacement, displacement-energy, and contact force vs. time history are used to identify damage initiation. C-scan and digital photographic techniques are used to find out different damage modes. Load vs. displacement curves, energy absorbed and damage mechanisms are compared between quasi-static punch-shear and low velocity impact loading. The quasi-static punch-shear and low velocity impact experiments are simulated in ABAQUS and LS -DYNA 960 to evaluate different failure criteria. This study is found useful in predicting the damage and energy absorption in woven composites. It has also been observed that the major damage mechanisms in woven composites are delamination and fiber breakage.

Smart Fins - Actuation of Laminated Composite Plates by Anisotropic Piezoelectric Layers

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In recent years, there has been a growing interest in using intelligent materials in various types of structural members. Once embedded into the host structure, the intelligent material provides a wide range of abilities to induce or to sense strain. Some types of intelligent materials can be embedded in the host structure during the manufacturing stage, whereas others can be attached or bonded to the outer faces of an existing structural element. These abilities make the intelligent materials a most adequate solution to various applications such as control of vibrations or acoustical generated noise and the static or dynamic shape control of beam, plate, and shell structures.

In this study, the feasibility to control the structural shape of a subsonic projectile fin using active piezoelectric materials, which are an example of an intelligent material, is investigated. The main objective of the study is to examine and demonstrate the capability of using anisotropic piezoceramic layers to induce **twist actuation** of the composite laminated fin and to achieve the rotations and deflections required for steering and trajectory corrections during flight. For this purpose, a comprehensive mathematical model for composite laminated plates of general layup with either embedded or bonded active piezoelectric layers is derived. The model is based on the variational principle of virtual work along with the classical laminated plate theory, it incorporates the anis otropic piezoelectric effects, and it accounts for both the in-plane and out-of-plane response of the active plate. The anisotropic piezoelectric effect, which is required for either in-plane shear actuation or out-of-plane twist actuation, is achieved by using piezoceramic fibers poled in the transverse direction and oriented in skewed principle directions within the active layer. The procedure derived for the solution of the mathematical model follows the principles of the Extended Kantorovich Method, which is imposed here on the variational ("weak") form of the generalized active plate problem. This formulation incorporates both the governing equations and the boundary conditions in the variational minimization requirement. Hence, it provides a powerful analytical tool for the analysis of piezo-activated composite plates of general layup and boundary conditions.

Finally, the derived model is used for the quantitative examination of four different concepts of design for the twist actuation of the investigated fin. These concepts of design include: (1) twist actuation of a cantilevered plate; (2) twist actuation of a central "shaft"; (3) asymmetric bending in a parallel configuration; and (4) asymmetric bending in a diagonal configuration. The results of the analysis clearly demonstrate that effective twist actuation can be achieved in all investigated designs and they reveal the advantages and disadvantages of these concepts. The paper is concluded with a summary, conclusions and some guidelines for future work.

Wave Propagation in Functionally Graded Materials

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Functionally graded materials are a new class of materials in which, in a macroscopic sense, material properties vary as the density of the reinforcement phase varies in space. While the use of these materials is considered for a variety of reasons, there is a need to investigate their dynamic response, as they are likely to be subjected to foreign object impact. Another objective is to determine whether or not a gradient in material properties will be useful in resisting impact loads.

In this study, one-dimensional wave propagation in a functionally graded layer is considered. Both the elastic properties and the density are assumed to vary both continuously and in a stepwise fashion. The layer is subjected to several types of impulses. Solutions are obtained using several methods including the method of characteristics and a modal superposition approach. Several types of response are obtained depending on the duration of the pulse relative to a characteristic time for wave propagation through the thickness of the layer.

Optimal Design of a Functionally Graded Elastic Strip Subjected to Transient Loading

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We investigate wave propagation in a finite elastic strip subjected to free-fixed boundary conditions. Our goal is

to find a design of functionally graded materials (FGMs) that provides the smallest amplitude of stress during the wave propagation along the strip. We are able to show that for all FGMs, the homogeneous design provides the smallest stress amplitude.

The direct benefit of this work is that it provides results for validation of a purely numerical scheme using finite elements as well as general practical observations for manufacturing of multilayered lightweight armor.

Key words: Stress Amplitude, Functionally Graded Elastic Materials, Optimal Design.

Ground Impact of a Sandwich Plate

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In order to apply failure criteria for composite sandwich plates, the full three-dimensional state of stress must be known. However, a finite element analysis with solid elements requires too many degrees of freedom. Therefore, two-dimensional plate type models need to be used with a capability for accurate computation of not only in-plane stress components but also the transverse stress components.

Under certain circumstances, when the face sheets are thick, when the plate is loaded by a concentrated or partially distributed load, or when the plate is on an elastic foundation, taking account of the direct transverse strain in the face sheets and the transverse shear strain in the face sheets in the expression for the strain energy allows one to obtain a higher accuracy of the stress computation. A model for such a plate must assume or lead to the nonlinear trough the thickness variation of the in-plane displacements both in the core as well as the face sheets. The authors introduce simplifying assumptions with respect to the variation of the transverse strains in the thickness direction of the face sheets and core of the sandwich plates. It is assumed that within the face sheets and the core the transverse strains do not depend on the z coordinate, but they can be different functions of coordinate x, y and time t in each face sheet and core. The assumed transverse strain together with displacements of the middle surface of the plate are the unknown functions of the problem, that are computed by the finite element method incorporating the von Karman strain-displacement relationships. The displacements in terms of the unknown functions are obtained by integration of the strain-displacement relations with the assumed transverse strains, and the constants of integration are chosen to satisfy the conditions of continuity of the displacements across the borders between the face sheets and the core. The in-plane stress are computed from the constitutive equations, and the improved values of transverse stress components are computed by integration of point wise equations of motion.

A problem of cylindrical bending of a simply supported plate under uniform load on the upper surface is considered, and comparison is made between the displacements, the in-plane stress and the improved transverse stresses with corresponding values of exact elasticity solutions

Keywords: sandwich plates, elastic foundation, through-the thickness strains, finite elements

Symposium on

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MEMS AND NANOTECHNOLOGY

SESSION M3L
Mechanical Properties of the Thin-films
and MEMS Materials

CGS Interferometry Applied to the Study of Large Deformations and Instability Regimes of Si Wafers

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This presentation describes coherent gradient sensing (CGS) as an optical, full-field, real-time, nonintrusive,

and noncontact technique for the measurement of curvatures and nonuniform curvature changes in thin film-substrate systems that undergo large deformations. Large deformation behavior prior to and after bifurcation of thin Al and W films on much thicker Si substrates are studied. Fringe patterns provide information on the gradient of the wafer topology through optical differentiation performed by CGS optics. As a result, curvature components, which are obtained from differentiation of the gradients, can be calculated directly from fringe number density. The measured curvatures, in two orthogonal principal directions, clearly show that an equilibrium shape changes from a sphere to an ellipsoid of revolution when bifurcation occurs. Their values are found to agree well with both analytical and numerical predictions of models based on large deformation theory. In contrast to the one-dimensional scanning method, which provides only normal curvature components, twist (shear) as well as normal components of curvatures can be obtained by CGS interferometry. A classical Mohr's circle representation is used to rationalize the evolution of twist curvatures before and after the bifurcation point.

Keywords: Large/thin wafers; curvature measurements; full-field, large deformations; curvature bifurcation

Nanoindentation Strain Effect on Photoemission of Self-assembled Quantum Dot Arrays

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A computational model is used to predict the effect of externally applied strain on the optical absorption spectrum of a self-assembled InAlAs/AlGaAs quantum dot array. The optical properties are computed from the spectrum of electron and hole states found for the ensemble, containing approximately 30 individual dots of different sizes and shapes. The energies and wave functions in the spectrum are computed using a strain-modified k-p Hamiltonian approach; the spectrum includes confined electron and hole states associated with individual dots, in addition to some delocalized states associated with coupled dots as well as the wetting layer. By modeling the entire ensemble of dots simultaneously, it is possible to consider the effect of an elastic strain field superimposed by indenting the sample with the near-field scanning optical microscope (NSOM) tip used to illuminate the dots and detect their emission. To do so, the linear elastic indentation strain field is computed analytically and accounted for in the Schrodinger equation using deformation potential theory, as is the nonuniform mismatch strain due to quantum dot self-assembly. The absorption peaks of the individual dots and the ensemble are shown to shift as a function of indentation depth. Results of the calculation compare favorably to recent experimental data.

Keywords: nanomechanics, quantum dot, indentation, optical properties

Spatial Stiffness Variations in Polysilicon by Atomic Force Acoustic Microscopy

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Recent nanoscale microscopy research has focused on dynamical methods in which an atomic force microscope (AFM) probe is vibrated while in contact with a specimen. Atomic force acoustic microscopy (AFAM) is one such dynamical technique, which utilizes the linear, flexural vibration response of the AFM cantilever. AFAM has been shown to be a useful tool for determining specimen stiffness quantitatively. In addition, surface stiffness variations may be imaged concurrently with topography. In this presentation, the use of AFAM for investigating the mechanical properties and spatial variations in polysilicon are discussed. Polysilicon is a primary material for many microelectromechanical systems (MEMS). AFAM is ideal for characterization of MEMS since it provides in-situ stiffness information without damaging the MEMS. The fundamentals of the AFAM are first described, including the calibration of the vibrations using specimens with known elastic modulus. Then the results on bulk polysilicon and polysilicon MEMS are presented. Two primary observations are reported. First, the stiffness of the grains is shown to vary from grain to grain. The microstructure is typically thought to have a dominant $< 110 >$ out-of-plane texture. However, the AFAM results show that the grain stiffness can vary considerably across the surface of the sample. The nominal AFAM

measurements were found to be 10-20value of 158 GPa. The reason for this discrepancy is thought to be a combination of inaccurate information of the AFM tip geometry and the neglect of adhesion in the contact mechanics model. More surprisingly, stiffness variations within single grains were consistently observed. Whether this internal structure is the result of residual stresses or some other mechanisms is still under investigation.

[1] Research supported by the U.S. Air Force Office of Scientific Research and the UNL Center for Electro-Optics

Fracture, Fatigue and Strength of Silicon and Silicon Carbide MEMS

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Polycrystalline silicon (poly-Si) is the most commonly used material to fabricate microelectromechanical systems (MEMS) devices that operate at relatively low temperatures, and silicon carbide (SiC) offers promise for high temperature applications. However, for these materials the properties required to predict component and system structural reliability (fracture toughness, fatigue crack growth rates, and environmentally assisted crack growth rates) are not well characterized. We have developed a series of poly-Si and SiC fracture/fatigue/strength specimens that could be used to develop a data-base of these properties as functions of processing procedures, and to determine whether there are differences in failure characteristics between micron size structures and bulk structures. The specimens have been fabricated using standard MEMS processing techniques, and so have characteristic dimensions comparable to typical MEMS devices (cracks and uncracked ligaments of several micron lengths). These specimens are fully integrated with simultaneously fabricated electrostatic actuators that are capable of providing sufficient force (less than one millinewton!!) to ensure catastrophic crack propagation. Thus the entire experiment takes place on-chip, eliminating the difficulties associated with attaching the specimen to an external loading source. The electrostatic actuator can also be resonated at very high frequencies, mimicking actual MEMS operation and enabling fatigue experiments in reasonable times. Specimens have been tested with and without micromachined blunt notches, as well as atomically sharp cracks formed by indentation. Results are presented for fracture toughness, high cycle fatigue, bend strength, and environmentally assisted crack growth of poly-Si and SiC.

Multi-range Nanoprobe for Mechanical Properties Testing

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A new instrumented nanoindenter has been developed. The instrument has maximum load capacity of 500mN, maximum stroke of 50μm and force and displacement noise floors of 100nN and 2.5nm, respectively. The instrument greatly expands the range of investigation for bulk/interfacial fracture and delamination phenomena on large scale well defined material systems.

To overcome inherent difficulties of voice coil and permanent magnet designs, which introduce thermal gradient and associated instrument drift the proposed instrument offers a successful integration of piezoresistive loading and capacitive sensing technologies which opens up new horizons in nanomechanical test instrumentation with sub-Newton load capability. This modern design incorporates sub-nanometer scale capacitive displacement and sub-micro Newton force sensing by means of dedicated proprietary load and displacement sensors. An over damped loading system and high bandwidth ensures displacement rates up to 5μm/s. Thermal drift is compensated by means of passive and active design methods and usage of advanced engineering materials. Force and displacement feedback control loops control the actuator. A sub-nanometer precision surface sensing is achieved by the innovative pre-contact A-scan based probing technique. High performance top down optics and precision stages enables submicrometer sample positioning. Dynamic characteristics of the instrument will be presented together with examples of nanometer and micrometer scale mechanical properties characterization on several bulk and thin film material systems.

Computational Techniques for Sub-micron/nanoscale Fluid Dynamics

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The interaction of sub-micron scale objects with fluids is an important problem encountered in miniaturized systems. Various physical phenomena should be modeled simultaneously for a fundamental investigation of these systems. Our objective is to develop a direct numerical simulation tool to better understand the motion of sub-micron objects in complex geometries.

We report: (a) A novel methodology to simulate the Brownian motion of objects in fluids, (b) A technique to simulate the motion of electrically charged bodies with thin Debye layers & (c) An innovative approach to simulate the motion of flexible bodies. The goal is to develop numerical techniques for each of these problems such that they can be unified or interfaced to allow simultaneous description of complex physical phenomena. Preliminary work has been accomplished.

Keywords: Brownian motion, hydrodynamic fluctuations, electrophoresis, flexible macromolecules.

Computational Methods for Electrostatic MEMS

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Computational analysis of electrostatic MEMS requires self-consistent solution of the coupled interior structural domain and the exterior electrostatic domain. Conventional methods for coupled domain analysis, such as FEM/BEM, require mesh generation, mesh compatibility, re-meshing and interpolation of solution between the domains. These procedures can be difficult and time consuming for complex geometries. To overcome the difficulties, we propose an efficient approach to perform static and dynamic analysis of electrostatically actuated MEMS.

The primary contributions of the paper are: (1) Our approach employs a meshless Finite Cloud Method (FCM) to solve the interior structural domain. The Finite Cloud Method is a true meshless method which combines a fixed kernel interpolation and a point collocation discretization. This method completely eliminates the meshing process and radically simplifies the analysis procedure. (2) A Boundary Cloud Method (BCM) is used to analyze the exterior electrostatic domain to compute the electrostatic forces acting on the surface of the structures. The BCM utilizes a meshless interpolation and a cell based integration. Besides the flexibility of the cell integration, the BCM is an excellent match to the FCM for coupled domain analysis since both of them have meshless interpolations. (3) A Lagrangian description of the boundary integral equation is developed and implemented with BCM. The Lagrangian description maps the electrostatic analysis to the undeformed position of the conductors. The electrostatic forces and mechanical deformations are all computed on the undeformed configuration of the structures. The Lagrangian description eliminates the requirement of geometry updates and re-computation of the interpolation functions.

Keywords: meshless, finite cloud method, boundary cloud method, electrostatic MEMS

Compliant Micro-mechanisms with Distributed Compliance

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Elastic deformation-based, joint-less compliant mechanisms are widely used in MEMS instead of jointed, rigid-body mechanisms. The principal reason for this is the ease of fabrication. Growing interest in developing tools for micro-scale mechanical testing of materials, biological cells, and nano-scale specimens calls for versatile compliant micro-tools. Many systematic topology optimization design methods have been developed for the synthesis of compliant mechanisms. These methods are shown to generate designs that are not intuitive for human designers. However, they often tend to give topologies that contain narrow and thin segments connected to rigid segments. In other words, the compliance is lumped to a few local regions. This increases the stress levels in the mechanism. Hence, it is preferable to have distributed compliance wherein the deformation and stress are uniformly

distributed throughout the mechanism. In this paper, we present two methods to obtain such compliant topologies.

In the first method, we present a new differentiable metric for distributed compliance. This metric is used as the objective function. The second method is motivated by "point hinges" that are often seen in compliant topologies. Point hinge arises when two elements are connected at only one node. We trace this problem to the lack of C1 continuity in displacement fields across the elements. We overcome this problem by proposing a C1 continuous plane-stress element using higher-order polynomial shape functions. The distributed compliant designs obtained with the new method are compared with the lumped compliant designs obtained with the earlier approaches. For the same input force, new designs are much more flexible and have lower maximum stress. We present applications of distributed compliant mechanisms to MEMS including a nonintrusive force-sensor and micromanipulation.

Multi-scale Analysis of Au/Si MEMS structures

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Layered Au/Si materials have numerous applications in the field of Micro-Electro Mechanical Systems (MEMS). By tailoring the dimensions and thermal processing of these bi-layer systems, various out of plane displacements can be generated in these layered structures via thermal expansion mismatch. These out of plane displacements can be utilized to create functional actuators or to generate curved surfaces. Although early work has provided proof of concept for layered Au/Si materials in MEMS applications, the present work is focused on developing a detailed understanding of the response of these structures over time as critical for long-term reliability. The effects of thermal cycling, thermal hold periods, and mechanical cycling are examined. Emphasis is placed on discovering and modeling phenomenon at various length scales using interferometric curvature measurements, microscopy, atomic level simulations, and micro-mechanical finite element simulations. An overview of the current results is presented along with future directions.

Mechanical Characterization of Microfabricated Elastomeric Membrane

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This papers reports on a novel method to characterize the mechanical properties, such as the elasticity, of microfabricated elastomeric membranes using central point load-deflection method. An ultra-precision instrument was developed and constructed to simultaneously measure both the displacements and the resultant forces of the membrane under a central load. An optical system applied for viewing deformed membranes in the loading axis reveals the complete deformation profiles of the deformed membranes. In the current experiment, measurements were performed on a thin, circular silicone rubber membrane of 200 m in thickness. A theoretical linear elastic solution is applied to quantitatively correlate the elasticity to the central point load-deformation characteristics of the membrane. The good agreement among the experimental results facilitates the determination of the elastic modulus of microfabricated, thin elastomeric membranes using central point load-deflection method. The characterization will be essentially useful for improving the performances or design of microfabricated membrane, which is widely used in microelectromechanical systems (MEMS), such as pressure sensors, valves, and bubble actuators.

Application of Asymptotic Expansion Homogenization to Atomic Scale

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Molecular dynamics and statics simulations are being increasingly used to model the behavior of systems at atomic scales, where atomistic details play a critical role, e.g. nanoscale structures, grain boundaries [1]. Several such atomic scale problems can be modeled as systems with periodic heterogeneity manifested at the atomic scale (grain boundaries or dislocations), yet influencing

the overall macroscopic behavior. In such cases, it becomes necessary to consider the heterogeneity effects of atomic scale within the framework of the macro scale problem. Asymptotic expansion homogenization (AEH) is a mathematically rigorous approach to homogenization of periodic structures [2]. It has been used in the study of heterogeneous materials consisting of two natural scales, e.g. composite materials and porous media. AEH decouples a heterogeneous multi-scale problem into a macro scale homogenous problem and a micro scale problem. We propose a methodology for multi-scale simulation by adapting AEH to atomic scale. We postulate that materials comprise two different scales; a hyperelastic macro scale and a microscale described by atomistics, with a scaling parameter ϵ relating the two. The field equations for both the scales are separately derived. Those equations can then be solved in variational form using finite element method. The advantage of this method is that every point in the domain is described both by atomic and macro scales. Some illustrative examples are presented to demonstrate the viability of the approach.

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MEMS AND NANOTECHNOLOGY

SESSION T3L
Design of MEMS Devices

Modeling and Experiments of a Bi-stable MEMS Actuated by Radiation Pressure

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A micro mechanical beam, subjected to an axial compressive force by a MEMS actuator is considered. The actuator is supported by linear springs. A known force is applied at the middle of the beam along the transverse direction. A non-linear analysis of the beam-spring coupled system is performed to relate the transverse force with the transverse displacement of the beam for a known actuator force. It is shown that the system behaves as a spring with a linear and a cubic spring constant. The former is positive when the axial force is less than the lowest buckling load, it vanishes at the buckling load, and becomes negative with further increase of load. The cubic constant is positive. After buckling, the threshold force necessary to switch the beam from one buckled state to another varies as the cubic of the buckled displacement. The theoretical results are validated by experimental observations. It is noted that the force necessary to switch state at MEMS scale is on the order of pNs that can be generated by a moderate power incident laser beam due to radiation pressure (caused by photonic impacts). Laser experiments are conducted to demonstrate radiation pressure induced switching, which shows that the threshold laser power is also proportional to the cubic of the buckled displacement. Such bi-stable MEMS can be used to develop memory elements and computational logic elements for harsh environment applications.

Keywords: MEMS, buckling, radiation pressure, logic element

Experimental Investigations of MEMS Configurations

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Experimentation at the micron level requires specific tools and methods. Two components of experimental investigations will be discussed. One is concerned with the ability to strain very small specimens and the other with the potential for evaluating strain fields at the nano-scale.

To measure the elastic properties (Young's modulus and tensile strength) of surface micromachined specimens a special apparatus has been designed to allow reliable manipulation of very small specimens. The idea of gripping specimens through electrostatically induced friction has been demonstrated previously. This method places severe limitations on the magnitude of the forces that can be imposed and because of the sensitivity of the tips of probe microscopes to high electrical fields. The idea of electrostatically controlling the proximity between specimen and the mechanical link to the tensile apparatus has thus been transferred to the controlled administration of small amounts of UV-curable adhesive. .Thus specimens can be stressed well beyond levels where the electrostatic method fails. Typical polysilicon specimens possessing test sections 400 (m long and 2μm $\times$ 50μm cross section have

been examined with this tool with the aid of Digital Image Correlation (DIC). This method draws on the evaluation of surface topologies of the deforming specimen *via* Atomic Force Microscopy (AFM) to determine (fields of) strains. With this tool, high strength or non-linearly behaving materials under different environmental conditions can thus be tested by measuring the strains directly on the surface of a film with nanometer resolution. To explore the limitations of the DIC method an extensive study into error causing disturbances has been conducted. A number of process variables, encompassing subset size, out-of-plane deformation, displacement gradients and scanning noise introduced into the measurements have been studied. The results of this study will be presented.

On the Use of Self-Assembled Monolayers for the Suppression of Fatigue Damage Accumulation in Polycrystalline Silicon Thin Films

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Micron-scale structural films of polycrystalline silicon for microelectromechanical applications are known to be susceptible to premature failure until high-cycle fatigue loading conditions in ambient air environments. Recent work has shown that such failures can be attributed to a "surface dominated" process involving the mechanically-induced thickening of the native oxide film, moisture-induced subcritical cracking of the thickened film, and final catastrophic fracture of the silicon. In this presentation, we examine the role of self-assembled monolayer coatings, engineered (i) to suppress the formation of the native oxide film, and (ii) to further limit the access of moisture to the silicon surface. Initial results show that the use of such coatings can significantly reduce the fatigue susceptibility of polysilicon thin films.

Coupled *Ab-initio* and Finite-element Modeling of Nanoindentation[1]

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During the nanoindentation of well-polished metal surfaces, peak shear stresses beneath the indenter can exceed 10% of the elastic shear modulus. Peak hydrostatic stresses are even larger. *Ab-initio* techniques are used to calculate the non-linear stress-strain response of a variety of metals under these extreme conditions. These stress-strain curves are then used within a finite-element model to calculate the load-displacement response of a nanoindenter and the stress distribution beneath the indenter. We find good agreement between our theoretical predictions and experimental measurement. We also conclude that yielding in these systems can often be governed by the ideal strength of the metal, which is defined by the limit of elastic stability of the lattice.

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MEMS AND NANOTECHNOLOGY

SESSION T4L
Computational Approaches for the Modeling of Nano-objects

Nanoscale Mechanics of Fullerene Tubules and Structures

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Mechanics in nanometer scale is governed by atomic interactions and relaxation processes. We will review our earlier findings in linear and nonlinear elasticity [1] and report more recent results. Comparative analysis of carbon and BN "white graphite" nanotubes elastic properties and yield strength will be discussed, especially our lessons on sensitivity to the choice of interatomic potentials, from classical to quantum tight-binding approximation and ab initio density functional level [2]. We will present thus computed vibration frequencies of the "engineering modes" of isolated structures, and then describe an important role of interaction with environment, especially fluid media, and how it can affect the frequencies in experimentally detectable spectra. Novel kinetic approach in the theory of the nanotube strength and the reversible failure-welding [3], will be discussed in detail, especially the symmetry role (a molecular version of the Schmid's law?), time- and temperature dependencies of strength, and the predicted phase-shifted Evans-Polanyi rule between the thermodynamic and kinetic data.

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Atomistic-based Finite Deformation Continuum Analysis of Carbon Nanotubes

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The mechanics of carbon nanotubes are analyzed using a recently proposed finite deformation membrane theory [1]. The ubiquitously noted shell-like behavior of these nano-structures, together with the resilience of their bond network and the evidence that they undergo extremely large elastic–recoverable– deformations support a finite deformation continuum analysis. A hyper-elastic constitutive law that depends on the first and the second fundamental forms of the membrane is derived strictly from the atomistic description of the system, following the path of crystal elasticity. For this purpose, the fundamental kinematic hypothesis linking atomistic and continuum deformations, the so-called Cauchy-Born rule, must be generalized to deal with curved crystalline films. By investigating the underlying geometric structure of the Cauchy-Born rule in the context of finite kinematics continuum mechanics, the Exponential Born rule is proposed. The resulting membrane constitutive law combined with subdivision finite elements provides a simulation method alternative to computationally demanding atomistic calculations. Both energetic and configurational comparisons with atomistic results demonstrate that the proposed membrane model accurately mimics the mechanics of carbon nanotubes in the full nonlinear regime, beyond structural instabilities for bent, twisted, and compressed nanotubes. The model can also be exploited analytically. A one-dimensional hyper-elastic potential for nanotubes seen as rods is formulated. This reduced model encapsulates the mechanics of axially tested nanotubes. It provides information about structural as well as elastic properties of nanotubes and allows to isolate the individual effect on these properties of the radius and chirality of the nanotube.

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Equivalent Continuum for Dynamically Deforming Atomistic Particle Systems

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An equivalent continuum is defined for dynamically deforming atomistic particle systems treated with concepts of molecular dynamics. The discrete particle systems considered exhibit micropolar interatomic interactions which involve both central interatomic forces and interatomic moments. The equivalence of the continuum to discrete atomic systems includes (1) preservation of linear and angular momenta, (2) conservation of internal, external, and inertial work rates, (4) conservation of mass. This equivalence is achieved through the definition of (1) continuum stress and couple stress fields that make the same contribution to motion and deformation as internal interatomic forces and couples, (2) continuum fields of body force, body moment, surface traction, and surface moment that make the same contribution to motion and deformation as

external forces and moments on the atoms, (3) a continuum deformation field that is work-conjugate to the continuum kinetic fields and consistent with the atomic deformation field, and (4) continuum distributions of mass and moment of inertia that preserve the linear and angular momenta as well as kinetic energy. Construction of the continuum fields follows a process in reverse to finite element discretization. The momentum- and work-equivalence is achieved by virtue of the principle of virtual work for fully dynamic conditions. This equivalence holds for the entire system and for volume elements defined by any subset of particles in the system; therefore, averaging and characterization across different length scales are possible and size-scale effects can be explicitly analyzed. The framework of analysis provides explicit account of arbitrary atom arrangement, admitting applications to both crystalline and amorphous structures. The analysis also applies to both homogeneous materials with identical atoms and heterogeneous materials with dissimilar atoms.

Self Excitation and Frequency Locking of NEMS Oscillators

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Nanomechanical oscillators are an important class of NEMS systems for which there are a large number of potential applications, including filtering for telecommunication devices, mass detection, and scanning force microscopy. Parametric amplification of vibration of the oscillator is often desirable as it narrows resonance peaks, allowing more precise filtering and can be used to amplify small motions.

We have recently discovered that a low power, modulated laser can be used to parametrically amplify disk shaped Si oscillators, 40m diameter and 0.25m thick, oscillating at 1 MHz. The mechanism of stiffness change is the thermal stress due to laser heating. Experimental measurements of amplification and of frequency shift show excellent agreement with theoretical and computational analyses of the oscillators.

We also observe self-generated motions of the oscillator under DC laser power and we observe frequency locking within a range of about 10has both DC and AC components. As the oscillator moves within an interference field it creates, it heats and cools, self-generating the double frequency parametric amplification observed using modulated laser power. Simple models coupling the thermal and mechanical problems will be presented to explain these phenomena.

Stress at the Atomic Level

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In dealing with mechanical properties at the atomic level, one must first define proper stress and strain measures. In particular, there has been considerable confusion in the literature with regard to the correct atomic scale stress measure. The vast majority of work here has made use of either the so-called bulk stress tensor, or a variant, the atomic stress tensor. These stress measures are, however, strictly valid only for a spatially constant stress field and do not satisfy conservation of linear momentum. In a major, but little appreciated, advance in this area, Lutsko (*J. Appl. Phys.* **64**, 1152, 1988) obtained a closed-form solution to the equation expressing conservation of linear momentum at the atomic level, up to the inclusion of an arbitrary solenoidal term, *i.e.*, a term that identically satisfies $\partial\sigma_{ij}/\partial x_j = 0$. If Lutsko's solution for the local stress is integrated over a finite volume, a volume-averaged local stress tensor results for which specific numerical values can be obtained (Cormier, Rickman, & Delph, *J. Appl. Phys.* **89**, 99, 2001). We discuss a particular example: the stress field in the neighborhood of an inclusion in an fcc crystal. Here computed values of the averaged local stress tensor in the neighborhood of an inclusion in an fcc cyrstal were found to agree very well with those values obtained from the continuum solution at distances up to a few atomic spacings from the inclusion. At distances closer to the inclusion, the averaged local stress values deviated appreciably from those of the continuum solution, indicating the breakdown of the continuum solution at this length scale. Particularly noteworthy, however, is the fact that, in the region where the averaged local and continuum stress values agreed well, there was considerably poorer agreement with the values obtained from the bulk stress tensor.

MEMS AND NANOTECHNOLOGY

SESSION W3L
Mechanics of Nanomaterials and Nanocomposites

Molecular Dynamics Investigation of the Fracture Behavior of Nanocrystalline Fe

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We report studies of fracture behavior of nanocrystalline a-iron samples with grain sizes ranging from 6 to 12 nm are at temperatures going from 100K to 600K using atomistic simulations. The fracture toughness is found to decrease due to grain size refinement. For all grain sizes, a combination of intragranular and intergranular fracture is observed. Intergranular fracture is shown to proceed by the coalescence of nanovoids formed at the grain boundaries ahead of the crack. The simulations also show at an atomistic scale that the fracture toughness and plastic deformation energy release mechanisms increase with increasing temperature.

Shape Memory Polymer Based Nano-Reinforced Composites

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Shape memory polymers have the ability to recover extremely large strains (nearly 100%) when subjected to a unique thermo-mechanical cycle. Aside from larger recoverable strain levels compared to shape memory alloys, shape memory polymers are also relatively cheap and compatible with recent polymer MEMS batch processing techniques. However, the primary drawback of these materials for MEMS applications is their inherently low modulus, which limits generated force levels during actuation. Reinforcing shape memory polymers with nanoparticulate c eramic materials increases the low modulus of the matrix material and provides a unique opportunity to tailor the structural and recoverability of these smart polymer materials. The present talk overviews recent results on the study of shape memory polymers and the micro-casting and characterization of SiC reinforced shape memory polymer composites. It is shown that the hardness and modulii of the miniature beams increases with the volume fraction of SiC. In addition, the unconstrained recovery response of the nano-composites also depends on the fraction of SiC. Future routes for processing and characterizing these materials are discussed.

Fracture of Polystyrene/Clay and Polystyrene/Nanoporous Silica Nanocomposites

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Although clay-based polymer nanocomposites provide enhanced chemical properties, the mechanical properties and in particular, the effects of the nanoscale particles on mechanical properties, are not yet well understood. For this study, two types of raw polystyrene specimens, three polystyrene/clay nanocomposites, and one polystyrene/nanoporous silica nanocomposite were investigated. The clay nanocomposites differed in that one was produced through mechanical mixing, one through in situ polymerization, and one through exfoliation of the clay. These three clay-based nanocomposites result in very different microstructures. Standard three point bend fracture tests were performed to determine the fracture toughnesses of the different polystyrene nanocomposites. An optical stereo microscope was used to view the crack before and during propagation. Acoustic emission was monitored throughout the experiments. Distinct differences in crack propagation, acoustic emission, and fracture toughness were observed for the different material systems. These differences are also linked to observations of the fracture surfaces. At this time all composite polystyrene systems have lower toughnesses than the raw polystyrene.

Interfacial Characteristics of Carbon Nanotube-Polystyrene Composite System

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The performance of a composite material system is critically controlled by the interfacial characteristics of the

reinforcement and the matrix material. Here we present a study on the interfacial characteristics of carbon nanotube (CNT)-reinforced polystyrene (PS) composite system through molecular mechanics simulations and elasticity calculations. In the absence of atomic bonding between the reinforcement and the matrix material, it is found that the non-bond interactions consist of electrostatic and van der Waals interaction, deformation induced by these forces, as well as stress/deformation arising from mismatch in the coefficients of thermal expansion. While all of these contribute to the interfacial stress transfer ability, the critical parameter controlling material performance, the former two may be more important in governing the interfacial characteristics of multi-wall CNT/PS systems. Result of CNT pullout simulation (Fig. 1) suggests that the interfacial shear stress of the CNT-PS system is about 160 MPa, significantly higher than most carbon fiber reinforced polymer composite systems.

Keywords: carbon nanotube, polymer, nano composite, interface.

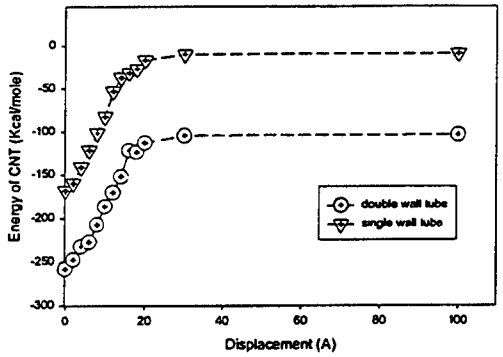


Fig. 1 - Results of simulation of pullout of CNT from PS matrix.

MEMS AND NANOTECHNOLOGY

SESSION W4L

Size Scale Effects in Plasticity and Fracture

Size Effects on the Plasticity and Fracture of Freestanding Gold Thin Films

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The quality and mechanical response of thin films depends on many factors. A major feature is the existence of film thickness effects that arise because of geometrical constraints on dislocation motion. Several pioneering studies have experimentally identified the existence of size effects in the last decade, however, the techniques subjected the specimens to localized non-uniform straining. To date, few studies exist concerning size effects in the absence of strain gradients.

We have used the Membrane Deflection Experiment (1,2) to study size effects on thin films in the absence of strain gradients. The MDE test involves the deflection of freestanding membranes in a fixed-fixed configuration. That is, the membrane is attached at both ends and spans a micromachined window beneath. A nanoindenter applies a line-load at the center of the span to achieve deflection. The geometry of the membranes is such that it contains tapered regions to eliminate boundary-bending effects. The result is direct tension, in the absence of strain gradients, of the gauged region.

We will present stress-strain signatures obtained on thin gold films 300, 500 and 1000 nm thick. Elastic modulus was consistently measured in the regime of 54 GPa. Several size effects on the mechanical properties were observed including yield stress variations with membrane width and film thickness. The size effects here reported are the first of their kind in the sense that the measurements were performed under a macroscopically homogeneous axial deformation. The experiments reported here illustrate the need for the development of experimental techniques that can examine the atomic structure of metal films as a function of deformation while independently measuring stress and strain.

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Photo-Acoustic Characterization of Mechanical Properties and Residual Stresses in Thin-Film MEMS Structures

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Free-standing or supported thin films are in widespread use in industry. Many MEMS devices such as pressure sensors and optical-switches use thin film membranes that are nanometers thick and microns wide. Micron-sized

hard coatings on substrates are used to provide enhanced wear properties of roller bearings etc. In both cases, it is important to accurately and nondestructively measure the mechanical properties of the film. Current methods for obtaining mechanical properties and residual stresses include nano-indentation, bulge, and resonance frequency tests. Unfortunately these measurements are either destructive or depend critically on knowledge of how the films are supported. Laser ultrasonics (photo-acoustics) is a potentially powerful tool for nondestructive and non-contact characterization of thin films. This paper describes a photo-acoustic microscope (PAM) which has been configured for non-contact high-resolution mapping of the mechanical properties of nanometer-sized free-standing thin film MEMS devices and hard coatings. The PAM head consists of a photo-acoustic generation unit and an optical interferometer. Photo-acoustic (also known as laser ultrasonic) generation is achieved by the deposition of pulsed laser energy on to the object which causes rapid thermal expansion leading to the generation of high frequency ultrasonic waves in the structure. The resulting ultrasonic displacements are monitored interferometrically at several distances from the source, using both a Michelson-type interferometer and an adaptive holographic interferometer. Experiments on 200nm to 5 micron thick films have been performed using the photo-acoustic microscope. The elastic properties (as well as residual stresses in some cases) of these thin film structures are extracted from the photo-acoustic measurements. Results of the photo-acoustic experiments are compared with those of contact acoustic microscopy.

Plastic Slip Gradient-Induced Lattice Rotation at Submicron and Nanometer Scales

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In the presence of plastic slip gradients, compatibility requires gradients in elastic lattice rotation and stretch tensors. For a crystal lattice, the gradient in elastic rotation causes bond angles to change. The corresponding strain energy is represented in three-body interatomic potentials. A couple stress tensor arises in the continuum limit. The resulting stress and couple stress, strain and strain gradients satisfy a balance law and boundary conditions originally due to Toupin [1962]. Toupin's theory has been extended in this work to incorporate constitutive relations for the stress and couple stress under multiplicative elastoplasticity. This higher-order continuum theory is exploited to solve a boundary value problem involving deformation at the deep submicron and nanometer scale. It has applications to grain rotation in polycrystals, and to single crystal and polycrystalline nano-devices. The significance of continuum couple stresses formulations will be examined. The important implication is derived, that the assumed deformation mechanism makes nanostructures significantly more compliant in bending-dominated situations.

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Atomistic Studies of Crack Propagation in Nanocrystalline Ni

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Crack propagation studies in nanocrystalline Ni samples with mean grain sizes ranging from 5 to 12 nm are reported using atomistic simulations. For all grain sizes pure intergranular fracture is observed. Intergranular fracture is shown to proceed by the coalescence of microvoids formed at the grain boundaries ahead of the crack. The energy released during propagation is higher then the Griffith criterion, indicating an additional grain boundary accommodation mechanism.

Molecular Dynamics Studies of Phase-transitions and Plasticity in Nano-scale Materials

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Recent advances in computing technology has allowed direct simulations at the classical level of the the response of materials to shockwave loading and unloading. In dense monatomic, chemically unreactive fluids, the profile or structure of a shock wave is rather boring, being well described by viscous flow. In solids, on the other

hand, the structure is far more complex, being dominated by plastic flow mechanisms as well as phase transformations. At Los Alamos National Laboratory we have developed a high performance parallel MD code (SPaSM) which has been designed to perform very large scale simulations with 10^8-10^9 atoms. I will discuss some of the recent advances we have made in simulations of shock waves and related phenomena, including plastic deformation, phase-transitions, and fragmentation. As experimental observations become more and more refined, and molecular-dynamics simulations become larger, even approaching the mesoscale, fruitful overlap is achievable in the near future.

Glass-Modified Waves for Measuring Adhesion of Ultrathin Layers and Multilayers

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Laser-generated transient stress pulse profiles with 2 ns rise-times and 16-20 ns post-peak decay times have been remarkably modified through propagation through various glasses. The resulting profiles have a gradual rise-time of up to 50 ns, and a reverse shock profile characterized by a post-peak decay time of only 0.2 ns. The gradual rise time is a result of glass densification due to transformation to one of the several metastable states possible, while the reverse shock profile is thought to occur from overcrowding of the faster moving post-peak wave profile into the significantly decelerating pulse front. Such a pulse allows generation of a peak tensile amplitude at a thin film interface equal to its inital compression pulse amplitude. Thus, interfacial strength in ultra thin layers and multilayers can be measured for the first time. Adhesion measurements in systems involving nanoporous silica layers, osteoblast cells, and multilayer devices will be discussed.

MEMS AND NANOTECHNOLOGY

SESSION R3L

Nanotribiology/Nanomachining

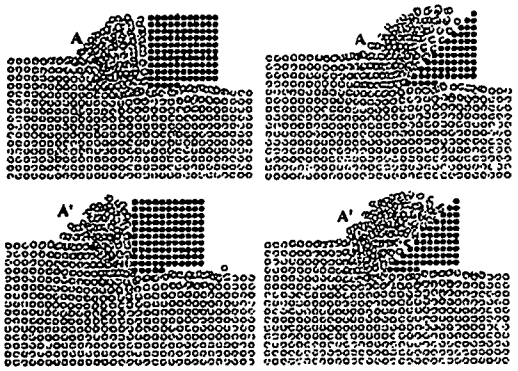
Molecular Dynamic Simulation for 3-D Nanometric Cutting Process

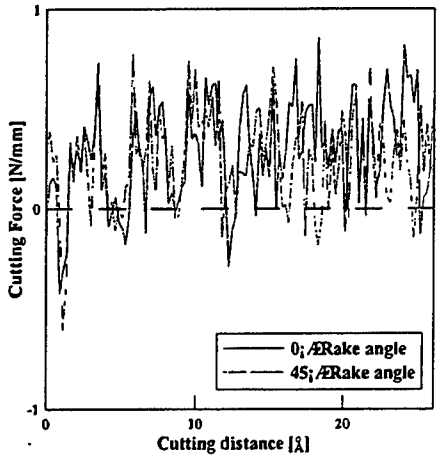
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Many precision devices such as computer hard discs, lenses and mirrors are manufactured by ultraprecision machining using single-crystal diamond tool at extremely low depths of cut. In this study, 3-D molecular dynamic simulations are performed to investigate the nanometric cutting processes of Cu and Al materials. Simulations are carried out by varying the rake angle of tool(0■45°), cutting depth of a few atomic layer(1.25Å■1.5Å) and cutting direction < [−100], [−110], [−210] >. Morse potential is used to model the interaction of each molecule and between tool and work piece. Variation of the cutting force, chip generation, and subsurface deformation with the tool geometry are investigated. It is certain that the cutting force per unit length is strongly vibrated in -0.6■$0.8[N/\ ]$. The cutting resistance increases with the rake angle of cutting tool, and the roughness of surface machined on copper is smoother than that on aluminum.

Keywords: Molecular dynamics simulation, Nanometric cutting, Morse potential, Cutting force





Triboemission of Charged Particles and Nanotribology

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The phenomena of triboemission of charged particles is reviewed with a focus on the role of such particles in some tribochemical reactions, in particular in the mechanism of tribopolymerization, which are known to produce very-thin lubricant layers.

A new instrument, which was developed by the authors, is presented for the measurement of charge intensity and energy distribution of charged-particles triboemitted in high vacuum. A summary is included of most relevant triboemission measurements for A-on-B ceramic systems (alumina, sapphire and aluminum when scratched by a diamond pin) and for an A-on-A (alumina-on-alumina) system for low loads and speeds.

Connections are made with the surface mechanisms by which triboemission is thought to proceed (e.g., initiation and growth of surface microfracture), and with emission during closely related phenomena (e.g., nanoindentation and surface tensile-deformation). Finally, the possibility is discussed of including triboemission considerations in the study of nano-scale surface modifications and of MEMS.

Keywords: Triboemission, Nanotribology, Nano-scale surface modifications.

Material Removal Mechanisms in Micro and Nano-Machining

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Surface machining is becoming an integral processing step in multilevel metallization designs for integrated circuit (IC) manufacturing for ensuring local and global surface planarization. The surface machining process employ micro and nano particle abrasives with a soft polishing pad to remove material from the surface. The corresponding mechanisms of material removal of ductile copper and aluminum films on silicon wafers are studied both experimentally and numerically. The experimentally observed trends of the deformation pattern and the force profiles from micro and nano-single scratch experiments are used to guide numerical simulation using finite element simulation at the continuum scale and molecular dynamics simulation at the atomistic scale. Such integrated approach has provided several plausible mechanisms for material detachments through a combination of surface plowing and shearing under the abrasive particles. The gained insights can be integrated into mechanism-based models for the material removal rate in these processes as well as addressing possible defect formation.

A Coordinated Theoretical and Experimental Approach for Large-Scale Simulation of Nanoindentation

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Recent interest in the manufacturing and engineering utilization of nanostrutures and nanodevices has created the need for simulation tools that are capable of predicting the microscopic and macroscopic behavior of the nanosystems. Nanoindentation experiments have been found to be extremely useful in measuring the mechanical and tribological properties of thin films or layers. However, as the thickness of the films or layers continues to decrease, interpretation of data from nanoindentation experiments becomes more and more difficult due to possible cracking and phase transformation caused by large stresses in the vicinity of the indenter. The availability of predictive tools would play a key role in developing and accelerating new nanosystems. We develop a coordinated theoretical and experimental program for developing large-scale, physically-based simulation tools that are capable of predicting the behavior of the nanoindentation over a wide range of length scales.

A multi-scale model is proposed based on a combination of a novel quasicontinuum approach, a dislocation nucleation formulation, and a crack evolution model.

The novel quasicontinuum approach furnishes a computational scheme for seamlessly bridging the atomistic and continuum realms. Unlike traditional finite element methods, the nonlinear elastic effects, the symmetries of the underlying crystal, and the possibility of phase transformations are naturally included in this framework. We perform a range of simulations, based on the multi-scale model, of nanoindentation experiments on silicon and aerogel thin films, each of which is motivated by the recent results of an on-going micro electro-mechanical systems (MEMS) research.

Acoustic Measurements for Nanomechanical Test Instruments

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Acoustic methods have been used successfully for microscale contact non-destructive evaluation, but until very recently, were not available for the nanometer scale.

Nanomechanical test instruments offer nanometer scale quantitative determination of thin film mechanical properties through evaluation of quasi-static loading-unloading curves. These tools coupled with in-situ Scanning Probe Microscopy (SPM) - type imaging and simultaneous acoustic response monitoring open new instrumentation horizons for micro/nano fracture mechanics. Correlation between quasi-static loading-unloading curves and simultaneously monitored acoustic phenomena, augmented by pre- and post-indentation SPM-type imaging, enables real-time investigation of phenomena such as film delamination and dislocation activity. Both active and passive acoustic methods can be utilized to characterize a large variety of substrates and coatings. Examples of Acoustic Emission monitoring of nanoindentation/scratch on data storage media will be presented. Plastic deformation induced events can be separated from contact friction events by identifying AE signatures associated with nanoindentation/scratch and wear tests.

As another application, active ultrasonic methods can be utilized for nanoscale characterization of tribological surfaces. A friction coefficient reduction of up to 20 percent was observed on an ultrasonically excited surface during scratch testing and was further investigated using post-scratch SPM-type imaging.

Recent trends suggest the possibility of combined nanoindentation/AE applications for evaluation of viscoelastic biological materials. A synergy of localized ultrasonic monitoring and nanoindentation technique can lead to the development of new and promising instrumentation for characterizing in-vivo/vitro biological tissues at the molecular level. Examples on evaluating ultrasonically transmitted signal through biological samples will be discussed.

MEMS AND NANOTECHNOLOGY

SESSION R4L
Mechanics of Nanostructures II

A Numerical Approach for the Design of Nanomechanical Biodetectors

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A numerical method is presented for the detailed investigation of the coupled motion of arrays of nanoscale elastic cantilevers immersed in a fluid environment in the presence of confining boundaries. The purpose of the resulting computational tool is to assist in the analysis and design of nano-electromechanical systems (NEMS) for the assay and characterization of biologically interesting molecules, [1].

The proposed numerical approach is based on a fully Lagrangian finite element formulation of the coupled dynamics of the elastic cantilevers and the incompressible viscous fluid. The principal advantage of this unified Lagrangian approach lies in the natural treatment of boundary conditions at the interface between the fluid and the solid, i.e. the fluid-solid coupling. As opposed to Eulerian approaches, boundary conditions are enforced at material surfaces *ab initio* and therefore require no special treatment. The finite element formulation provides the additional advantage of being very flexible, allowing for the definition of complex cantilever geometries and configurations, characteristic of real experimental systems, with little effort. The Lagrangian formulation for the fluid follows the approach originally proposed by Radovitzky *et al* [2] for the Navier Stokes equations of incompressible viscous flow. Although our primary focus is on the linear response of the system, large-deformation nonlinear effects are included as part of the formulation, and can be used to assess limitations of the linear response analysis. It bears emphasis that the proposed numerical framework furnishes a numerical approximation of the fully-coupled

equations of elasticity and incompressible viscous flow without the restrictive assumptions present in previously proposed approaches [3]. In particular, the effect of confining walls as well as the presence of neighboring cantilevers is fully taken into account and the approximation that the fluid is acting on a beam of inifinite length is abandoned.

Numerical results are shown for the resonant response to external driving and the thermal fluctuation spectrum for a single and a pair of cantilevers. In the latter case, the correlated fluctuation spectrum is computed *via* the fluctuation-dissipation theorem.

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Cochlear Outer Hair Cell: a Biological Piezoelectric Actuator

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Outer hair cells play a crucial role in the active amplification and sharp frequency selectivity of the ear. The active energy is produced by the cell and pumped into vibrating components of the cochlea. The cell membrane exhibits piezoelectric-type behavior that, at the nano-level, is associated with molecular motors that undergo conformational changes in response to the application of an electric field. These conformational changes contribute to the active strain, force, and energy production by the cell. We use previously proposed mechanically linear and electrically nonlinear constitutive relations to analyze energy modes in the cell membrane. We derive balance of the mechanical and electrical energies. We introduce the active and passive modes of the mechanical energy associated, respectively, with the motors and the passive part of the membrane. We also introduce another mode of the active energy and the stored electrical energy that enter general balance of energy. Two modes of the active energy coincide in the electrically linear case. The stored electrical energy is determined by membrane capacitance, an important characteristic of the active outer hair cell. We show that the value of "effective" (measurable) capacitance is between those corresponding to two extreme cases of the zero-strain and zero-resultant conditions. The difference between the two extreme values of the capacitance can be expressed in terms of the active strain and active force, and we propose this difference as a criterion of the effectiveness of the cell as a piezoelectric actuator. We compute and plot major modes of energy as functions of the membrane potential and the force applied to the cell. Active membrane, energy modes.

Inorganic Nanotubes and Inorganic Fullerene-like Materials from Concept to Applications

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We have proposed that nanoparticles of layered compounds will be unstable against folding and close into fullerene-like structures and nanotubes (IF). Initially this hypothesis was realized in WS2 and MoS2. Subsequently, nanotubes and fullerene-like structures were prepared from numerous compounds of 2D habit. Much progress has been achieved in the synthesis of inorganic nanotubes and fullerene-like nanoparticles of metal dichalcogenides as well as with numerous other layered compounds over the last year or two.

In collaboration with L. Rapoport, it was formerly shown that addition of small amounts of IF-WS2 to lubricating fluids largely improve their tribological characteristics. Major progress has been recently achieved in applying IF-WS2 for self-lubricating matrixes. This work and future developments in this context will be discussed in brief.

Stuffed Carbon Nanotube Materials: Production and Properties

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As today's device engineers face technical and economic difficulty in further miniaturizing transistors with

present fabrication technologies, the need for alternative functional devices is particularly pressing. Recently, carbon nanotubes have been successfully used for nanometer-sized devices such as diodes, transistors, and random access memory cells. Despite these achievements, efforts to integrate these unit devices into functional systems have not yet succeeded. In this talk, I will report a method for constructing self-assembled, multiple quantum dots in a semiconducting carbon nanotube encapsulating endohedral metallofullernes (the so-called, peapods)[1-3] and demonstrate a spatial modulation of the band gap using a low-temperature scanning tunneling microscope (LTSTM). In semiconducting nanotubes the band gap can be varied from $\sim$ 0.5 to $\sim$ 0.1 eV with inserted $Gd@C_{82}$ endohedral metallofullerenes[4] with spatial periodicity of 1.1 nm to 8.0 nm, depending on the density of the fullerenes[5]. The change of the band gap can be explained by local elastic strain and charge transfer at sites where metallofullerenes are inserted. This technology for self-assembly of one-dimensional multiple quantum dot system can potentially be used for optoelectronics and quantum-computing technology, accelerating progress towards an era of molecular electronics.

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Mechanical Modeling of Finite Deformation of Fullerene Balls, Graphene Plate, and Carbon Nanotubes

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At present molecular dynamics (MD) simulations are the major tools being used to investigate the mechanical behavior of nano-sized structures. However, it is indicated by several theoretical studies on carbon nanotubes that the classical continuum mechanics is quite reliable in predicting the mechanical behavior of these nano structures, even in treating intrinsically discrete objects only a few atoms in diameter. In this paper, we study the deformation of fullerene balls, graphene plates, and carbon nanotubes using both molecular mechanics and continuum mechanics.

A shell model is used to analysis finite deformation of the fullerene balls under axial compression, by means of an equivalent continuum method based on the energy equivalence between the graphene structures and the corresponding continuum objects. The energy change and finite deformation of the elastic model are calculated and analyzed for C^{60}, C^{80} and C^{180}. Results of the calculation with this model are in very good agreement with those of MD simulations. The elastic response of a circular single graphene sheet under a transverse central load, and carbon nanotubes under three-point bending and cantilever bending, are also studied using MD, closed-form nonlinear elasticity solution (EL), and finite element method. Results showed that the mismatch in deformation profiles of graphene sheet between MD calculations and continuum mechanics methods decreases with an increase in central deflection. Deformation profiles of carbon nanotubes under three-points bending obtained by MD and EL are in good agreement with each other. However, mismatch occurs at larger deformation as a result carbon nanotube buckling. Our systematic approach on carbon-based nano structures illustrates that continuum mechanics could be used with confidence to predict the mechanical behavior of structures at the nanometer scale.

Keywords: fullerene ball, graphene, carbon nanotubes, molecular dynamics.

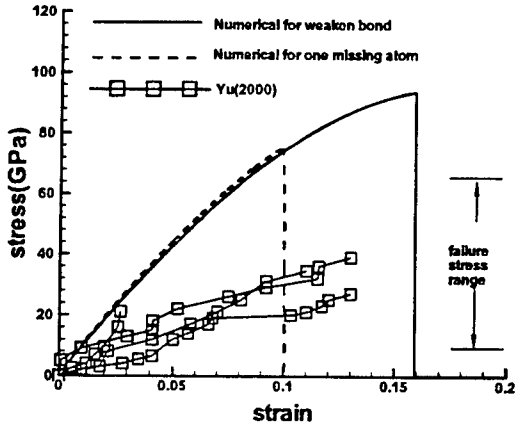
Continuum Models and Fracture of Nanotubes

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Coupled continuum/molecular dynamics models have been developed for the analysis of Carbon nanotubes. A problem of particular interest is the fracture of nanotubes, since nanotubes appear to be a potentially very strong material. We have found that molecular mechanics fracture models of Carbon nanotubes are very sensitive to the location of the inflection point in the potential force field. The well-known Tersoff Brenner potential is not successful in duplicating any experiments even coarsely because the cutoff introduced at about 15fracture stress and fracture strain. Therefore, we have used a modified Morse potential. We have also found that defects play a strong role in the fracture behavior. A comparison of our computations with the experiments is shown below. As can be seen, that results overestimate the fracture strength, although with the addition of a single missing atom defect, the strength goes down substantially. We have found that

we can duplicate the upper end of this range with multi-atom defects. It can also be seen that as in the experiments, the fracture is brittle.



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Symposium on

The Rate and Pressure Dependent Constitutive and Damage Behavior of Polymers and Discontinuous Polymer Matrix Composites; Experimental Data and Modeling

Organizer:
Professor R. K. Garrett, Jr.
(Naval Surface Warfare Ctr., Dahlgren)

THE RATE AND PRESSURE DEPENDENT CONSTITUTIVE AND DAMAGE BEHAVIOR OF POLYMERS AND DISCONTINUOUS POLYMER MATRIX COMPOSITES; EXPERIMENTAL DATA AND MODELING

SESSION W4E

Stress Relaxation from Non-Equilibrium Deformation of Polymer Segments

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In a polymer network, polymer segments usually interact with their surrounding medium. The deformation along a segment is not uniform, in contrast to the usual assumptions in traditional network theories. Although the uniform state of deformation is the equilibrium state of polymer segments, for many polymers, such as polyisobutylene, we estimate that the relaxation from a non-uniform state of deformation to the equilibrium state can take up to a few hundred seconds and sometimes even longer. This feature results in stress relaxation in polymeric solids.

To model this effect, a statistical theory is employed to study the dynamics of the network of polymer chains. Interactions of polymer segments with their surrounding medium are modeled as elastic springs immersed in a viscous fluid. The stress relaxation is expressed in terms of a history integral. The relaxation kernel of the integral is found to be proportional to $(1/\sqrt{t})$ for short times, and to decay exponentially for long times. While the long time behavior described by this work agrees with the Maxwell model used in many engineering calculations, the short time behavior is new and is significant for high strain rate deformations. This theoretically predicted behavior of the relaxation is conformed by experiments.

Physical Properties and Ballistic Data Analysis of Filled Energetic Materials

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Physical properties such as elastic and failure moduli can be correlated with the ballistic performance of energetic materials across the operational temperature range. As the energetic materials combust, ignition or combustion pressure can deform or create small surface fractures

in the unconsumed material, which manifests itself in the form of increased burn rate and/or temperature sensitivity. This phenomenon is more pronounced in highly filled materials since they are more susceptible to stress from high thermal gradient and deformation rate due to the material coefficients mismatch at the interface. We study the influence of adhesion between the polymer binder and the filler particle on the ballistic performance of energetic materials based on the closed bomb vivacity data and the linear burn rate analysis. Ballistic data indicates that the vivacity for the more ductile propellant is less progressive and temperature sensitive compared to the more brittle propellants. Different process conditions were used to manipulate the adhesion between polymer binder and filler particles such as high solvent strength and by pre-wetting the filler particles before mixing. Results indicate that if filler particles adhere or wet into the polymer binder well, the vivacity shows a regressive trend toward the end of the burning period. High moisture levels, however, tend to reduce the interface adhesion and increase the burn rate and temperature sensitivity. The contributing factors for material properties of energetic materials include parameters such as filler particle size and geometry, extrusion rate and conditions, and solvent or moisture levels. Improvement of methods to optimize physical properties and development of material models to link the interface adhesion and the burn rate characteristics are needed for better charge design and more consistent temperature sensitivity of energetic materials.

The Temperature and Strain Rate Response of Polymeric Materials

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Compressive stress-strain measurements have been made on a range of commercial polymers (Nylon, Teflon, PMMA, PC, etc.) and polymeric binders used in explosives (Estane, HTPB, etc.) as a function of temperature (−197 C to +220 C) and strain rate. A split-Hopkinson-pressure bar (SHPB) was used to achieve strain rates of about 2500/s and conventional testing machines were used for strain rates between 0.001 and 1/s. A large variation in mechanical response over the range of temperastures tested was observed. Some materials showed visco-elastic behavior and others exhibited "yield" and "plastic" deformation. The visco-elastic recovery of some of the polymers is seen to dominate the mechanical behavior at temperatures above the glass transition temperature (Tg). The polymers exhibited increasing elastic loading moduli, E, with increasing strain rate or decreasing temperature. Also, the Tg shifts to higher temperatures as the strain rate is increased. Some of these polymers are shown to be more sensitive to strain rate and temperature below Tg than others. Below Tg The polymers exhibit a yield behavior, followed by an increasing maximum flow stress, sm, or the strain-at-maximum stress, em, which occurs when the binder first yields for increasing strain rate or decreasing temperature. Predictive models are being developed based on the constitutive response of these materials that will simulate deformation.

Material Testing and Constitutive Modeling of PTFE 7C

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Previous principle uses of Teflon have exploited its chemical inertness, low coefficient of friction, dielectrical properties and resistance to environmental degradation. Traditionally, Teflon has been used as a nonstick coating for cookware, to seal and lubricate plumbing, in high frequency microwave circuitry, and in cable insulation and anti-graffiti coverings.

In recent years, there has been increased interest in using polymers, such as Teflon, in polymer-bonded explosives and rocket propellants subjected to extreme strain rates and temperatures. Existing available mechanical properties are tensile strength, elongation, flexural modulus, impact strength and hardness. However, since the rate and temperature effects on the stress-strain response of Teflon are not important in conventional applications, very little information is available. It is therefore necessary to characterize the behavior of Teflon for use in computational simulations and subsequent design for these applications. ASTM standard test specimens were used to obtain tensile and compressive properties at quasi-static strain rates under different temperature conditions. A split Hopkinson bar was used to obtain compressive properties at higher strain rates under different temperature conditions. The measured stress/strain data from these experiments were implemented into a thermal activation constitutive model.

Keywords: Teflon, constitutive modeling, rate sensitivity, thermal activation model

Fracture Toughness Evaluation of PTFE 7C (Teflon)

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The objective of this preliminary work was to explore the fracture resistance of polytetraflouroethylene (PTFE) (Dupont Tradename Teflon). This material is being utilized in structural applications and little mechanical property data is available on this material since it is commonly used only as a coating material with the dominant properties being its low friction coefficient and high application temperature. End products of the "7C" derivative include sheet, gaskets, bearing pads, piston rings and diaphragms. While the material demonstrates high ductility when loaded quasi-statically at ambient temperature, higher loading rates and/or lower test temperatures give dramatically different properties and a transition to fracture is readily observed.

In this work, standard round tensile specimens and standard ASTM E1820 compact C(T) fracture toughness specimens were machined from a 14 mm thick sheet of this material obtained from NSWC Dahlgren Laboratory and these specimens were tested at three test temperatures and four test rates to characterize the fracture toughness of this material and how the fracture toughness depends on the test temperature and specimen loading rate. Non-linear fracture toughness procedures now available in ASTM E1820 utilizing the J-integral approach are applied to this problem. The experimental approaches used, and the problems encountered are described in detail.

The major results are that while crack extension is difficult at ambient (20°C) temperature, for temperatures slightly below ambient, a rapid degradation of fracture resistance occurs. This reduction in fracture resistance is enhanced by rapid loading, and the material loses approximately 75% of its toughness (fracture energy absorption ability) at −18°C (0°F) if the crack opening loading rate of the C(T) specimen approaches 0.25 m/s.

Modeling the Constitutive Response of an Al-Teflon Composite under High Strain Rate Loading[1,2]

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The constitutive response of Teflon (polytetrafluoroethylene, PTFE) blend ed and sintered with aluminum powder (25surprising dependence on confining pressure and strain rate. In this work, we present a description of the mechanical response of the material and the constitutive model developed to capture this response for high strain rates. In order to exercise the constitutive model, it has been implemented into the shock physics wavecode, CTH. This talk will present the details of the material's response, it's constitutive model representation, and the wavecode simulations conducted in order to fit and validate the model.

Keywords: Constitutive Response, Confining Pressure, High Strain Rate, Aluminum-Teflon

[1]Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

[2]This work supported by funding through the Naval Surface Warfare Center, Dahlgren Division, and the Office of Naval Research.

Symposium on

Symposium on Computational Geomechanics

Organizer:
Professor Marte Gutierrez
(Virginia Tech)

COMPUTATIONAL GEOMECHANICS

SESSION F2O

Large Deformation Cam-clay Theory for Granular Media

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We present a finite deformation constitutive theory for granular media. The material model falls in the family of the so called Cam-clay theories. As typical of Cam-clay models, soil is assumed to be frictional with logarithmic compression. The same state boundary surface

–described by ellipses– is taken as yield and plastic potential surface. Hardening is related only to plastic volumetric strains. The large deformation theory is based on the multiplicative decomposition of the deformation gradient into elastic and inelastic parts. We extend the stress update algorithms from small-strain plasticity to finite plasticity through the logarithmic and exponential mappings. We adopt a fully variational characterization of the viscoplastic constitutive updates.

A Numerical Model for Soil Liquefaction at Depths

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Current seismic safety analysis techniques for dams and other structures assume that there is no depth limit to liquefaction of soil deposits. Recent, limited studies of liquefaction at depth indicate there is a limit to the amount of excess pore water pressure that can be developed. The centrifuge studies at ERDC have shown that the generation of excess pore pressure is capped at a level below 100 percent for vertical effective confining stresses exceeding around 300Kpa. The result is verified by a numerical/material model which shows more accurately represents the relationship between stress state, liquefaction potential, and deformation for a dam-foundation system, and to quantify the levels of damage that a dam that can tolerate. As a result, our understanding of the liquefaction behavior and the level of damage at very large depths are enhanced.

In this project, numerical studies with a first-principle soil model are conducted to interpret centrifuge system response results for deep sand deposits. Comparison between numerical and physical model results is discussed.

Keywords: liquefaction, modeling, numerical, centrifuge

This research as part of collaborative efforts between the Jackson State University, and the Army Engineer, Research, and Development Center, Waterway experiment Station was supported by the Stennis Space Center. The support is gratefully appreciated.

A Multi-Scale Effective Moduli Model for Concrete Incorporating ITZ Water-Cement Ratio Gradients

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Water-cement ratio gradients are modeled through the interfacial transition zone (ITZ) of concrete with idealized spherical aggregates. The local ratios are a function of the overall water-cement ratio, volume fraction and size distributions of aggregates, volume fraction of entrapped voids, specific gravity of cement, and thickness of ITZ. Based on experimental data from the literature, the dependence of saturated, homogeneous cement paste is modeled as a function of water-cement ratio to yield the spatially varying elastic properties of the cement paste which is subsequently integrated into an effective elasticity model for concrete. Application of the model to data in the literature pertaining to elastic wave speeds in saturated mortars composed of 20-30 screened sand with an overall water-cement ratio of 0.3 yields a mean ITZ thickness of 48.3 microns which is consistent with optical measurement of the ITZ thickness.

Using an ITZ thickness of 50 microns, as measured from the mortar data, the model is used to predict the effect on the effective elastic properties from changes in, for example, overall water-cement ratio, fraction of aggregate, relative fraction and size distribution of fine and coarse aggregate, maximum size of coarse aggregate, volume of entrapped air. The model conserves the volume fraction of the ITZ and, most significantly, the overall water-cement ratio while modeling the non-homogeneous local water-cement ratios.

Issues related to applying the model to optimize the mix design of concrete will be presented as will future research efforts toward other effective properties of interest.

[1] Nadeau, J.C., "Water-cement Ratio Gradients in Mortars, and Corresponding Effective Elastic Properties," Cement and Concrete Research, in press.

A High-Pressure High Strain Rate Quasi-linear Viscoelastic Model for Concrete

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A series of quasi-static triaxial compression tests were conducted on concrete at confining pressures varying

from 0 to 500 MPa. The experiments were performed following a step-wise loading-creep-unload-reload procedure, which allowed accurate separation between elastic and time dependent effects on the material behavior. These tests were complemented with Split Hopkinson Pressure Bar test to estimate its strain rate sensitivity. A new 3-D quasi-linear viscoelasic model has been developed to predict the observed high-pressure, high-strain rate compression and shear response. At difference with the classical viscoelastic models, the proposed model can describe: (i) the combined effect of deviatoric (shear) stress components and mean pressure on the volumetric strain response (ii) the influence of mean stress on the deviatoric strain response. By a suitable choice of the mathematical expressions of the relaxation boundaries creep, stress relaxation, strain rate as well as the fundamental mechanical property exhibited by most porous materials i.e. to be compressible and/or dilatant could be reproduced. Comparison between the model predictions and data for dynamic and quasi-static conditions are presented. The results appear qualitatively very good throughout all the stress conditions and loading rates indicating the model should be applicable to a wide variety of engineering applications.

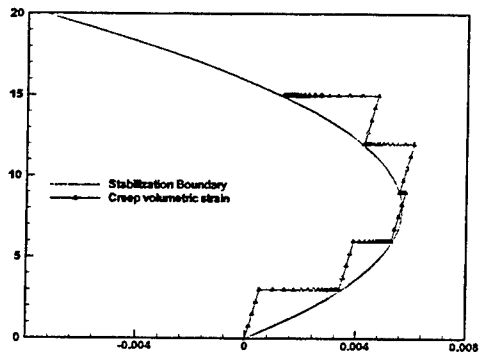


Figure 1: Stress vs. volumetric strain predicted by the model in a creep test with a stepwise increase in stress of 5 MPa, duration of each creep phase of $\Delta t = 30$ min.

Keywords: Strain rate sensitivity; compressibility/dilatancy; viscoelasticity; concrete.

Localization Effects in Slope Stability Analysis[1]

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A main difficulty with the use of finite element technique in stability analysis of soil slopes is the loss of well posedness of the boundary value problem due to the onset of bifurcation in the underlying elastoplastic constitutive model that generally follows a non-associative flow rule. In the past few years, several regularization techniques have been developed and applied to problems involving localization. Here we discuss the challenges associated with the application of one of the well known regularization techniques, i.e. the weak/strong discontinuity approach. It is shown that this techniques is useful in allowing the slope stability analysis to be carried out far enough, so that the effect of soil volume change on stability (1) can be examined. It is further confirmed that the volume change effects in some cases could be significant and therefore it is important to include these effects in the design of soil embankments and slopes[2].

[1] The support by the National Science Foundation through a Grant, CMS-9988557, with the George Washington University is gratefully acknowledged.

[2] M. T. Manzari and M. A. Nour, Significance of Soil Dilatancy in Slope Stability Analysis, J. Geotech. Geoenvironment. Engrg., ASCE, 126, (2000), 75-81.

COMPUTATIONAL GEOMECHANICS

SESSION F3O

Elastoplastic Constitutive Model with Vertex Effect and Anisotropic Hardening

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Experimental results of sand ([1], [2]) examining the dependency of the plastic strain increment direction to the rotation of the stress increment direction, so-called stress probe test, indicate that the direction of plastic strain increment is not given uniquely in deviatoric stress plane. In order to simulate the dependency of the plastic stretching direction on the stress rate direction, various constitutive models in plasticity theory with rate linear formulation have been proposed by considering vertex or vertex-like structure on yield/loading surface, i. e. consideration of the tangential stretching induced by a stress rate component tangential to the loading surface ([3], [4] etc.). As reviewed by Hashiguchi and Tsutsumi (2001), among them

however, only the subloading surface model with tangential stretching would be applicable to the materials with an arbitrary smooth loading surface obeying arbitrary mixed hardening/softening rule. In this study the model is extended to exhibit not only the vertex effect but also the induced (or inherent) anisotropy by introducing the rotational hardening variable. The applicability to the prediction of the deformation behavior of sand is evaluated by simulating the directional dependency of the plastic strain increment on the stress increment directions with constant mean stress and also the inelastic deformation during the rotation of the principal stress axes directions under constant mean and deviatoric stresses.

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[2] Gutierrez, M., Ishihara, K. and Towhata, I. (1991), Flow theory for sand during rotation of principal stress direction, Soils and Foundations, 31(4), 121-132

[3] Rudnicki, J.W. and Rice, J.R. (1975), Conditions for localization of deformation in pressure-sensitive dilatant materials, J. Mech. Phys. Solids, 23, 371-394

[4] Hashiguchi, K. and Tsutsumi, S. (2001), Elastoplastic constitutive equation with tangential stress rate effect, Int. J. Plasticity, 17(1), 117-145

Assessment of 3-d Predictive Capabilities of Bounding Surface Model for Cohesive Soils

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The mathematical modeling of cohesive soils was greatly enhanced by the advent of critical state soil mechanics. The critical state approach provided a rational means by which to link a soils' stress-strain response to its volume change characteristics within the framework of rate independent elastoplasticity. The sundry shortcomings of critical state models led to the development of more robust models for cohesive soils. One family of such models is based on the concept of a bounding surface.

Bounding surface models improve upon critical state models in two fundamental ways. First they allow for inelastic behavior to occur within the bounding surface at a pace dependent on the distance in stress space between the actual state point and a uniquely defined "image" point on the bounding surface. Thus, unlike the case of classical elastoplasticity, inelastic states are not restricted only to those lying on the surface. Compared to critical state models, this results in a more realistic stress-strain response, particularly for overconsolidated soils.

Secondly, unlike critical state models, which are formulated in triaxial stress space, bounding surface models are fully three-dimensional. Consequently, they can, in theory, be used to predict the response of soils subjected to general states of stress. The three-dimensional predictive capabilities of the bounding surface model for cohesive soils have not, however, been systematically investigated.

The proposed paper will present the results of a preliminary investigation of the three-dimensional predictive capabilities of the bounding surface model for cohesive soils. These results were generated using available true triaxial experimental results for clays. Based on the level of agreement between model predictions and experimental results, the predictive capabilities of this model are assessed and suitable modifications proposed.

DSC-Based Constitutive Modeling of High Performance Concrete

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Due to improved strength, low permeability, increased density, reduced drying shrinkage and lower creep, high performance concrete (HPC) has become an increasingly popular construction material during the last 25 years. In spite of significant increase in application, very little information is available on the load-deformation (constitutive) behavior of HPC, particularly under multi-axial loading. A combined laboratory testing and numerical modeling effort was undertaken in this study to examine the behavior of HPC under three-dimensional loading. A high capacity cubical device (HCCD), having a maximum pressure rating of 207 MPa (30 ksig), was used to evaluate the load-deformation behavior of HPC under three selected stress paths: Hydrostatic Compression (HC), Conventional Triaxial Compression (CTC), and Simple Shear (SS). An elasto-plastic constitutive model, namely Hierarchical Single Surface (HiSS) model developed by Desai and co-workers within the framework of the Disturbed

State Concept (DSC) was used to predict the stress-strain response of HPC for the same stress paths and the predicted response was compared with the experimental data. The DSC is a novel approach for modeling stress-strain behavior of engineering materials. In the development of DSC, two reference states are considered: initial continuum or relative intact (RI) state, and the fully adjusted (FA) state that results from the transformation of the RI state. These states are connected through a coupling function, called the disturbance function, D. As noted by Desai[1], as the deformation process continues, the FA state grows and the material part in the RI state decreases continuously in which the micro-structural changes can involve annihilation of particle bonds leading to a decay process. One of the advantages in this approach is that the formulation does not require particle or micro-level characterization because the responses of the parts in the references states (RI and FA) are defined on the basis of the macro-level responses measured ordinarily on laboratory specimens.

The aforementioned laboratory tests were used to determine the parameters for the HiSS-DSC model and these parameters were then used to back-predict the stress-strain behavior of HPC. A comparison between observed and predicted stress-strain response for a CTC test show that the predicted stress-strain response agrees well with the experimental values for low to average values of stresses (up to 50% to 70% of failure stress) in the compression regime. Somewhat higher differences (but less than 5%) are noticed with increasing stresses. However, in the tension regime much larger differences (as much as 15%) are evident, particularly at high stress levels. For simple shear (SS) stress path relatively larger differences (about 5% to 10%) are observed between the experimental and predicted values. Overall, the model exhibited a better performance for the stress path that was used in the determination of material parameters in comparison to the stress path that was not used in the parameter evaluation, as expected. From these results and additional results reported by Chin[2] one can conclude that the stress-strain response of HPC under three-dimensional loading can be adequately represented by the HiSS-DSC model.

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Analytical Solutions for the Three-Invariant Cam Clay Model: Drained Loading and Comparisons

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Analytical solutions are derived for the three-invariant Cam clay model subjected to drained loading based on the infinitesimal strain theory. Proportional and circular loading histories are addressed. Solutions for the specific volume, volumetric and generalized shear strains are presented in terms of the modified deviatoric and mean effective stress ratio. In the case of the proportional loading only straight effective stress paths are considered while in the case of the circular loading the maximum possible change in Lode's angle is $\delta/3$ due to the plastic isotropy. Additionally, deviatoric stiffness is defined and analytical expressions are derived for the hardening modulus.

A direct comparison between responses obtained in cases of drained and undrained loadings is presented on the example of Weald clay. In the case of the conventional triaxial compression comparison shows that the soil is stiffer in undrained loading in terms of deviatoric stiffness, while normalized hardening and shear moduli are higher for drained loading mostly due to the increasing mean effective stress. A drained circular loading is a special case of loading where the shear strain rate is composed entirely from the plastic shear strain rate, which is caused by the change in Lode's angle. A direct comparison with undrained circular loading for the same set of overconsolidation ratios (1.1, 1.3, 1.5, 1.7 and 1.9) shows that the soil is stiffer and more resistant to failure during drained circular loading. In summary, discovery of analytical solutions enabled qualitative and quantitative analyses, which resulted in improved understanding of the model.

Keywords: Constitutive behavior; Elastic-plastic material; Geological material; Analytical solutions

A New Integration Algorithm for Strain-Hardening Elastoplastic Soils

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Numerical modeling of elastoplastic response by soil is necessary to accurately model soil behavior which cannot

be explained by the laws of elasticity. However, problems are often encountered during the numerical integration of elastoplastic models. Elastoplastic models require that soil which is yielding lies on the yield surface. To account for elastoplastic response, most common integration algorithms use predictor-corrector methods in which elastic stresses are applied to soil, and the stresses are subsequently corrected until the stress point lies on the yield surface. A problem with integration is that there are many methods by which the trial stress point may be corrected back to the final yield surface. The final equilibrium stress calculated for a given loading condition can vary significantly, depending on the load step size and integration procedure.

A new solution algorithm is presented to converge on an accurate prediction of elastoplastic behavior for strain-hardening geomaterials. The algorithm uses the fact that for strain-hardening materials, the plastic strain parameter lambda is always bounded by a minimum value (equal to 0 for elastic response) and a maximum value (which corresponds to perfectly plastic response). The maximum value for lambda can be determined analytically for most geomaterials. The algorithm uses iteration to simultaneously converge to an equilibrium value of lambda and the correct position of the updated yield surface. Since the solution is bounded, no problems with divergence of solution occur. The method can be used for many elastoplastic models and strain-hardening responses on the constitutive level.

COMPUTATIONAL GEOMECHANICS

SESSION F4F

Mechanistic Model for Scale Effects in Rock Joint Behavior

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Rock joint shear behavior often exhibits scale effects. Experimental data has shown that, for certain rock joints, the peak shear resistance decreases with the joint scale. Experiments have also shown that the overall pre-peak shear stress-deformation behavior as well as the softening and the dilatation behavior have a significant dependence of joint scale. From a mechanistic viewpoint, these phenomena are related to the material mechanical properties, the interface roughness and the evolution of interface roughness as the joint is sheared. In this paper, we utilize a micromechanical approach that explicitly considers asperity interactions on joint surface to study these rock joint phenomena. Elastic deformations and inelastic frictional sliding are considered at inclined asperity contacts. Rock joint roughness is modeled via distributions of asperity heights and asperity contact orientations. Evolution laws for asperity heights and asperity contact orientations are introduced to account for the change in interface roughness resulting from asperity damage under shear. The micromechanical approach developed in this paper shows a clear link between the scale effects and the joint surface geometry as described by the distributions of asperity heights and asperity contact orientations and their evolution during shear. The micromechanical model is also shown to replicate the experimentally measured rock joint shear behavior culled from the literature.

Application of the Free Hexagon Method to Stability of Tunnel Face

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The free hexagon method belongs among a large scale of distinct element methods, and enables us to describe cracking (generally discontinuities of displacements in both normal and shear directions) in rock media. The plastic behavior is described inside each element and generalized Mohr-Coulomb hypothesis is applied along contacts between adjacent elements. The material behavior oinside the elements is solved by the BEM, and "tuned" with real situation in situ, or results from scale modeling in laboratories by eigenparameters. The eigenparameters may express either plastic strains, or relaxation stresses. The Eshelby trick is used to avoid convected terms following from the BEM by interchanging integration and differentiation.

One of the obvious advantages of the free hexagons is the fact that in comparison with another distinct element methods the elements can cover entire domain describing the rock. Consequently, the geomechanical parameters determined for continuum can easily be delivered from laboratory tests and moreover, the cracking is dependent of parameters like angle of internal friction and shear strength (cohesion for soil). The applications to practical problems is mostly connected with bumps or rock bursts in deep mines. Generally, the velocity of mining can be involved into the computation, and gas extrusion is also possible to consider. Most such phenomena are simulated by virtue of eigenparameters again.

The results of this paper has been financialy supported by GACR, project number 103/00/0530, and by project of Ministry of Education, MSM:210000001,3.

Navier-Stokes Simulations of Fluid Flow in a Rough-Walled Rock Fracture

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Most models of fluid flow in rock fractures assume that the local hydraulic transmissivity is equal to $h^3/12$, where h is the local fracture aperture. This so-called cubic law is equivalent to assuming that the flow is governed by the Reynolds lubrication equation. However, this assumption has been recently questioned, based on both experimental and computational considerations. Mourzenko *et al.* (*J. Phys. II*, 1995) and Brown *et al.* (*Geophys. Res. Letts.*, 1995) found, using computer-generated aperture fields, that the Reynolds equation predicted a flow rate at least two times greater than the more fundamental Navier-Stokes equation. Yeo *et al.* (*Int. J. Rock Mech.*, 1998) measured the aperture field of a fracture in a sandstone, solved the Reynolds equation through that aperture, and measured the transmissivity experimentally, and found that the Reynolds equation overpredicted the transmissivity by about 20-100%.

The implication has been that the Navier-Stokes equations will provide the correct model for flow in a real fracture, although this has never been verified. To test this, we have measured the surfaces of Yeo's fracture casts with a laser profilometer, to within an accuracy of better than ± 2 microns, every 10 microns in both the x and y directions. Flow through the fracture was simulated using both the Reynolds equation and the Navier-Stokes equations. The Navier-Stokes simulations yielded transmissivities about 10-50% lower than those predicted by the Reynolds equation, depending on the relative roughness. This range is similar to the range found by Yeo *et al.* and others for the discrepancies between the Reynolds predictions and experiments.

Keywords: rock fractures, Navier-Stokes, Reynolds equation, FEM

Non-linear Finite Element Analysis of Anisotropic Shear Walls

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This paper presents an analytical procedure based on the finite element method for the solution of the problem of the non-linear analysis of anisotropic shear walls. In particular, the fundamental principles of the mathematical theory of plasticity, based on a regular yield surface, that is, a surface defined by a single equation of the form f()=0, are established. In order to implement the method, a specific computer program for a 2D non-linear finite element elastoplastic analysis has been developed. The computer program is divided into four parts as follows; the first part consists of the routines for the control and data input modulus, the second part consists of the routines for the macro-solution and output modulus, the third part consists of the solution of the non-linear equation systems using the initial stress procedure, and the fourth part consists of the graphics routines. This code has been developed using the FORTRAN programming language and possesses the capability of automatic mesh generation. Using this program a thorough parametric investigation of the variables affecting the strength of anisotropic masonry shear walls has been carried out and a variety of numerical results in graphical form is presented, emphasizing on the yielding pattern.

Keywords: masonry, non-linear FE analysis, computer code, yielding pattern.

Symposium on

Recent Advances in Three Dimensional Flow Modeling

Organizer:
Professor E. E. Khalil
(Cairo University)

RECENT ADVANCES IN 3-D FLOW MODELING

SESSION M3E

The Art of Mathematical Modeling of Fluid Flow Regimes Interactions in Complex Geometries

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The recent advances in numerical methods and the vast development of computers had directed the designers to better development and modifications to airflow pattern and heat transfer in complex geometries such as combustion chambers, aluminum reductions cells and surgical theatres. The Present work fosters mathematical modeling techniques to primarily predict what happens in three-dimensional complex geometries and presents a summary of its status quo. Applications include, among others, combustion chambers,it also includes predictions of flow and heat transfer in Aluminum reduction pots full with the molten metal and electrolyte in the anodes- cathode void under magnetic field and forces. The flow in air-conditioned operating theatres is also addressed in this paper.

The governing equations of mass, momentum, species and energy, expressed in a general finite difference form, are solved with the aid of SIMPLE Algorithm. The results are obtained in this work with the aid of the three-dimensional program; applied to complex geometries. The numerical grid comprises, typically, $80 \times 60 \times 30$-grid mesh of total 144000-grid nodes; the residual in the governing equations were typically less than 0.001 %. The obtained results include velocities, turbulence , temperatures and wall heat fluxes. Flow regimes and heat transfer were found to be strongly dependent on turbulent shear, mixing, blockages, wall conditions and inlet conditions. Examples of large industrial furnaces, reduction cells and operating theatres are shown and are in good agreement with experiments found in the open literature.

One may conclude that flow patterns, turbulence and heat transfer in complex geometries are strongly affected by the inlet and boundary conditions; both micro and macro mixing levels are influential. The present modeling capabilities can adequately predict the local flow pattern and turbulence kinetic energy levels in Complex geometries.

Three-Dimensional Analysis of A Scramjet Combustor

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The improvement of the mixing process and the method of flame holding in scramjet engine combustors become very important due to the short fuel-residence time, and the limited length of the combustor. During the past years, researchers were concerned about improving the mixing process and how to increase its efficiency. Considerable fundamental research has been conducted in response to the increased interest in the development of scramjet propulsion systems.

The present study is a part of ongoing research to simulate the mixing and combustion processes in dual-mode scramjet combustors. A three-dimensional dual-mode scramjet combustor configuration is investigated numerically. The dual-mode engine consists of three parts, constant area isolator, constant area combustor with a rearward facing step, and a 1.7° divergent duct. A similar geometry (but not identical) has been previously investigated. The number, the diameters and the location of the fuel injectors are different in the present study than that in the previous studies. Hydrogen is used as the fuel and is injected through eighteen orifices placed on the combustor walls. Fuel is injected at sonic speed normal to a Mach 2.5 incoming vitiated airstream. The objective of the current study is to investigate the effect of the new arrangement of the fuel injectors on both mixing and combustion.

In the present study the numerical analysis was carried out using the CFD code FLUENT. The FLUENT is a finite volume code for solving the Reynolds-averaged Navier-Stokes equations. The code uses first/second order finite volume discretization method coupled with explicit/implicit solver. Numerical results are obtained for the three-dimensional model using unstructured grids with size of about 265,000 cells.

Results show an improvement in the combustion efficiency due the new arrangement of the fuel injectors. In addition, a significant upstream interaction in noted in the isolator duct.

Experimental and Numerical Investigations of Air Flow Regimes in Operating Theatres

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Recent advances in air conditioning technologies and applications had led to better performance, development and modifications to air flow pattern in air conditioned rooms design for ultimate comfort. Recent development of experimental measuring techniques for air temperature, relative humidity, velocities, and turbulence intensities in flow regimes had aided better understanding of flow phenomena, heat transfer and turbulence interactions. Extensive efforts are exerted to adequately predict the air velocity and turbulence intensity distributions in the room and to reduce the energy requirements and noise to ultimately produce quite and energy efficient air conditioning systems.

Pioneers in the medical applications enforced many restrictions to the comfort criteria requirements to form health criteria. These criteria were accumulated and compiled to healthcare standards such as ASHRAE standard for the residential and commercial applications and the National Health Service (NHS) standard for the healthcare applications.

The present work investigates the airflow patterns in a full-scale operating theatre under actual operating conditions; the present work also utilizes the 3DHVAC program by Khalil with the aim to forecast the air flow characteristics in the operating theatre. Comparisons between the measured and predicted flow pattern are shown and analyzed. The present work demonstrates factors affecting the flow in operating rooms, and the limitation of these factors. On the other hand, the present work demonstrates the capabilities of the numerical procedures to adequately represent the flow regimes, heat transfer and turbulence in complex flows.

Three Dimensional Numerical Study and Analysis of Cylindrical Assemblies Trees

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A computational fluid dynamics (CFD) code has been used to analyze Cylindrical Assemblies Trees of Pin Fins (CATPF). The geometry under investigation, and is similar to that of (Almogbel and Bejan) [2000].

In the present study the numerical analysis was carried out using the CFD code "Fluent". The Fluent is a finite volume code for solving the Reynolds - averaged Navier - stokes equations. The code uses first/second order finite volume discretization method with coupled explicit/implicit solver.

Unstructured grids has been used to discretize the three dimensional numerical domain. Prior to obtaining final results, different grids were used. After detailed numerical experimentation for grid independence, the one that yielded grid independence result and gave excellent agreement with the experimental data has been used.

The numerical results were compared extensively with data of Almogbel and Bejan [2000]. The results provide acceptable agreement in comparison with the analytical results.

Important results will be presented in the final paper. Key results of this study will be included in the final version of this paper.

Simulation of Free-surface Flow in Curved Channels with Velocity-Pressure-Free Surface Correction

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This paper presents a numerical study of free surface viscous flow in curve channels. A numerical model of velocity-pressure-free surface with coupled correction is developed and validated. The model solves the incompressible, full three-dimensional Reynolds-averaged Navier-Stokes equations with the standard $k-\varepsilon$ model. To reduce the numerical avoid resulted from the numerical oscillation due to the free-surface variations, the fluid pressure is decomposed into the hydrostatic component and the hydrodynamic component, and the power law (POW) scheme is used to discretize the convection terms in the equations with a finite-volume method. The SIMPLEC algorithm with velocity-pressure-free surface coupled correction is developed. The model is applied to simulate the flow through a 180° curved open channel. Comparisons between the computations and the experiments reveal that the model is capable of predicting the detailed

velocity field, including changes in secondary motion, the distribution of bed shear, and the variations of flow depth in both the transverse and the longitudinal directions. The numerical simulations provide satisfactory results in comparison with corresponding measurements.

Keywords: Free-surface flow, Curved-channel, Free-surface elevation, Free-surface slope, Velocity-Pressure-free surface correction

RECENT ADVANCES IN 3-D FLOW MODELING

SESSION M4E

Three-Dimensional Numerical Simulation of the Human Body Heat Loss in Surgical Operating Theatre

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A principle purpose of heating, ventilating, and air conditioning systems is to provide conditions for human thermal comfort. A widely accepted definition is, "Thermal Comfort is that condition of mind that expresses satisfaction with the thermal environment", ASHRAE 1992. In general, comfort occurs when body temperatures are held within narrow ranges, skin moisture is low, and the physiological effort of regulation is minimized, ASHRAE 2001.

The present work introduces different suggested formulae that can simulate the human body heat loss in the three-dimensional numerical studies. The present formulae are investigated in the present numerical simulation of a surgical operating theatre using 3DHVAC program, Khalil 1994, 1999, 2000, Kameel 2000,2002, and Kameel and Khalil, 2000, 2001, with the aim to forecast the human thermal exchanges with the environment.

The heat loss from human body was introduced here and depend on the formulae of Fagner 1967, 1970, Hardy 1949, Rapp and Gagge 1967, and Gagge and Hardy 1967 which gave quantitative information on how to calculate the heat exchange between people and environment. The present work also investigates the effect of different methods of human heat loss simulation on the airflow and heat transfer near the human body and on the overall airflow pattern.

Computations of Air Flow Regimes Regimes in Air-Conditioned Operating Theatres

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One of the main objectives of good air distribution in heating, ventilation, and air conditioning systems is to create proper combination of temperature, humidity, and air motion in the occupied zone of the air-conditioned room. The recent advances in air conditioning technologies and implementation had led to better performance, development and modifications to air flow pattern in air conditioned rooms design for ultimate comfort, Berglund 1998, Hosni et al. 1996, and Medhat 1993.

Recent development of experimental measuring techniques for air temperature, relative humidity, velocities, and turbulence intensities in flow regimes had aided better understanding of flow phenomena, heat transfer and turbulence interactions. Extensive efforts are exerted to adequately predict the air velocity and turbulence intensity distributions in the room and to reduce the energy requirements and noise to ultimately produce quite and energy efficient air conditioning systems. The present work investigates the airflow patterns in a full-scale operating theatre under actual operating conditions. Also the present work utilizes the 3DHVAC program, Khalil 1994, 1999, 2000, Kameel 2000,2002, and Kameel and Khalil, 2000, 2001, with the aim to forecast the air flow characteristics in the operating theatre. The turbulence model used in the present work is the classical two-equation model and is compared to the zero-equation model of Zhao et al 2001. Comparisons of the two models predictions and the experimental measurements are also show in terms of flow patterns.

The present work demonstrates the factors that affect the flow in operating rooms, and the limitation of these factors. On the other hand, the present work demonstrates the capabilities of the numerical procedures to adequately represent the flow regimes, heat transfer and turbulence in complex flows.

Effect of Pilot Energy on the Combustion of Hydrocarbon Fuels in Scramjet Engines

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A numerical study is presented to investigate the effect of the pilot gaseous flame on the stability and characteristics of the hydrocarbon fuels in the scramjet engines. Ethylene has been selected in this study as a gaseous hydrocarbon fuel that is likely to exist as intermediate fuel during the decomposition process of the liquid higher hydrocarbon fuels such as kerosene and the jet fuel.

The configuration used in the present study features a rearward-facing step located at the upper longitudinal wall. Sonic pilot ethylene is injected parallel to the incoming air stream via three holes that are equally distributed at the base of the step. The incoming air is a 1.756-Mach-vitiated air to simulate the enthalpy level of the typical flight conditions at the combustor inlet. A 15°-wedge is located downstream of the step and upstream of the main normal injection. The combination of the rearward-facing step and the wedge forms a cavity-like configuration that helps in enhancing the fuel-air mixing in addition to initiating and stabilizing the main flame. The transverse injection evolves the 3-D nature of such physical problems. Accordingly, the numerical study was conducted using the 3-D version of the code. Unstructured grid is used for accurately meshing the circular cross section of the injection holes. The existence of the wedge along the full width of the combustor adds another means for creating recirculation regions in the flow field to enhance the mixing. Pilot ethylene is injected with the different equivalence ratios ranging from 0 up to 0.1 to study the effect of the pilot energy on the main ethylene flame characteristics and stability limit.

The numerical analysis conducted uses the "Fluent" commercial code, which is a finite volume code solving the Reynolds-averaged Navier-Stokes equations. The quadratic upwind interpolation scheme (QUICK) is used to integrate and interpolate the governing partial differential equations.

The effect of the wedge is examined first by comparing its flow field and temperature qualities to that of the base line case that comprises alone the rearward-facing step without the wedge. The step configuration proved a successful tool to hold the flame in supersonic air streams. This can be attributed to the strong recirculations in the step base area that leads to a good fuel/air mixture after ignition generates hot medium. These hot gases envelope the upstream side of the fuel injection helping in igniting and holding its flame. The 15°-wedge imbedded in the second configuration downstream of the rearward-facing step forms a cavity that increases the temperature level in the upstream of the normal injection. The cavity configuration provided increased overall flow field static temperature along the combustor length over the generic step configuration. While using the second configuration, three-sonic pilot ethylene injections parallel to the incoming air stream are equally distributed at the base of the step in the third case study. The pilot injection enhances the flame holding mechanism for the normal fuel injection in the supersonic air streams by maintaining higher temperature surrounding the normal injection compared to the other two cases under investigation. The pilot injection does not affect the temperature levels in the flow field downstream of the normal fuel injection.

Keywords: Scramjets, Combustion, Hydrocarbons, Mixing

Modelling Self-Similarity in Turbulent Velocity Fluctuations

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The main problem of fully developed turbulence is the energy-cascading process. It has resisted all attempts at a full mathematical formulation. The main reasons are related to the hierarchy of scales involved and non-linear character in Navier-Stokes equations. Beside this, there is presented the spatial intermittency of the dynamically active regions. To account more complex cascading process suggested by the experimental data on inertial range structure, a multifractal model of a fine-scale intermittency has been introduced. These statistical models are insufficient, because they cannot give any information about the intermittent structures in real space. To overcome these limitations, the wavelet transform was used in order to analyse the velocity field, obtained from the experimental data. Wavelets are able to decompose arbitrary signals into localised contributions that can be labelled in terms of time and scale, thus overcoming the limitations of Fourier analysis. Wavelet transform provides a two-dimensional unfolding of one-dimensional signals, resolving both the position (in time or space) and the scale as independent variables. This time - scale analysis shows the evidence of the Richardson cascading process and its fractal character. The results also indicated the multifractal nature of this process.

A multifractal model of a fine-scale intermittency has been introduced to account for the more complex cascading process suggested by the experimental data on inertial range structure. Scaling interpretation is determined using the self-similar properties of fractal measures at different length scales. The period-doubling transition to chaos is presented by the wavelet transform of golden-mean trajectory, calculated using the sine circle map. Both processes exhibits a similar fractal character, which is evident in wavelet transform map. The results indicate that the energy cascading process has remarkable similarities to the deterministic construction rules of the golden-mean sine circle map.

Numerical Computations of Relative Humidity in Operating Theatres and Experimental Verifications

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Proper airflow distribution plays an important role in the surgical operating theatre. Airflow into the surgical operating theatre and removal of air through the exhaust vents remove airborne microorganisms to enhance effective infection control. That proper airflow aid to protect patients and health care worker (HCW) from infection. High ambient airborne particle concentrations may be generated if the airflow in the surgical operating theatre is turbulent rather than unidirectional laminar flow. Turbulence would cause stir up of previously settled particles on horizontal surfaces. Turbulence promoters in operating theatre include, among others, the improper positioning of supply diffusers and exhaust grills, opening of doors, blocking of exhaust grills by equipment, movement of medical staff, etc, Gurry 1997.

The recent advances in numerical methods and the vast development of computers had directed the designers to better development and design modifications to airflow pattern in air-conditioned rooms. Extensive efforts are exerted to adequately predict the air velocity and turbulence intensity distributions in the room, to reduce the energy requirements and enhance noise abatement to ultimately produce quite and energy efficient air conditioning systems.

For that purpose, the present work fosters mathematical modeling techniques to primarily predict the humidity characteristics in the air-conditioned surgical operating theatre. The present work also demonstrates the effect of surgical operating theatre design and operational parameters on model. That study is a part of a complete investigation about the factors affecting the air environments in surgical operating theatre. Measured and predicted humidity profiles are shown to be in good agreement.

Symposium on

Electrohydrodynamics

Organizer:
Professor Boris Khusid
(New Jersey Institute of Technology)

ELECTROHYDRODYNAMICS I

SESSION R3C

Assembly of Colloids in 2-D Electrohydrodynamic Flows Near Electrodes

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Cooperative motion and clustering of particles into dense films has been observed during electrophoretic deposition in *dc* and *ac* fields. This self-assembly occurs through pair-interactions between particles and between clusters that are loosely deposited on an electrode. Electrokinetic (electroosmotic) phenomena govern the 2-D dynamics of particles in *dc* fields in fluids with finite conductivity; the rates of inter-particle motion scale as the product zE where z is the zeta potential of the particles and E is the field. Experimental results compare very well with the theory for *dc* fields. In *ac* fields, however, the relative motion between two particles is independent of z, implying a polarization mechanism behind the particle motion. Experiments with particles in *ac* fields show that the relative motion of particles depends on the choice of electrolyte and on both the magnitude and frequency of the electric field. There are two striking differences between *dc* and *ac* fields in addition to the varying role of z. First, the fields required in *ac* at 100 Hz are about 100 times greater than needed in *dc* to achieve the same rate of attraction or separation between two particles; and second, while *dc* fields drive two particles into essential contact on the electrode, in *ac* fields the two particles attain a final steady-state gap between them at long times that

is about one-half the particle radius. A theory based on convection resulting from electrolyte polarization at the electrode can explain some of the experimental ac field results.

Shear-Flow Structure of Electrorheological Fluids

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When there is no shear force applied on an electrorheological (ER) fluid, upon application of an external field, the dielectric particles first form chains in the field direction, then the chains aggregate into thick columns. If the external field is strong enough, the columns have a body-centered tetragonal (bct) lattice structure. When there is a shear force applied on the ER fluid, the fluid structure is different. Our computer simulations have found the following fluid structures. If the shear force is weak or moderate, the fluid has a flowing-chain structure, consisting of tilted and broken chains. Under drive of the shear flow, these chains break into parts, drift, and rejoin while retaining the basic order of a chain. As the shear stress exceeds a critical value, the fluid develop into a flowing-hexagonal-lattice structure, consisting of several two-dimensional layers which are parallel to the flow direction and the field direction. Within one layer, particles form several strings in the flow direction. Each string is sliding over a string right beneath. Under this structure, the fluid has its effective viscosity substantially reduced. There are now several experiments support the above simulation results. The discovery of a transition from a flowing-chain structure to a flowing-hexagonal-layered structure in the dynamic case has established a physical ground for the shear-thinning effect which puzzled ER experiments for years. This discovery of flow structure transition has also brought important fundamental physics questions to particulate mechanics, especially the dynamic behavior of particulate materials under a shear force.

Keywords: ER fluid, Shear flow, Layer structure, Structure transition

Fluid Flows in Alternating and Rotating Electromagnetic Fields

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Ferrohydrodynamic flows where magnetization depends on both an applied magnetic field **H** and on flow profiles are examples of general structured-continuum fluids. As such they are characterized by the presence and effect of long-range body-couples and non-symmetric viscous stresses, as well as couple stresses representing the direct-contact transport of microstructure angular momentum. A scientifically and commercially important example of such fluids is ferrofluid, a suspension of permanently magnetized colloidal particles, where the magnetization **M** is often not collinear with the applied field **H**.

Recent analysis and measurements have shown anomalous behavior of ferrofluids in alternating and rotating magnetic fields whereby the effective fluid viscosity can be increased or decreased and the ferrofluid can be pumped but the flow direction can reverse as a function of magnetic field amplitude, frequency, and direction. Such behavior is illustrated by performing rheological experiments on a ferrofluid subjected to such time-varying magnetic fields. Experimental observations using a cylindrical-Couette viscometer will be presented, showing the first experimental evidence of zero and negative effective "magnetoviscosity."

The observed anomalous flow behavior in alternating and rotating magnetic fields is then shown to correspond to the effect of spin-magnetization coupling in the magnetization relaxation equation. This is done through analysis of plane-Poiseuille/Couette and cylindrical spin-up flows of ferrofluid subjected to a magnetic field which is uniform and rotating in the absence of ferrofluid. The analysis shows how the so-called magnetoviscosity is a parameter characterizing magneto-mechanical coupling in the flow rather than a material property of the polarized fluid. It is also shown how under certain conditions the overall flow may reverse direction, in agreement with experimental observations in spin-up flow of ferrofluids.

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Dielectrophoresis and Aggregation in Suspensions Subjected to High-gradient Electric Fields

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We consider the motion and aggregation of suspended polarizable particles under the action of spatially non-uniform ac electric fields when the dielectrophoretic force concentrates particles in certain areas of an electric chamber where they then undergo a field-driven phase transition. Experiments were conducted in a parallel-plate channel where a suspension of heavy, positively polarized spheres was exposed to an ac field under conditions such that the field lines were arranged in the channel cross-section perpendicular to the streamlines of the main flow. To prevent gravitational settling of the particles, the channel was slowly rotating around a horizontal axis. Following the application of a high-gradient strong ac field (several kV/mm), the particles were found to move towards both the high-voltage and grounded electrodes and form arrays of "bristles" along their edges. The model for the particle motions included the dielectrophoretic, viscous, and gravitational forces acting on a single particle, and required no fitting parameters because the particle polarizability was calculated independently by measuring the frequency and concentration dependence of the complex dielectric permittivity of a suspension in low-strength field. The predictions of this model were consistent with experimental data for the rate of the particle accumulation on the electrodes but not for the aggregation pattern appeared to be governed by the interparticle interactions, even in dilute suspensions. Experiments revealed a two-step mechanism for the pattern formation. Next we fabricated several electro-hydrodynamic microfluidics. We found that the particle behavior in micro- and macro-flows appears to be quite similar and can be predicted by our theoretical models.

[1]The work was supported in parts by grants from NASA, the Office of Naval Research, and the New Jersey Commission on Science & Technology MEMS Initiative.

[2]The suspension complex dielectric permittivity and the particle size distribution were measured in the NJIT W.M. Keck Foundation Laboratory for Electro-hydrodynamics of Suspensions.

Electrohydrodynamic enhanced Capillary Pumped Loop Bubbly Flow

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Thermal management systems in space technology applications are becoming more important with ever increasing power densities of electronic equipment. Capillary Pumped Loops (CPLs) are two-phase heat transfer devices that have been proposed for space missions. CPLs can transport heat over longer distances when compared with traditional heat pipes. However, the start-up of CPLs are problematic due to de-priming at the evaporator. Electrohydrodynamic (EHD) pumps, which are quite simple in design and do not encroach on the payload weight restrictions, can be used as primers. Power supplies, based on D.C. to pulse conversion, can operate EHD pumps on spaceflights. Placement of an EHD pump between the condenser and evaporator on a CPL is desirable for maximum pumping of the two-phase refrigerant. However condensing vapour bubbles exist in this section of the loop, and therefor it is advantageous to measure and model the bubbly flow in an EHD pump. In this work we analyze fluid flow, in particular the movement of gas bubbles in a liquid medium with the use of Travelling-Wave Dielectrophoresis. EHD pumping of liquids can be achieved through the use of an energized electrode array that produces dielectrophoretic forces on the working fluid. An accelerating/decelerating motion of the bubbles are noted when crossing each 3-phase set of electrodes [3]. To explain this phenomena we use negative dielectrophoresis - the fact that gas bubbles are attracted to electric field intensity minima [1] and the shape of the equipotential surfaces from the substitute charge method [2]. We propose that the bubble position resides at this surface gradient minima (i.e. the bubbles are trapped in a potential well) throughout the transport through the fluid. It can be shown that the acceleration/deceleration motion is controlled by these equi-potential surfaces as they change shape with time. EHD Pump; Dielectrophoresis; Bubbly Flow; Travelling Wave Electric Field

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Plane Parallel Isothermal Laminar Flow of Conducting Incompressible Fluid in MHD-Unpressured Device with Inclined Bottom and Its Stability in Transversal Homogeneous Magnetic Field

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The problem, which was noted in title, in particular case $K = 1$ (K parameter describes current regimes of MHD-device) has been considered in [1].

Statement of problem. The basic flow with free surface of liquid metal satisfies next conditions:

$$\mathbf{V}_0 = (u_0(x_3), 0, 0),\ h = h_0 = const,$$
$$\mathbf{B}_0 = (b_{01}(x_3), 0, B_{00} + b_{03}(x_3))$$

where h_0 is depth of liquid layer along normal to bottom, with incline angle θ about horison, $B_{00} = const$ is quantity of applied magnetic field ($\mathbf{B}_{00} = B_{00}\mathbf{k}$), $x_i (i = 1, 2, 3)$are cartisian coordinates and others notation are well known. The axises Ox_i $(i = 1, 3)$ correspondingly are directed along symmetry axis of bottom and perpendicular to him.

It does supposition, that MHD-device is largest and longest; $h_0/l \ll 1$, $h_0/L \ll 1$, so that it can neglected end-saiding effects. l and L are longitudinal and transversal sizes of MHD-device.

It should be noted that, MHD-device is MHD-channel for transportation of liquid metals or liquid-metallic special contact incline rigid plane wall, is invisaged in conceptual project in fusion reactors of series UWMAK for protection its first wall from high temperatures.

Perturbances of basic flow are: for full velocity - $\mathbf{v} = (u_1, 0, u_3)$, $(\mathbf{V} = \mathbf{V}_0 + \mathbf{v})$, for pressure - p_1, $(p = p_0 + p_1, p_0 = p_n + p_m)$, for stimulated magnetic field - $\mathbf{b} = (b_1, 0, b_3), (\mathbf{B} = \mathbf{B}_0 + \mathbf{b})$ and for free surface - $\zeta(t, x_1)$. It's supposed, that elevation of free surface is small ($\zeta/h_0 \ll 1$). Consequently, considering problem studies in linear approximation. According to Squire's theorem [2] one can consider plane motion of exited basic flow. Hence, all perturbances depend on two coordinates: x_1, x_3 and time t. The system of second order liearizing partial differential equations, describing basic and exited MHD-flows to corresponding boundary conditions: on free surface ($h = h_0 + \zeta(t, x_1)$) and to bottom ($x_3 = 0$) is solved exactly for premiary problem and by asymptotic expansion of solutions with respect to small parameter k (k is wave number), e.i. for long surface waves approximation.

Main result.

In the long-wave approximation, additional term in stability condition, which is contained dimensionless parameter $Be = B_{00}^2/\mu_0\rho g h_0 \cos\theta$ as multiplier (first time, it was introduced in this work) and is stipulated by parameter K, considerably increases stability diapason of plane parallel (shearing) isothermal laminar flow of incompressible conducting liquid layer for applied homogenous magnetic fields with intensity $B_{00} \geq (3 \div 6)10^{02}$T, even for magnetic Reynolds number with order $(4 \div 7.9)10^{-3}$, for all carrent regimes of MHD-unpressured device, except idling ($K = 1$).

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ELECTROHYDRODYNAMICS II

SESSION R4C

The Use of Magneto-Hydrodynamics to Pump, Control, and Stir Liquids in Micro Fluidic Systems[1]

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We study fluidic networks consisting of individually controlled branches. The network's basic building blocks are conduits equipped with two electrodes along two opposing walls. When a prescribed potential difference is applied across each electrode pair, it induces current in the liquid (assumed to be a weak electrolyte solution). The entire device is either subjected to an external uniform magnetic field or fabricated within a magnetic material. By judicious application of the potential differences at various network branches, one can direct liquid flow along any desired path without a need for mechanical pumps or valves. Ideas of linear network theory are extended to allow one to determine the flow rates in various branches as functions of the applied fields and to determine the control variables needed to achieve desired flow paths. Moreover, by equipping network branches with centrally located electrodes, the branches can double up as stirrers capable of inducing chaotic advection. The paper describes the basic building blocks for such a network, an example of a network fabricated with low temperature co-fired ceramic tapes, a general theory for the analysis and control of fluidic magneto-hydrodynamic networks, and theory and experiments pertaining to the chaotic stirrer.

[1] The work described in this paper was supported, in part, by DARPA (Dr. Anantha Krishnan Program Director) through a grant to the University of Pennsylvania.

Negative Viscosity in Magnetic Fluids: Mechanisms, Manifestations, and Connected Effects

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A magnetic fluid (MF) or ferrofluid is a colloidal dispersion of a ferromagnetic material in an ordinary liquid. A point of peculiar interest is an ability of suspended magnetic grains to rotate relative to a surrounding liquid matrix. This internal (hidden) rotation can be partially transformed into the hydrodynamic (i.e., visible) form, or, vice versa, it can be created at the expense of a hydrodynamic flow. The direction of this transformation depends on the sign of the rotational viscosity coefficient K. A stationary or slow varying applied magnetic field impedes free particle rotation, so they rotate slowly than surrounding liquid and then decelerate the flow. The additional resistance is manifested as an additional viscosity $K0$.

Conversely, at a high enough frequency of a linearly polarized magnetic field the grains rotate faster than the fluid and thereby spin up the flow. The acceleration happens, naturally, at the expense of alternating field energy and manifests itself in the Negative Viscosity effect (NVE): $K < 0$ The theory predicts a tight connection between NVE and the Vortico-Magnetic resonance (VMR) of the off-axis (i.e., transversal to the field direction) component of MF magnetization. Both these phenomena are spectacular manifestations of a curious mechanism of the energy conversion in MFs. Indeed, depending on the ratio of the field frequency f to the fluid vorticity F the magnetic grains behave either as nanomotors or as nanogenerators changing their working regime at the crossover point $f = F$. It has been observed experimentally that near this point K changes its sign and the transversal magnetic susceptibility has a sharp-edge resonance. Thus a direct and vivid evidence of the Negative Viscosity effect through its relation with the Vortico-Magnetic resonance in MF has been obtained.

Ferrofluid Flow and Torque Measurements in Rotating Magnetic Fields

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Previous analyses have shown anomalous behavior of ferrofluids in rotating magnetic fields, including flow reversals and negative magnetoviscosities as a function of magnetic field amplitude and frequency. Three sets of experiments will be presented that quantitatively describe ferrofluid flow and torque measurements in uniform and nonuniform rotating magnetic fields. The first experiments measure the ferrofluid viscous torque and effective magnetoviscosities on a stationary or constant rotation electrically insulating viscometer spindle. The magnetic field amplitude is varied over the range of 0-130 Gauss rms and frequency is varied over the range of 1 Hz-5 kHz, for clockwise and counterclockwise rotating magnetic fields. We believe that these measurements are the first to report viscometer viscosity readings that are zero or negative. The second set of experiments describes the ferrofluid surface flow and spin velocity profiles. A small floating plastic ball that can spin freely on its axis is placed on the ferrofluid surface at a fixed position. In the presence of a rotating magnetic field, the ferrofluid surface will rotate, causing the floating ball to spin. If the ball is not constrained to a fixed position, it will also move around on the ferrofluid surface. By videotaping the translating and spinning ball at various radii and analyzing its angular and spin positions frame-by-frame, we have obtained values for the ball spin rate and linear velocity as a function of radius and magnetic field amplitude and frequency. In order to separate the effects of surface and bulk flows induced by the rotating magnetic field the third set of experiments describes the volume flow profile by using a rotating electrically insulating cylinder that is immersed at a controlled depth in ferrofluid. Using videotape analysis we have measured cylinder spin rates as a function of immersion depth, radius, and magnetic field amplitude and frequency.

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[2]Prof. June-Ho Lee contributed to this work as an MIT Visiting Scientist.

Alternating and Traveling-Wave Magnetic-Field Induced Flow of Ferrofluid

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Flow of a ferrofluid through a closed tubing system exposed to an external magnetic field has a pressure drop that depends on the magnetic field amplitude, direction, and frequency. Measurements are presented for oscillating and traveling-wave fields versus flow rate for various amplitudes, frequencies, and directions of the applied magnetic field. The results indicate a controllable magnetoviscosity with possible application to micro and nanoscale flow systems.

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Spin-Magnetization Coupling in Spin-Up Flow of Ferrofluids

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Spin-up flow of ferrofluids, where flow is induced in a cylindrical container by the action of an externally applied rotating magnetic field, has received considerable attention during the development of the field of ferrohydrodynamics. The observed flow is generally rigid-body and may be shown to co- and counter-rotate with the applied field depending on magnetic field magnitude and frequency, as well as other physical parameters such as free-surface curvature.

The original analysis [1], based on the general structured-continuum theory for polarized continua, possesses the observed rigid-body character but fails to correctly predict the observed flow direction or magnitude. The problem is compounded when one considers surface-excess magnetic forces on the curved ferrofluid-air interface. Observations of curvature-dependent flow direction [2] imply that these surface-excess magnetic forces could be responsible for the observed free-surface flow.

We extend the original analysis [1] by considering flow of ferrofluid in the gap of an idealized two-pole magnetic stator that imposes a uniform rotating magnetic field in the absence of ferrofluid. A regular perturbation scheme in the small parameter $\epsilon = \omega\tau$, with τ the magnetic relaxation time and ω the characteristic spin rate is applied to solve the coupled ferrohydrodynamic problem for the zeroth- and first-order magnetic and fluid mechanical fields. This approach ensures that the spin-magnetization coupling term in the magnetization equation, neglected in the original analysis, is considered. The zeroth-order solution is shown to correspond to the classical spin-diffusion result whereas the first-order contribution is shown to exhibit the same basic features, but with flow in the direction opposite to magnetic field rotation. The analysis predicts flow reversal under certain conditions of magnetic field amplitude and frequency, in agreement with experimental observations.

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This work has been sponsored by a National Science Foundation Graduate Research Fellowship to CR and US National Science Foundation Grant #CTS-0084070.

Simulating Buoyancy-Induced Thermo-Magneto-Viscoelastic Flow in a Darcy-Brinkman Porous Medium using the "Caltech-Keller" Implicit Scheme

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A two-dimensional computational fluid mechanics analysis of steady state thermal boundary layer flow of a viscoelastic (second order) fluid past a horizontal wedge

in a Darcy-Brinkman porous regime, in the presence of a hydromagnetic field, is presented. The governing equations are transformed from Cartesian co-ordinates (x,y) into a sixth order system of partial differential equations in a $\xi - \eta$ co-ordinate system. These complex equations are then reduced to a set of first order equations which are solved using the robust Keller implicit finite difference method, and a block tridiagonal iterative solver, **VISDAPTHERM-SOLV6**. It is shown that heat transfer magnitude is depressed by magnetic field parameter (Hartmann number, Ha) and also considerably reduced with increasing viscoelasticity parameter (K). Surface shear stresses are also seen to fall considerably with increase in viscoelasticity of the fluid. Effects of other hydrodynamic and thermal parameters on the flow are discussed in detail.

ELECTROHYDRODYNAMICS III

SESSION F3C

Micro PIV Mesurement of the Electrothermal Effect

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Micron-resolution Particle Image Velocimetry (micro-PIV) is used to measure the motion of nominally one-micron diameter polystyrene particles suspended in an 8.5% sucrose and 0.3% dextrose sugar/water solution in a wedge-shaped microdevice. Particle motion is induced by a non-uniform electric field through dielectrophoretic (DEP) forces and through viscous interactions with the fluid. The motion of the fluid is governed by electrothermal forces arising from temperature-induced gradients in the electrical properties of the fluid near the electrodes and through the viscous interaction with the particles. Non-uniform Joule heating, resulting from the non-uniform electric field, creates the temperature gradients in the fluid.

The wedge-shaped device consists of two brass electrodes sandwiched between two glass wafers, spaced approximately 100 microns apart. A voltage of 10V RMS at 10 kHz was applied to the electrodes. The Clausius-Mossotti factor is $K = -0.5$ for the current conditions, producing a negative DEP force. The velocity field is characterized by a saddle point at the center of the wedge, with four recirculating vortices. Comparisons between finite element calculations and experimental micro-PIV results confirm qualitatively that electrothermal forces play a major role in the motion of the particles.

Manipulation of Particles in Microfluidic Channels by Means of Travelling - Wave Dielectrophoresis - Design and Analysis

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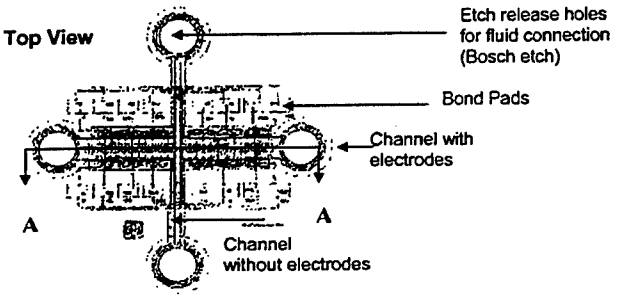
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Multilayer microfluidic channels have been developed for manipulation of cells and particles using travelling wave and conventional dielectrophoresis. Dielectrophoresis is a powerful tool for the diagnosis and separation of particles, cells, and microorganisms.[1] A specific kind of dielectrophoresis known as travelling wave dielectrophoresis (twDEP) involves the movement of particles upon the application of a travelling electric field. The horizontal velocity of the particles due to the twDEP force depends largely upon the effective polarizability and size of the particles. Hence, a mixture of different particles can be fractionated into "bands" along a microfluidics channel.

A module of seven dielectrophoretic microfluidic channels including a dielectrophoretic separation channel integrated with a cell splitting device is being manufactured using Sandia's multilayer Summit V process (www.mdl.sandia.gov/Micromachine). The electrode spacing along the dielectrophoretic separation channel was varied from 5, 10, to 15 microns. A typical dielectrophoretic channel is shown (Figure 1). The electrodes along the channel enable the separation of particles using twDEP or DEP and flow control in the cross channel allows particles of interest to be separated into a different flow stream. The spacing is the smallest manufactured thus far and should allow for high resolution separation of particles.



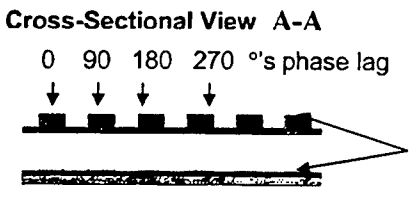


Figure 1. Mask layout of a micromachined cell manipulation device - and cross section of channel with electrodes for travelling wave dielectrophoresis.

The CFDRC (Computational Fluid Dynamics Research Corporation www.cfdrc.com) commercial computational fluid dynamics code is used to calculate the travelling wave force as well as the particle motion based on the permittivities the particles and suspending medium, applied voltage, and frequency. Particle motion as a result of travelling wave dielectrophoresis is observed for various dielectrophoretic microfluidic channel designs using suspensions of particles such as latex beads, blood cells, and yeast cells.

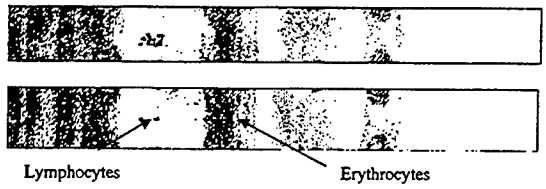


Figure 2. Figure 2. Electric potential in microfluidics channel. Upper channel shows erythrocytes and lymphocytes mixed together. Lower channel shows separation of cells into bands as a result of twDEP. Erythrocytes move down channel and lymphocytes stay stationary upon the application of the travelling wave at 20 V and 250 Mhz

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contact DE-AC04-94AL95000.

Keywords: dielectrophoresis, travelling wave, cellular manipulation, surface micromachining

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[2] The work is supported by Sandia National Laboratories, and the NewJersey Institute of Tech. NSF AGEP-MAGNET #992118

Studies of the Particle Motions in a Suspension Subject to High-gradient ac Electric Field

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We study the motion of the particles in a dilute (0.1suspension subjected to a high-gradient ac electric field. The work involved experiments on suspensions with a large density difference between the particles and the suspending fluid. To overcome the gravitational sedimentation of the particles, we developed a setup in which a suspension flowed through an electric chamber rotating around a horizontal axis along with a special technique to energize the electrodes. The electrodes in the chamber were configured in such a way that the electric field lines were arranged in the channel cross-section perpendicular to the streamlines of the main flow.

On the images acquired through the channel top, the particles appeared as shiny dots due to light being scattered by them. The relative changes of the gray level on the consecutive black & white images taken at equal time steps were used to estimate the kinetics of the field-induced particle motions and their segregation. The theoretical model for the particle motions included the dielectrophoretic, viscous, and gravitational forces acting on a single particle. The theoretical predictions were found to be in reasonable agreement with the experimental data.

[1]The work was supported in parts by grants from NASA, the Office of Naval Research, and the New Jersey Commission on Science & Technology MEMS Initiative.

[2]The suspension complex dielectric permittivity and the particle size distribution were measured in the NJIT W.M. Keck Foundation Laboratory for Electro-hydrodynamics of Suspensions.

Numerical Simulation of the Dielectrophoretic Forcing of Particle-Laden Flows

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Electrostatic forcing of fluid flow in microfluidic devices is currently of great interest. At the small scale of microfluidic devices electrical forcing can be used with great effectiveness to drive bulk flows and to both separate out and mix components of these flows. Numerical simulations have been carried out to investigate the physics and to test mathematical models of the aggregation of particles induced by dielectrophoresis. This work is being done in conjunction with experiments performed at the City University of New York.

Both two- and three-dimensional numerical simulations have been carried out. Both pure dielectrophoresis and dielectrophoresis with some conduction (leaky dielectrics) have been investigated. Our mathematical model of electro-hydrodynamic phenomena consists of strongly coupled field and flow equations supplemented by constitutive equations for the dielectric polarization and for the electric-field induced contribution to the energy and stresses in the suspension. The suspension is treated as an effective Newtonian fluid with a concentration dependent viscosity. For the electric energy and stress we employ a microscopic theory that is applicable to both dilute and concentrated suspensions with electric energy dissipation.

Our three dimensional calculations are of channels with periodically placed electrodes. On the microscopic scale, we will be presenting data on phase separations within the fluid suspension, and on the formation and structure of fronts between phases. On the macroscopic scale, results will be presented on collection rates and aggregation patterns of the particles about the electrodes, on any induced secondary flows, on perturbations caused by small amounts of electrical conduction, and on the effects of particle aggregation on the electrical field.

Direct Simulation of Electrorheological Suspensions

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A finite element code based on the distributed multiplier method (DLM) is used to study the transient motion of particles in electrorheological (ER) suspensions subjected to spatially uniform and non-uniform electrical fields. The electrostatic force acting on the polarized, but non-charged, spherical particles is modeled using the point-dipole approximation. The code is used to study the time evolution of particle-scale structures of ER suspensions in channels subjected to simple shear and pressure driven flows. When the imposed electric field is spatially uniform and the hydrodynamic force is small compared to the electrostatic force, the particles form chains that are aligned approximately parallel to the electric field direction. However, when the magnitude of the hydrodynamic force is comparable to that of the electrostatic force the particle chains orient at an angle with the direction of the electric field. In a spatially non-uniform electric field the particles move to the regions where the magnitude of electric field is maximum or minimum.

Keywords: distributed multiplier method, electrorheological suspensions, finite element

Couple-Stress in Peristaltic Transport of a Magneto-Fluid through a Porous Medium

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Peristaltic pumping by a sinusoidal travelling wave in the walls of a two-dimensional channel filled with a viscous incompressible couple-stress of a magneto-fluid through a porous medium, is investigated theoretically. A perturbation solution is obtained, which satisfies the momentum equation for the case in which the amplitude ratio (wave amplitude: channel half width) is small. The results show that the mean axial velocity decreases with increasing the couple-stress parameter η and the magnetic

parameter M, and increases with increasing the permeability parameter k. A reversal of velocity in the neighborhood of the centre line occurs when the pressure gradient is greater than that of the critical reflux condition. Numerical results are reported for various values of the physical parameters of interest.The lymph is an example of a couple-stress fluid. Its clear, watery appearing fluid found in the lymphatic vessels(start as closed endothelial tubes that are permeable to fluid and high-molecular-weight compounds), closely resembles blood plasma in composition but has a lower percentage of protein, isotonic. The lymph elevated protein level in thoracic duct lymph due to protein-rich lymph from the liver and small intestine. The lymphatic fluid (the lymph) is pumped out of the tissues by the Peristaltic contraction of the large lymph vessels. The rate of lymph flow varies in different organs and depends on tissue activity and capillary permeability. Normal lymph flow is about 2L/day for the entire body, and this volume contains approximately 200 g of protein. Some tumors may be thought of as porous masses of cells interpenetrated by blood vessels. The walls of these vessels are permeable to plasma and some solutes. Hence fluid from the vessels continually leaks into the tumor. One method of chemotherapy involves the injection into the blood of specific chemicals that travel throughout the vascular system, including the vasculature of the tumor. When these chemicals leak into the tissue region of the tumor, they act on the proliferating cells and kill them. MRI has a magnetic field of over 10,000 gauss. The Magnetic Resonance Imaging MRI focuses on the nuclei of atoms of a single element in a tissue and determines their response to an external force such as magnetism. The part of the body to be studied, ranging from a finger to the entire body, is placed in the scanner(magnet), exposing the nuclei to a uniform magnetic field. MRI is used for diagnosis of brain, vascular diseases and all the body, it uses.

Keywords: couple-stress. magneto-fluid. porous medium.

AMS Subject Classification Codes: 76Z05. 76S05

ELECTROHYDRODYNAMICS IV

SESSION F4C

An Electroosmotic Chaotic Stirrer[1]

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Complex electroosmotic flows in closed cavities and in open conduits are investigated theoretically. Non-uniform, time-modulated zeta potentials exist along the solid surfaces that are parallel to the externally imposed, time-independent, uniform electric field. The use of slip boundary conditions in the presence of pressure gradients is justified rigorously through the use of boundary layer theory and matched asymptotic expansions. Steady complex flow fields are computed for various spatial, time-independent distributions of the zeta potentials along the cavities' walls by using the methods of superposition and series acceleration [1]. It is demonstrated that, by periodic time-modulation of the zeta potential, one can induce chaotic advection in the confined liquid. The temporal modulation of the zeta potential can be achieved, among other ways, by embedding electrodes beneath the liquid-solid interface and modulating the electric field normal to that interface [2]. The proposed stirrer is particularly useful for microfluidic systems in which the flows are highly laminar and it is difficult to incorporate mechanical stirrers.

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[1] The work described in this paper was supported, in part, by DARPA (Dr. Anantha Krishnan Program Director) through a grant to the University of Pennsylvania.

Particle Migration Velocity in an Electrostatic Precipitator

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Dust and aerosol particle collection in an electrostatic precipitator (ESP) is essentially a process of mass transfer which depends on a large number of fluid mechanic and electrodynamic parameters. The particulate mass transfer and particle migration velocity stipulated by it in a high-strength electrical field defines the collection efficiency of the ESP. The most important forms of particulate mass transfer are:

- electrostatic convection under the action of Coulomb forces and electric wind;
- turbulent diffusion of aerodynamic and electrodynamic origin;
- inertial drift.

The calculated migration velocity, using the fundamental motion equations of particles in an electrohydrodynamic field, differs very much from the effective migration velocity obtained experimentally.

The new concept discussed in the paper is based on the theory of dimensional analysis and a large number of ESP tests. This allows us to obtain a universal relationship between migration velocity and an ESP similarity number.

Keywords: Electrostatic precipitation, Migration velocity, Collection efficiency

Magnetohydrodynamic Bearings under Oscillating Electric Fields

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The slider and the journal bearing using an electrically conducting fluid as lubricant are considered. Applying electric and magnetic fields, pressure can be produced even if the bearing is fixed and the shaft doesn't rotate. Two cases are discussed:

a) A constant and uniform external magnetic field is applied in radial direction and a harmonic electric field is oriented in axial direction. The slider, the bearing and the journal are assumed to be perfect insulators.

b) A constant and uniform external magnetic field is applied in axial direction and a harmonic electric field is oriented in radial direction. The slider, the bearing and the journal are assumed to be ideal conductors.

To calculate the pressure field, the MHD basic equations are simplified using the ordinary assumptions of lubrication theory. The flow is assumed to be isothermal. Moreover, the short bearing approximation is applied. To reduce the Maxwell's equations, induction effects are neglected, i. e., the magnetic Reynold's number is assumed to be zero. The oscillations of the slider and the shaft are determined by a system of non-linaer ordinary differential equations with time dependent coefficients which is solved numerically. The simulations show stationary oscillations in form of a limit cycle for a large parameter range. Only stable attractors have been observed.

Keywords: magnetoghydrodynamics, lubrication flow, oscillating electric field, non-linear vibrations

Control of Vortex Shedding from Cylinder by Electromagnetic Field

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The goal of this work is to suppress vortex shedding from cylinder by means of a Lorentz force generated by electrodes and magnets placed on the cylinder surface alternatively. Unlike previous control schemes that were based on a crude planar structure model for the expression of the Lorentz force, our new model is based on the electro-magnetic potential function and cylindrical structure for the weakly conductiong fluid in two dimensional flow. Asymptotic method is used to simplify the result. The new formulation eliminates the discontinuity of Lorentz force in azithumal direction and leads to a continuous force distribution around the cylinder surface. Optimal control theory is used to derive an active feedback control algorithm aiming at determining the optimal force at each time.

The support of the New Jersey Commission of Science and Technology through the New Jersey Center for Micro-Flow Control is acknowledged.

Peristaltic Transport in a Tapered Channel of a Magneto-Fluid through a Porous Medium

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2000 Mathematics subject classification: Primary 76Z05, 76S05. The axisymmetric peristaltic flow of a viscous incompressible Newtonian fluid in a tapered channel through a porous medium under the effect of a constant magnetic field, $\underline{B} = (0, B_0, 0)$ has been investigated when the wave propagating along the wall of the channel is sinusoidal and the initial flow is Poiseuille flow. A perturbation technique has been employed to analyze the problem where an attempt has been made to account for the nonlinear convective acceleration terms. Two particular cases have been studied in detail. The first is the case when the Reynolds number Re is small. The second is

the case when the wave number α is small. The analysis is based upon second order approximations. Numerical results are reported for various values of the physical parameters of interest.

Keywords: Peristaltic Transport, Magneto-Fluid, Tapered Channel-Porous Medium

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INSTABILITY IN SOLIDS AND STRUCTURES I

SESSION M3N

Macroscopic Shear Response of Porous Materials

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Shear testing of porous core sandwich panels have shown strong dependence on the core thickness, wherein the shear strength and modulus increased when the gauge height was less than approximately two-cells. To understand this macroscopic response, the porous material response is modeled through a non-local constitutive relation, which incorporates micropolar theory for an order lattice structure to account for cell level rotation, stretch and bending. The constitutive framework is built into ABAQUS finite element as a user material subroutine to study various loading configuration. From the numerical results, the effect of the boundary on the macroscopic shearing stiffness of the sandwich structure approximately limited to gage length of less than 8-10 cells. While the trend is the same however, the difference in the gage length amplitude is attributed to the heterogeneities of the experimentally tested structure.

A Study of the Evolution of the Biaxial Deformation Patterns on Circular Honeycomb Based on an Energy Approach

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The appearance of a stress plateau in the compressive stress-strain curve of honeycomb foams is associated with the formation of heterogeneous deformation patterns resulting from a sequence of cell collapsing processes. Different deformation patterns have been observed according to the biaxial loading ratio and the relative orientation of the honeycomb with respect to the principal direction of the load. For example, under uniaxial loading the collapse process commences with the formation of narrow bands, which later thicken and coalesce, while under equi-biaxial conditions, a flower-like pattern is observed[1,2]. To investigate the formation and the development of these flower-like pattern an energy-based approach is resorted, where energy minimizers are sought for different stages in the loading process. In order to have an analytically traceable model, we restrict the kinematics of the cell deformation in such a way that each cell is constrained to deform homogeneously. Also we limit the material response to linear elasticity. These assumptions render a stiffer system but the model captures the characteristic features. The results indicate that there is a transition in the local deformation pattern as the external loading is increased. For stretching ratios larger than -0.7 a homogenous pattern of nearly circular cells minimizes the energy. For smaller ratios, however, a heterogeneous pattern formed by one circular and 3 ellipsoidal cells (flower-like pattern) provides lower deformation energy. These predictions are in agreement with experimental and computational studies.[1,2]

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2 S.D. Papka and S. Kyriakids *Int. J Solid. Struct.* **36** (1999) 4397-4423.

Dynamic Properties of Aluminium Foam: Measurements and Modelling

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Metallic foams are potentially of great use for many packaging and impact/blast mitigation systems. However measuring and describing the properties of these foams at increasing loading rates poses significant experimental and theoretical problems.

The dynamic crushing behaviour of metallic foams has proved difficult to quantify, with experimental investigations on the effects of loading rate producing apparently contradictory results. In order to clarify the effect of strain rate and impact velocity, the authors have conducted an extensive experimental study using a direct impact technique. Closed-cell aluminium foam specimens were fired directly at a Hopkinson pressure bar load cell at impact velocities up to 200ms-1, corresponding to a nominal strain rate of 4500s-1. The inertial effects associated with the dynamic localisation of crushing and the microinertia of the cell wall/edge material on the dynamic strength enhancement will be discussed.

A one-dimensional shock model based on a rate-independent, rigid-perfectly-plastic-locking (r-p-p-l) idealisation of the nominal stress strain curve for foams provides a first order understanding of the various parameters involved on the crushing process. This shock model predicts well the dynamic strength enhancement that is measured experimentally. However the cellular nature of the material is not accounted for in the analysis. Consequently there are discrepancies in the predictions, particularly at lower impact velocities. The limitations and shortcomings of the shock model are compared to those for discrete models.

The financial support of EPSRC (grant GR/R26542) and the supply of foam specimens by Hydro Aluminium, a.s. through NTNU (Trondheim, Norway) is gratefully acknowledged.

On the Axisymmetric Progressive Crushing of Circular Tubes Under Axial Compression

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Moderately thick circular tubes under compression crush progressively by axisymmetric folding. The paper presents a combined experimental analytical study of the onset of collapse, its localization and on the subsequent progressive folding. Results from four displacement controlled crushing experiments are presented on tubes of various radius-to-thickness ratios made of different metal alloys. The experimental results include the crushing response, careful measurements of the geometric characteristics of the folds and the mechanical properties of the alloys. A finite element model of the crushing process has been developed and results from simulations are directly compared with the experiments. The model is found to reproduce the crushing response to a significant degree of accuracy. The mean crushing load is essentially the same as in the experiments; the calculated wavelength of the folds are within a few percent from measured values as are other geometric variables considered. Thus, the crushing energy per unit length of tube is predicted to a very good accuracy. In addition, the model was used to demonstrate that changes in the loading cycles which take place as the number of folds increases, are due to small differences between the inner and outer folds which in turn affect the self contact of the fold walls. Three simpler models taken from the literature in which steady-state folding is modeled by kinematically admissible collapse mechanisms are critically reviewed by comparing predictions of key variables to measured values.

The Influence of Material Response on the Stability Behaviour of Finitely Deformed Solids

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The material stability of incrementally linear solids is usually assumed as the positiveness of the instantaneous tangent moduli tensor associated with a conjugate stress rate-strain rate pair. This restriction represents the infinitesimal stability condition of a homogeneusly deformed and uniformly stressed material element subject to surface traction representing the uniform element

stress state. Obviously, characterisation of material response requires the choice of a suitable strain measure and, therefore, the material stability condition depends on this choice. As an example, the logarithmic, the Biot and the Green-Lagrange strain measures have been proposed. In particular, the first strain measure has been proposed by Hill [1]. On the other hand, the Biot strain measure seems to avoid geometrical effects and thus corresponds to an appropriate representation of the material response [2-3].

In the present paper, the influence of the choice of the constitutive equation on stability and bifurcation behaviour of solids is investigated by adopting several conditions of stable material response. After some general results obtained for material characterised by a non-linear homogeneous incremental constitutive relation, the classical plane tension test of Hill and Hutchinson [4] is examined for an incrementally linear material. Boundary conditions leading both to homogeneous and diffuse modes are considered. The influence of material response is more evident for boundary conditions leading to homogeneous modes. The results show that, when diffuse modes are possible, different regimes for the governing equations can be available depending on the choice of material response characterisation.

Keywords: material stability, finite strain, structural stability, bifurcation

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In-Plane and Lateral Buckling, Postbuckling, and Imperfection Sensitivity of Arches

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In recent years, large wood arches have been used to cover sports facilities as well as other halls. In this connection, buckling, including postbuckling behavior and imperfection sensitivity of arches, has received some, but probably not sufficient attention.

In the town of Aalborg in Denmark a large congress and sports facility called *Gigantium* has been built, where the wood arches span more than 80 m, are a little over 20 m high, and have cross-sections of $1.5\,\mathrm{m} \times 0.215\,\mathrm{m}$ at the supports and $1.0\,\mathrm{m} \times 0.215\,\mathrm{m}$ at the crown. Clearly, such a slender structure is susceptible to experience buckling, which is only taken into account in a rather crude way in most current building codes.

The present study is aimed at establishing a method to assess the nonlinear behavior of such structures. The first issue to consider is the choice of beam theory, and it was found that several of the more commonly used theories provide unreliable results. The reason is inconsistencies in the order of terms that are kept in the various strain measures. Another important point is whether it is acceptable to assume that the arch in question experiences plasticity or remains linear elastic throughout a realistic load history. At least for the *Gigantium* arch it is found that plasticity does not play a significant role because the arch is very slender. Based on a satisfactory beam theory a kinematically nonlinear finite element program as well as a finite element program based on *Koiter's* asymptotic expansion for postbuckling and imperfection sensitivity analysis of linearly elastic structures was written. Both programs consider in-plane and lateral buckling of arches and were utilized to study the stability characteristics of, among other structures, the *Gigantium*.

Full nonlinear analyses were used to test the validity of results obtained by application of the asymptotic expansion. It turned out that the two sets of results lie so close that the computationally inexpensive asymptotic method could be applied with confidence *for the cases studied.*

On the other hand, for other arches with parameters that differ substantially from the current ones, the asymptotic method may provide inaccurate predictions of the load-carrying capacity. Therefore, the recommendation must be that a full nonlinear analysis is carried out to check the asymptotic method, which may the be used to study variations of the load-carrying capacity with (smaller) changes of the arch geometry.

Effects of Imperfections on the Buckling Response and Failure of Composite Shells

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The proposed paper will describe the results of an experimental and analytical study of the effects of traditional initial geometric shell-wall imperfections, and variations in other nontraditional geometric and material parameters, and loading conditions on the buckling response of unstiffened thin-walled graphite-epoxy cylindrical shells with different shell-wall laminates and thicknesses. Traditional shell-wall geometric imperfections and several nontraditional imperfections were measured, and representations of these imperfections were included in nonlinear analyses of the shells. The effects of initial geometric shell-wall imperfections, shell-wall thickness variations, shell-end imperfections, variations in loads applied to the ends of the shell, and variations in boundary conditions and boundary stiffness on the buckling response of these thin-walled shells will be discussed. The nonlinear shell analysis procedure used to predict the buckling and nonlinear response of the shells will be described, and the analysis results will be compared with the experimental results. The unstable postbuckling response of the shell was predicted using the nonlinear transient analysis option of the code. Failure analyses were conducted along the stable and unstable response paths of the shells to predict when failure may occur during the buckling and postbuckling responses. The use of this nonlinear shell analysis procedure for determining accurate, high-fidelity design knockdown factors for shell buckling and collapse, failure, and for determining the effects of variations and uncertainties in shell geometric parameters on shell buckling will be discussed. The results from this high-fidelity nonlinear analysis procedure can be used to form the basis for a shell analysis and design approach that addresses some of the critical shell-buckling design and failure criteria and design considerations for contemporary composite shell structures.

Buckling Behavior of Long Anisotropic Plates Restrained Against Thermal Expansion and Contraction

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Buckling behavior of thin-walled structures that are subjected to combined mechanical and thermal loads is an important consideration in the design of aerospace vehicles. Often, the sizing of many structural subcomponents of these vehicles is determined by stability constraints. Anisotropic, laminated plates are presently being considered for subcomponents of future high aspect ratio wing structures, and as semimonocoque shell segments that are used for advanced fuselage and launch vehicle structures. Thus, understanding the mechanical and thermal buckling behavior of laminated plates is an important part of the search for ways to exploit plate orthotropy and anisotropy to reduce structural weight or to fulfill special performance requirements.

The effects of membrane orthotropy and anisotropy, and the effects of flexural orthotropy and anisotropy, on the buckling behavior of rectangular plates that are restrained against thermal expansion and contraction and subjected to uniform heating or cooling are becoming better understood. However, there remains a need for work that addresses, in a broad way, the effects of the various orthotropies and anisotropies and the effect of a compliant, elastic restraining medium on the thermal buckling of plates that are restrained against thermal expansion and contraction. The compliance of the restraining medium is important because, in reality, it is practically impossible to completely restrain a plate from thermal expansion and contraction.

The proposed presentation will describe an analytical approach to synthesizing buckling results and behavior for long, balanced and unbalanced symmetric laminates that are subjected to restrained thermal expansion or contraction. The effects of an elastic restraining medium is included in a very general manner. A nondimensional buckling analysis for long anisotropic plates that are subjected to combined mechanical loads will be described and useful nondimensional parameters will be presented. In particular, nondimensional compliance coefficients will be presented that are used with stiffness-weighted thermal expansion parameters to determine critical temperatures, for a wide range of laminate constructions and

elastic restraining media, in terms of physically intuitive mechanical buckling coefficients. This general approach includes, the effects of membrane orthotropy and membrane anisotropy on the thermally induced prebuckling stress state. Results will be presented first for some common laminates to facilitate the introduction of subsequent, generic buckling design curves. The results to be described in the proposed presentation provide physical insight into the buckling problem of restrained thermal expansion or contraction and supply useful design data. Specifically, results will be presented that can be used to indentify the effects of laminate thermal expansion, membrane orthotropy and anisotropy, flexural orthotropy and anisotropy, and inplane boundary restraint on thermal buckling of plates in a very general and encompassing manner.

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Bucking of Long, Sandwich Cylindrical Shells Under Pressure

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Sandwich construction has become increasingly very popular in the design of future transportation industry, especially aircraft. The paper deals with the theoretical prediction of buckling loads for sandwich long cylindrical shells with metallic and laminated facings and foam core. The loading is a uniform hydrostatic pressure. Several fiber materials are used in the laminated facings. They are: Boron/Epoxy, Graphite/Epoxy and Kevlar/Epoxy laminates with 0° orientation with respect to the hoop direction. These various materials are employed to provide comparative data that can be used in design. Results are generated by various closed form theoretical solutions. Shell theoretical results with and without accounting for the shear effect are generated (see Refs 1 and 2). Moreover, theoretical results based on three-dimensional elasticity (Ref 3) are also generated for comparison purposes. The facings are 0.1 inches and the core 1.0 inches, respectively. Therefore the total thickness is 1.2 inches. Two values of R/h_{tot} are used in order to asses the effect of transverse shear; $R/h_{tot} = 30$ and 60.

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Nonlinear Response of Fuselage Panels with Cracks and Subjected to Combined Loads

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The results of a numerical study to assess the effect of skin buckling on the internal load distribution in a stiffened fuselage panel, with and without longitudinal cracks, are presented. In addition, the impact of changes in the internal loads on the fatigue life and residual strength of a fuselage panel is assessed. A generic narrow-body fuselage panel is considered. The entire panel is modeled using shell elements and considerable detail is included to represent the geometric-nonlinear response of the buckled skin, cross section deformation of the stiffening components, and details of the skin-stringer attachment with discrete fasteners. Results are presented for a fixed internal pressure and various combinations of axial and shear loads. Results are presented for the pristine structure, and for the case where damage is introduced in the form of a 4.0-inch-long longitudinal crack adjacent to a stringer. The results indicate that skin buckling due to axial compression and shear loads can have a significant effect on the circumferential stress in the skin, and fastener loads, which will influence damage initiation. The results indicate that skin buckling can have a comparable effect on stress intensity factors for cases with cracks, which will influence damage propagation rates and the residual strength of the panel.

INSTABILITY IN SOLIDS AND STRUCTURES III

SESSION T3N

Onset-of-Failure Surfaces in Periodic Solids - I - Theory and II - Applications

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For ductile cellular solids with regular (i.e. periodic) microstructures, which are loaded primarily in compression, their ultimate failure can be related to the onset of a buckling mode. Consequently, one can define as onset of failure the occurrence of the first bifurcation away from the fundamental solution in which all cells deform identically. These theoretical failure surfaces can be defined for all periodic media of infinite extent. The corresponding calculations are based on a Bloch wave type analysis on the deformed unit cell.

The general theory is subsequently applied to several classes of materials: We first present results for fiber reinforced composites and aluminum honeycomb, for which careful experimental data are available. In each case, failure surfaces have been calculated for all possible directions in 2D macroscopic stress space for the honeycomb and strain space for the fiber-reinforced composites and foams. The usefulness of these failure surfaces for actual (i.e. imperfect, non-periodic) composites comes from the fact that the periodic solid's failure surfaces are upper bounds for the failure of their imperfect counterparts. Calculations for finite size imperfect honeycomb specimens, which include a large number of unit cells, are also presented.

The next set of applications involves periodic media with continuum unit cells. A straightforward extension to continuum unit cells requires prohibitively time consuming numerical calculations. To this purpose a special algorithm has been developed which reduces the size of stability matrices by an order of magnitude. For the case of solids with prismatic unit cells (i.e. infinite in one direction), these techniques can be extended to address three-dimensional loading. Results from ongoing calculations involving cellular and fiber reinforced solids will be presented.

Effects of Texture Gradients on Shear Band Localization in FCC Polycrystals under Plane Strain Tension

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The effects of through-thickness texture gradients on the formation of localized shear bands in FCC polycrystals under plane strain tension is investigated. An in-house finite element code based on rate dependent crystal plasticity has been developed to simulate large strain behaviour. Each material point in the specimen is considered to be a polycrystalline aggregate of a large number of FCC grains. The Taylor theory of crystal plasticity is assumed. This formulation accounts for initial textures, as well as texture evolution during large plastic deformations. The numerical analysis incorporates certain parallel computing features. A set of discretized orientations of approximately 400 grains, measured at 7 different locations through the thickness of a rolled commercial aluminum sheet alloy, was employed in the simulations of shear band formation during plane strain tension. The numerical results are compared with experimental data, and the effects of through-thickness texture gradients on the formation and prediction of shear bands are investigated.

Keywords: Crystal plasticity, Localized shear bands, Texture gradients, Finite element simulations.

Shear Band Instabilities in Metal Powder Compaction

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Flow localization during metal powder compaction is studied by use of a simple model for analyzing shear band development in uniformly strained solids. This type of model has been used previously by a number of authors.

Earlier analyses of metal powder with full inter-particle cohesive strength have predicted formation of shear bands under tensile loading, but no localization was found under compressive loading (Redanz and Tvergaard, 1999). The analyses were based on the FKM model (Fleck et al., 1992) and the Gurson model. In contrast, shear bands are able to develop in compression when the powder aggregate consists of particles with no or little cohesive strength (Tvergaard and Redanz, 2001; Fleck, 1995).

Prior to compaction, the metal powder has often no inter-particle cohesive strength, but as the particles deform, cold welding takes place at the contacts leading to an increase in cohesive strength between the particles. We propose a modified version of the above mentioned material models and explore shear band formation in powder materials where the increase in inter-particle cohesion during deformation is accounted for.

Keywords: shear band, metal powder compaction

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Shear Band Development in a Bulk Metallic Glass Under Dynamic Loading

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Bulk metallic glasses have relatively high strength; failure is typically initiated through shear bands formation. Previous work has shown that the failure strength of several bulk metallic glasses decreases with increasing strain rate. In this work, we investigate the dynamic failure process in bulk metallic glass Zr_{57} $Ti_5Cu_{20}Ni_{18}Al_{10}$. We have implemented a recovery technique in the compression Kolsky bar to obtain dynamically deformed, intact specimens with various stages of shear band development. The characteristics of the shear band development in these recovered samples were examined using scanning electron microscopy (SEM) and optical microscopy. High-speed photography was also used to examine the failure process. The dynamic failure mechanisms of this bulk metallic glass are discussed on the basis of these experimental results.

Keywords: Bulk metallic glass, Shear band development, Recovery experiment, Kolsky bar

INSTABILITY IN SOLIDS AND STRUCTURES IV

SESSION T4N

Necking Instabilities in Electro-Magnetically Formed Rings

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The electromagnetic forming process (EMF) is an attractive technique, which uses electromagnetic body (Lorentz) forces to fabricate metallic parts. The technique has several advantages, of which the two most important are: i) rapid forming times - in the order of microseconds - and ii) an increase - as compared to a purely mechanical process - in the ductility of the formed part.

Unlike classical (i.e. purely mechanical) forming processes, the study of EMF processes involves the coupled electromagnetic and thermo-mechanical response of the solid, in which finite strains, rate effects and inertia are essential features of the problem. Not surprisingly, the experimental studies of EMF processes are much more rare than their mechanical counterparts. As expected, a comprehensive modeling of the fully coupled electromagnetic and thermo-mechanical EMF processes of metals does not exist - to the best of the authors knowledge - even for the simple ring expansion problem, which is hence the object of this work.

An aluminum ring is placed outside a fixed coil, which is connected to a capacitor. Upon the capacitor's discharge, the time varying current in the coil induces a larger current in the ring specimen and the resulting Lorentz forces push the ring specimen to expand. The complete coupled coil-ring electromagnetic and thermo-mechanical problem is formulated and solved by taking also into account the specimen's inertia. The aluminum specimen's response is rate and temperature dependent, based on experimentally available data. Our calculations are based on an axi-symmetric response of the ring and give not only the time history of the various field quantities in the specimen, but also its final necking strain. Our results show that the necking strain of a given ring increases with increasing rate sensitivity and with increasing thermal sensitivity of the specimen, thus validating and also quantifying the experimentally observed increased ductility of EMF formed rings. The presentation is concluded with a discussion of extending our analysis to more complicated geometries.

Buckling of a Column on an Elastic-Plastic Foundation Under Cyclic Loading

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Several experimental studies have demonstrated that when metal structural members such as cylindrical shells, beams, columns, etc. are cyclically loaded into the plastic range, their structural response degrades progressively. The degradation is a result of the cycle-by-cycle growth of deflections in the shape of the buckling mode. In some cases, the buckling mode is global while in others it is periodic, with wavelength much smaller than the length of the specimen. It has been observed that, in experiments where the loading is conducted under constant amplitude displacement control, the long-term response of the specimens can depend on the type of buckling mode present. If the buckling mode is global, the accumulation of deflection tends to decelerate and the structural response reaches a limit cycle. If the buckling mode is periodic, the accumulation of deflections accelerates and leads to localization and collapse.

A simple model of a column on an elastic-plastic foundation has been developed to demonstrate the reasons for these differences in behavior. The buckling mode of the column can be changed from global to local by increasing the initial stiffness of the foundation. The column is modeled using sufficiently nonlinear kinematics to account for the interaction between lateral deflections and axial load. The constitutive behavior of both the foundation and the material of the column are modeled using the Dafalias-Popov kinematic hardening plasticity model.

As expected, the long-term behavior of the model reflects the observations made above. Analysis of the results of this simple model demonstrates the mechanisms that cause a structure to tend to long-term stability or instability depending on whether the buckling mode is global or local.

Thermally Induced Displacive Transformations in Bi-Atomic Crystals

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A well-known feature of some metallic alloys, such as NiTi, is their thermally induced, stress-dependent shape memory behavior. These alloys' remarkable properties are due to one or more martensitic transformations near room temperature, in which the crystalline configuration changes from a higher symmetry austenite (cubic lattice), to a lower symmetry martensite (rhombohedral, orthorhombic, tetragonal or monoclinic lattice) with decreasing temperature.

In contrast to existing phenomenological approaches, the present work consists of obtaining the continuum energy density function $W(\mathbf{F}, \theta)$ (where $\mathbf{F}$ is the lattice's uniform deformation gradient and θ its temperature) of a perfect periodic bi-atomic lattice from temperature-dependent atomic potential functions. Of interest in this work are the equilibrium solutions and their stability for stress-free crystals as functions of temperature. Although the full problem is solved numerically, an asymptotic theory is necessary to guide the numerical solution near the inevitable multiple bifurcation points. For a particular choice of the atomic potentials, we find that the stability of the austenitic phase changes at a critical temperature θ_c. Depending on the multiplicity n of the eigenvalue at the critical temperature, one can have three (for $n = 2$) or seven (for $n = 3$) bifurcated equilibrium branches. In the first case ($n = 2$) the three branches correspond to tetragonal phases while in the second case ($n = 3$) three branches corresponding to orthorhombic and four branches corresponding to rhombohedral phases. Similar analyses give monoclinic bifurcated branches emerging as secondary bifurcations from the above described rhombohedral or orthorhombic primary branches. These analytical asymptotic solutions near the multiple bifurcation points guide (and confirm when possible) the complicated numerical results obtained in the case of a pair potential example for a bi-atomic lattice.

Investigations of a Sharp-Interface Theory for Hydrogels using the Extended Finite Element Method

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We present a sharp-interface description of the coupled chemo-mechanical response and associated swelling behavior of synthetic hydrogels. In addition to bulk and interfacial equations of solute balance and standard force balance, the theory involves an ancillary interfacial equation imposing configurational force balance. The key constitutive ingredient of the theory is an expression for the

Gibbs energy density as a function of the deformation gradient. We numerically investigate the behavior of these equations using the extended finite element method (X-FEM). Our numerical studies of swelling take advantage of the enrichment techniques of the X-FEM designed for simulating phase transformations[1]. Specifically, a standard piecewise-linear polynomial space is enhanced, in the vicinity of the interface, with a generalized Heaviside function. This local enhancement provides a mechanism to capture interfacial discontinuities in chemical potential gradient and strain gradient, enabling the accurate simulation of the phase transition without remeshing. Our results include a parametric study of the characteristic swelling time that examines the effect of the discontinuous material properties of the phases and the local interfacial variables.

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Solitary Wave Interaction in a Beam on a Nonlinear Elastic Foundation†

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The phenomenon of localized buckling in long beams on a nonlinear elastic foundation is addressed by adopting a combination of analytical and numerical approaches. Informally, localized buckling can be thought of as a response in which the deflection is limited to a small part of the beam but which might occur almost anywhere along its length. This is in contrast with the classical studies on buckling which have always assumed a periodic deformation pattern. The non-dimensional equation we focus on is

$$y'''' + Py'' + y - y^2 + c_2 y^3 = 0, \qquad (1)$$

together with the appropriate boundary conditions; here, P is the loading parameter and c_2 controls the degree of restabilization afforded by the nonlinear foundation. This problem is related to the classical buckling of axially compressed thin circular cylindrical shells; however, the simplicity of the governing equations allows us to obtain sharper insight into the post-buckling phenomenon.

Localized solutions for (1) are identified with the so-called *homoclincs* of an associated dynamical system. Simple double-scale arguments are inadequate to isolate other than single-hump solutions (known also as primary solutions) so we have to employ a beyond-all orders analysis to reveal terms exponentially-small in the perturbation parameter which have macroscopic effects on the post-buckling behaviour and which explain the birth of multi-hump solutions. The primary solutions of (1) are known to exhibit *snaking phenomena* characterized by an infinite sequence of destabilizations and restabilizations which originate from an initially localized profile and evolve to one which is periodic. Our ambition with regards to (1) relates to the fate of double-humped solutions as c_2 is varied. These solutions share many of the features exhibited by the primary solutions but some more intricate behaviour is possible here and this is illustrated by the appearance of isolas in the bifurcation diagrams. The stability of the double-hump solutions of (1) is also briefly discussed.

Keywords: buckling, homoclinics, exponential asymptotics, snaking phenomena

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Symposium on

Constitutive Modeling of Shape Memory Alloys

Organizers:
Professor D. C. Lagoudas
(Texas A&M University)

Professor Valery Levitas
(Texas Tech University)

CONSTITUTIVE MODELING OF SHAPE MEMORY ALLOYS I

SESSION R2K

Stress-Wave-Induced Martensitic Phase Transformations in Ni-Ti Polycrystals

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Pressure-shear plate impact experiments have been conducted on Ni-Ti plates to determine the critical conditions for martensitic phase transformation to occur and

to gain understanding of the kinetics of the process. The experiments are of two types: (i) symmetric impact of two identical plates; (ii) impact of a thin specimen sandwiched between two hard plates. The former provides a measure of the critical shear stress required for the transformation from the maximum shear stress that can be propagated at the elastic shear wave speed. The latter provides a measure of the time required for the transformation to progress through the thin sample. To interpret the results of these experiments they are simulated using finite element modeling, using time-dependent Ginzburg-Landau equations to describe the kinetics of the martensitic phase transformations. The free energy is modeled by using the Eshelby theory approach to evaluate the interaction energy functional for the formation of a martensitic inclusion in a matrix of the parent material. To reduce the energy barrier for the transformation sufficiently for the transformation to occur at the critical levels of shear stress observed in the experiments, the inclusions are composed of self-accommodating groups of martensitic variants. Best agreement is obtained when all habit plane variants are included in a single group.

This research was supported by the Office of Naval Research and the NSF-MRSEC at Brown University

Dynamic Mesoscale Evaluation of Phase Transformation in Hybrid Porous Shape Memory Composite

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The main interest of this study is to investigate transformation mechanism under intermediate dynamic loads in hybrid porous SMA. A hybrid porous SMA can be described as a two-component composite made of porous SMA, and a passive or active material. In this study, the composite is assumed to be obtained by filling the pores with a passive material. The dynamic behavior of hybrid porous SMA under strain rates of 1000 /s is investigated by incorporating the porous mesostructure in the finite element analysis. X-ray computed tomography (XCMT) images are employed to synthesize statistical information that is utilized in obtaining suitable representative finite element meshes. The constitutive response of the material is obtained by simulating the split-Hopkinson bar test on the finite element specimen. An existing rate-independent model is used to describe the behavior of dense SMA. A parametric study based on pore volume fraction is carried out. A comparison of hybrid porous SMA and empty porous SMA is also performed.

FE Simulation Using Cellular Automata Approach of Martensitic Transformation Process in Single Crystal of TRIP Steel Based on Continuum Crystal Plasticity Theory

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Due to the strain-induced martensitic transformation (SIMT), the strength, ductility and toughness of TRIP steel are enhanced. The deformation behavior of TRIP steel is mainly yielded on this SIMT behavior and the deformation behaviors of the austenitic and martensitic phases. TRIP steel possesses such favorable mechanical properties due to the appropriate combination of these behaviors.

Recently, texture evolution by martensitic transformation is being focused on (Gall et al. [2000]) and it is possible that the control of such favorable mechanical properties will be realized by the control of transformation texture evolution. So the constitutive model on the single crystal level is necessary to predict this transformation texture evolution. To approach this goal, it is necessary to consider both the slip system of both phase and the multivariant system of SIMT. First, the constitutive equation of TRIP steels based on Continuum Crystal Plasticity (CPP) theory proposed by Peirce et al. [1983] is derived. The deformation gradient can be decomposed as following equation (Kratochvil [1973], Tanaka and Nagaki [1983]) because the SIMT occurs after the plastic deformation of austenite in the case of TRIP steel.

$$F_{ij} = F^3_{ik} F^p_{kl} F^{tr}_{lj}$$

Where F^e_{ij} is the deformation gradient tensor due to the stretch and rotation of the crystal lattice, F^p_{lj} is the deformation gradient tensor due to the plastic shear deformation along the slip planes and F^{tr}_{ij} is the deformation gradient tensor due to the SIMT along the habit planes as shown in the right figure.Based on above equation, the constitutive equation for TRIP steel based on CCP can be derived.

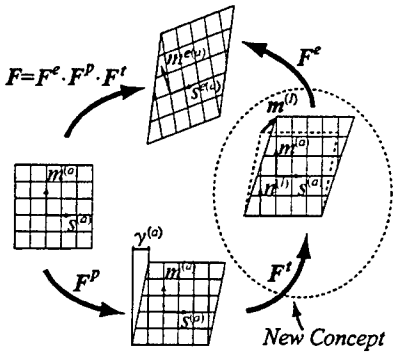


Fig. Decomposition of deformation gradient

Keywords: TRIP Steel, Strain-induced Marteensitic Transformation, Continuum Crystal Plasticity Theory, Cellular Automata Approach

Evaluation of Adaptability and Structural Stability of Fused NiTi Alloy by Means of Multifractal Parameterization Method

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Grave disadvantage of fusing *Nitinol* on iron-bearing materials is functional and mechanical degradation of SME owing to transition of basic-material elements into the *Nitinol* structure. Traditional methods of metallographic welds analysis founded on statistical data processing of grain-structure parameters do not allow a decision to be made concerning the stability of the layer of weld metal in depth without additional physico-mechanical investigations. Multifractal analysis allowed the quantitative estimation to be given both for the grain structure and its inhomogeneity, periodicity and stability depending upon the depth of layer of weld metal. In the field of homogeneous *Nitinol* an existence of plastic F-symmetry fractal sets with high stability threshold is determined. This fractal sets have the partial dislocations as the leader-defects of deformation mechanism. Starting with heat-affected zone the gradual transition of structural state from adaptation to degradation is occurred. In the boundary layer field the degeneracy of multifractal characteristics and spontaneous changing of F-symmetry type which controls this degeneracy are occurred. Fractal clusters cross the inelasticity threshold and go to the quasielastic F-symmetry field which has the vacancies as the leader-defects of deformation mechanism. In this field the plastic (adaptation) properties completely disappear. This structural instability is caused by effect of brittle intermetallics $TiFe$, $TiFe_2$ and also titanium carbide TiC formed in the boundary layer. Solution of this problem by means adding interlayer of pure nickel which can form an unlimited solid solution with Fe is suggested. Thereby one can get the ductile transitional layer ($Fe - Ni - NiTi$) with sufficient adaptation and structural stability.

Keywords: Nitinol, fusing, structural stability, multifractal analysis

Finite Element Analysis and Experimental Study on Superelastic Nitinol Stent

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The mechanical performance of a Nitinol stent generally requires experimental evaluation due to complexities resulting from large deformations and material nonlinearity. Such experiments include radial force tests (used to determine the radial resistive and chronic outward forces), pulsatile fatigue tests (used to determine the device life under a simulated straight in-vivo condition) and crush fatigue tests (to determine the sufficient crush resistance of the device). Still, finite element analysis is necessary in order to understand and predict the stent performance in more complex loading conditions, and to understand the impact of manufacturing variations on performance. Clearly the combination of both the experimental and the computational studies lead to better understanding of the stent performance. This paper presents comparisons between experimentally determined performance to predictions based on nonlinear finite element analyses. The radial force and crush force tests are used for comparisons. The analyses were performed using ABAQUS/Standard with two independently developed user material subroutines specifically for Nitinol. Despite the fact that the finite element analyses are complex and time consuming, good agreements between the simulations and the experimental data are shown for both user material subroutines.

CONSTITUTIVE MODELING OF
SHAPE MEMORY ALLOYS II

SESSION F2K

A 3-D Two-tier Multivariant Model Based on Hierachical Structural Characteristic of SMA Martensites

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A general 3-D Two-tier Multivariant model with correspondence variants (CV) as minimum units is developed. The model is further development of previous 3-D and Simplified 3-D Multivariant models. Previous models are based on habit planes variants (HPV) and use a thermodynamic and micromechanics approach. The Multivariant model accounts for the self-accommodating group structure and utilizes this in interaction energy calculation within a group. While the Simplified model removes explicit interaction energy calculations but predicts excellent results and allows anisotropy at single crystal level and much faster computation. However both are unable to consider the inherent hierachical features of SMA martensite, i.e., a HPV is either composed of two twinned CVs or a faulted CV.

The first tier is at the level of HPVs, which can form self-accommodating groups. The HPVs inside a group interact more directly (through an interaction energy term) although they also interact with HPVs of other groups (competing through driving forces). The second tier is at the level of CVS and there is also an interaction term conceptually similar to that within a group. A CV interacts with CVS of other HPVs through the interaction among HPVs. Note no limitation on what kind of interaction within a group and interaction inside a HPV has been imposed here. The authors are taking a very simple approach, i.e., no interaction inside a group and if the critical resolved shear stress in the shear direction on the twinning plane reaches a critical value detwinning will happen and the favored twin assume all the volume fraction. In short, the Two-tier model set up a generic framework in two ways: resembling the hierachical features martensites and allowing different forms of interactions within a group and/or a HPV. Comparison to experiments shows the Two-tier model predict excellent results in addition to handling more complicated conversion process, e.g. detwinning or defaulting.

Repeatable Bending Actuation in Polyurethanes Using One-way Shape Memory Alloy Wires

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Shape Memory Alloys (SMAs) are being embedded in smart structures for sensing and actuation because of the large amount of deformation that these materials can recover upon heating. Previous investigations have focused primarily on embedding single or opposing SMA wires exhibiting the two-way Shape Memory Effect (SME) into structures because of the simplicity with which the stable actuation behavior of the structure can be predicted. This stable actuation behavior is often achieved at the expense of reduced levels of recoverable deformation. Alternatively, many potential smart structure applications can employ multiple SMA wires exhibiting a permanent one-way SME to simplify fabrication and increase the recoverable deformation in the structure. In this investigation, the repeatable bending actuation of polyurethanes using multiple SMA wires exhibiting the one-way SME is characterized with the novel deformation measurement technique known as Digital Image Correlation. These results are compared with a one-dimensional actuation model previously developed for predicting the bending actuation of elastomeric rods embedded with opposing two-way SMA wires. Using appropriate recovery strains and constitutive bending responses, this model was used to characterize an "equivalent two-way SME" for the one-way SMA wires that could also be calculated from a kinematic model of the bending actuation. Repeatable bending actuation was achieved in polyurethanes using multiple one-way SMA wires prestrained 5of nearly 5%. These results indicate that repeatable bending actuation can be achieved in polyurethanes by using multiple SMA wires exhibiting the one-way SME instead of the two-way SME at a level 25% greater than reported for the two-way SME.

Clapeyron – Clausius Equations for the Phase Transitions in Thermoelastic Materials

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The new model of the phase transitions in thermoelastic materials is offered. The rela-tions on a strong discontinuity surface which moves on material particles and

separates phases of the solid material are deduced. It is shown that unlike classical case of the phase equilibrium of fluids the offered relations take into account the irreversibility of the phase transitions in solids, tensorial nature of the chemical potential and essential dependency on type of anisotropy of the phases. The irreversibility connected with singular source of dissipation on phase transition boundary allowed to model the hysteresis phenomenon in solids. The correlation between Lagrange and Euler tensor of chemical potential is formulated.

The Clapeyron – Clausius equation is proposed for thermoelastic solids with finite deformations. This equation defines the dependency of the phase transition temperature on deformation gradient (distortion) of the initial phase. New equation is suggested. This relation describes a differential dependency of the phase transition temperature on orientation of the phase boundary relatively to strain tensor and anisotropy axes. For isotropic material with finite strains is shown that the interphase boundary normal to which coincides with one of the principal axis of the deformation tensor of the initial phase delivers the extremum to the phase transition temperature. This exremum can be both minimum and maximum depend on material properties and boundarycoditions.

The phase transition in linear isotropic thermoelastic materials is considered in details. It is detected that small deformation approximation has as a consequence the small jump of rotation of material element. This fact is important for description of process of recrystallization of solids. It is determined that the increasing of small deformation of initial phase can imply the change of type of transition – the normal phase transition becomes enormous.

Two-phase Deformations and Phase Transition Zones

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Phase transitions of martensite type can result in the appearance of strain fields with interfaces which are the surfaces of discontinuity in deformation gradient at continuous displacements. We analyze conditions on the equilibrium interface. The conditions can be satisfied not for any material and not at any strains. Strains which can exist on the interface form the phase transition zone (PTZ) [1,2]. Deformations outside PTZ cannot exist on any interface whatever the loading conditions are. Since the PTZ is determined by the strain energy function, it characterizes a material. The PTZ boundary acts as a phase diagram or yield surface in strain-space. Various points of the PTZ correspond to various deformation states and to different types of strain localization due to phase transformations on different loading pathes. We develop a general procedure for the PTZ construction and give examples for various materials.

Then we study boundary value problems for elastic solids undergoing phase transformations [2,3]. Non-uniqueness and local stability of equilibrium two-phase states as well as energy changes due to phase transformations are examined. Two-phase deformation fields in stable and unstable two-phase states are related to the PTZ. Heterogeneous deformation due to multiple appearance of new phase areas is studied. Effective constitutive equations are derived which show strain softening effects on the path of the transformation. Applications of the results obtained to martensite transformations in shape memory alloys and localized orientation transformations in forms of crazes and shear band in polymers including brittle-ductile transitions due to stress state changing are considered.

Keywords: phase transitions, elasticity, constitutive equations

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Constitutive Equations for Two-Step Thermoelastic Phase Transition

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Using experimental data the set of hypothesis is formulated for two - step (rombohedral and martensite) phase transition in Nitinol - type shape memory alloys (SMA). Constitutive equations are created for description two parameters of phase state changing and mechanical behavior

of SMA undergoing such a phase transition. Model is calibrated for Ti-50.2Different statements of boundary value problems of solid mechanics (non - connected, connected, twice - connected, geometry linear and non - linear) are formulated in framework of these constitutive equations. The set of general proposition and theorem are proved for these statements of problems. Analytical and numerical methods of solution of these problems are created. By solving boundary problems for SMA undergoing two - step phase transition some new effects are revealed concerning behavior of SMA in the cases of non - uniform stress and temperature distribution.

Keywords: Rombohedral, Martensite, Phase, Transformation.

Phenomenon of Stability Loss due to Thermoelastic Phase Transition under a Copressive Loading

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Phenomenon of stability loss due to thermoelastic phase transition has been ascertained experimentally. Samples from Nitinol do not loss stability in isothermal conditions in the case of temperature suitable as for martensite so for austenite states loss stability during phase transition from one phase state to another. Critical loading for stability loss due to direct martensite phase transition is about three times less then critical loading for isothermal stability loss in martensite state and is about nine times less then critical loading for isothermal stability loss in austenite state. Critical loading for stability loss due to reverse martensite transformation is slightly less then critical loading for isothermal stability loss in martensite state.

Using new micro-mechanical constitutive equations for SMA this phenomenon has been investigated analytically and numerically. It has been formulated and proved the conception of "continuation of phase transition" for jump to adjacent equilibrium state during stability loss of SMA. It has been investigated phenomenon of isothermal stability loss due to phase inelastisity as well.

Keywords: Stability, Shape Memory Alloys.

CONSTITUTIVE MODELING OF SHAPE MEMORY ALLOYS III

SESSION F3K

Thin Film Shape Memory Actuators for Hydraulic Pumps

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In this presentation we will describe the ongoing effort to fabricate thin film shape memory actuators for use in miniature hydraulic pumps. The work focuses on characterizing the response of the film in contact with a liquid environment and evaluating the response of the actuator in several, different pump systems. We find that the frequency response of the film is sensitive to heating rate, boundary conditions, and flow properties of the fluid. Cyclic actuation of the film has exceeded 100 Hz but is not believed to represent the upper bound on attainable bandwidths. Actuation in the pumping system at these frequencies has led to large power densities for the material approaching 40 kW/kg. This represents one of the largest values measured for an active material system. While the films power density is large, the power density of the pumps has been relatively small due to non-optimal packaging issues. This presentation will describe the experimental results, non-linear- finite element models, and engineering optimization to increase the power density of thin film shape memory alloy mico-pumps.

Porous NiTi Fabricated using Powder Metallurgy Techniques: Characterization and Modeling

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Various fabrication techniques for producing porous NiTi using powder metallurgy techniques are reviewed and discussed in this work. Porous NiTi SMA has been fabricated using conventional sintering, Self propagating High-temperature Synthesis (SHS), and sintering at elevated pressures via a Hot Isostatic Press (HIP). Using the

HIP technique, porous SMAs with porosity levels as high as 50elemental powders. The established HIPping technique is also used to fabricate porous NiTi SMA from pre-alloyed powders.

Porous NiTi specimens with different volume fractions fabricated via HIPping are also characterized in terms of composition and phase transformation characteristics using calorimetric measurements. Mechanical behavior of the porous specimens is studied through quasi-static and dynamic load testing under compression and the shape memory characteristics as well as energy absorption capabilities are observed.

The behavior of porous NiTi is modeled using micromechanical averaging techniques. The porous SMA material is modeled as a two-phase composite with an SMA matrix and a second phase which represents the pores. The behavior of the dense SMA matrix is modeled using a rate-independent thermomechanical constitutive model with internal variables. The dense SMA constitutive model takes into account the development of transformation and plastic strains during loading as well as the evolution of the transformation hysteresis loop during cyclic loading.

The material parameters used by the model are estimated using the experimental data. The model simulations of the stress-strain response of porous NiTi are compared with the experimental results. To demonstrate the capabilities of the model various boundary-value problems are analyzed.

Keywords: Porous Shape Memory Alloy; Powder Metallurgy; Constitutive Modeling; Micromechanics

Pseudoelastic Behavior of Nickel-Titanium Melt Spun Ribbon

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The pseudoelastic behavior of NiTi shape memory alloys (SMA) is known to be sensitive to alloying and prior thermal history, but relatively little has been established concerning the influence of grain size, especially in the nanoscale regime. The research reported employs the technique of melt spinning to create continuous ribbons of equiatomic NiTi alloys with grain size of 1 to 10 μm. The NiTi ribbon is created from alloy produced by arc-melting Ni and Ti in a 50:50 atomic ratio. The melt spinning operation involves heating the alloy in a Y_2O_3 lined quartz crucible and discharging the molten mixture under argon pressure onto a cooled copper wheel rotating at 55m/s. This technique yields fine ribbons approximately 30 μm thick and ranging in length from a few millimeters to several centimeters. Tensile testing was conducted on the ribbon material in the as-spun condition at temperatures from 30°C to 85°C using an Instron micromechanical testing machine with an environmental chamber. No appreciable pseudoelastic behavior was observed in this temperature range. Samples were then aged for one hour at temperatures ranging from 300°C to 600°C. Subsequent mechanical testing at room temperature displayed modified mechanical behavior. Several samples exhibited transformation involving the R-phase and a small amount of pseudoelastic recovery. However, the mechanical properties were dramatically improved and the grain size was further refined by cold rolling the melt-spun NiTi ribbon. Ribbons were stacked and subjected to repeated cold rolling and folding passes. The resulting material displayed reduced grain size at the nanometer scale with the primary phase remaining B2 NiTi. This cold-worked material exhibited strong pseudoelastic behavior not observed in the as-spun ribbon, and did so without the use of a heat treatment step. The cold rolled melt-spun ribbon also exhibited a significantly diminished mechanical hysteresis stress.

Influence of Casting Technology on the Phase Transformation in NiTi-Based Alloys

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The casting properties of NiTi alloyed by Nb are investigated in this paper. Experimental data confirm that the method of alloy fabrication, the remelting technology and material of the mold are very important. A master ingot from the alloy containing $Ni_{(50)}Ti_{(50-x)}Nb_x$, $(1 < x < 10)$ has been produced by arc melting. The remelting was performed in arc-furnace too. For elaboration of the samples under study the alloy flooded in the molds made from different materials. The experimentally established temperature intervals of the martensitic transformations as well as characteristics of shape recovery for ingots confirm the possibility of the NiTi-based shape memory alloys as raw materials for casting.

Effect of Transformation-Induced Plastic Strains on the Mechanical Behavior of Porous NiTi SMA

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The development of unrecoverable strains during compressive loading of porous shape memory alloys (SMAs) has been experimentally observed on porous NiTi fabricated from elemental Ni and Ti powders. These strains have been attributed to transformation-induced plasticity in the SMA matrix. Thus, to be able to accurately model the behavior of porous SMAs an appropriate model for the dense SMA, capturing the development of plastic strains, must be established.

Motivated by the experimental observations, a thermomechanical constitutive model for fully dense shape memory alloys (SMAs) is developed in this work. The model accounts for development of transformation and plastic strains during martensitic phase transformation, as well as for the evolution of the transformation cycle. The developed constitutive model is used in a micromechanical averaging scheme to establish a model for the macroscopic mechanical behavior of porous shape memory alloys. The material parameters used by the model are estimated for the case of porous NiTi SMA. The results of the model simulations are compared with the available experimental data for compressive loading of porous NiTi bars.

Keywords: Porous Shape Memory Alloy; Constitutive Modeling; Micromechanics

Symposium on

Numerical Simulation of Turbulent Flows

Organizer:
Professor Krishnan Mahesh
(University of Minnesota)

NUMERICAL SIMULATION OF TURBULENT FLOWS

SESSION M3D

Simulation of Complex Flows on Cartesian Grids

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In recent years there has been an explosion of activity in developing numerical methods that compute flow fields with complex stationary and/or moving boundaries on fixed, Cartesian grids. The obvious advantage of this approach over the conventional body-conformal approach if that even for highly complex geometries, the grid retains a simple topology. Furthermore, for moving boundaries, Cartesian grid methods free the underlying structured computational grid from the task of adapting to the boundary, thus allowing large changes in the geometry due to boundary evolution. Methods that simulate flows with complex immersed boundaries on Cartesian grids can be broadly classified into two categories; First category is of those methods where the immersed boundary is represented as a "diffuse" interface of finite thickness and the second is where the boundary is represented as a "sharp" boundary. Both types of methods have been used in a wide variety of applications and we will discuss the advantages and disadvantages of these methods, especially viz-a-viz their application to the DNS and LES of complex turbulent flows. Finally, we will describe a sharp-interface Cartesian grid method that has been developed specifically for computing flows with moving boundaries and describe its application to a number of complex flow configurations.

Towards DNS and LES of Turbulent Flows in Engineering Geometries

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Direct numerical simulation (DNS) and large-eddy simulation (LES) have traditionally been restricted to very simple geometries. Most methods developed to simulate flow in engineering geometries have been developed with the mean flow in mind and lack the fidelity to simulate turbulence.

We will discuss a computational approach to DNS and LES of incompressible turbulent flows on unstructured grids. Our objective is to reliably perform LES at high Reynolds numbers in engineering geometries. A novelty of our approach is that it is discretely energy conserving for grids composed of arbitrary computational elements. This makes it robust at high Reynolds numbers without the use of numerical dissipation. The formulation has been implemented for parallel platforms and has been successfully run on as many as thousand processors. Results will be presented for a range of flows from isotropic turbulence to flow in an engineering gas-turbine combustor. The presentation will underline the importance of numerical method in DNS/LES of turbulent flows.

A High-Reynolds Number Update to the Comte-Bellot & Corrsin Experiment and Applications in Large-Eddy Simulation

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An experimental study on spatially decaying turbulence generated by an active grid has been performed in the Corrsin wind tunnel of the Johns Hopkins University. The active grid arrangement follows the studies of Mydlarski & Warhaft (1996). The main goal of this study is to update the results of Comte-Bellot & Corrsin (1971) based on turbulence at a higher Reynolds number. The experiments are carried out at $Re_\lambda \approx 750$. Measurements are performed using an array of four X-wire probes. This array enables us to obtain two-dimensional filtered velocities in the cross-stream and streamwise directions by invoking Taylor's hypothesis. We obtain the turbulence statistics including the decay of the turbulence kinetic energy, three-dimensional energy spectra and probability density functions of velocity increments at various displacements. Also documented are kurtosis coefficients of derivative moments of streamwise and cross-stream filtered velocity. These detailed experimental data can be compared to results of large-eddy simulation (LES) using various subgrid-scale models.

We present pseudospectral simulations using the traditional Smagorinsky, dynamic Smagorinsky, and dynamic mixed nonlinear models. We distinguish between consistent and inconsistent dynamic models. The latter involve test-filtering using filter types that differ from the basic grid-filter type. Overall, the various LES models predict accurate low-order statistics in isotropic turbulence when the models are formulated consistently. Dynamic models yield poor results when used in conjunction with inconsistent formulations (e.g. when using a Gaussian test-filter in an unfiltered spectral calculation in which the grid-filter is a cut-off filter). We also test the idea of performing simulations with a filter scale set to twice the grid filter scale, in cunjuction with Gaussian filters. In this case the dynamic mixed nonlinear model predicts slightly better results than the other models tested. Interestingly, all LES models tested here predict less intermittent streamwise velocity fields than is observed in experiment. This feature can be seen in PDFs of filtered velocity increments as well as in the hyperkurtosis. We also compare PDFs of subgrid-scale shear stress that have been measured in the wind-tunnel using the array of X-wires with those arising in the LES. For this SGS quantity, the dynamic mixed model performs markedly better than the Smagorinsky model.

Application of a Vortex-based Subgrid-scale Model to Large-eddy Simulation of Compressible Turbulence

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The use of a vortex-based SubGrid-Scale (SGS) model for the Large-Eddy Simulation (LES) of compressible turbulent flow will be described. First, the physical assumptions underlying the use of subgrid vortex elements as the building blocks for a viable SGS model will be reviewed. This will be followed by a discussion of the conflicting requirements for a basic numerical method that is shock capturing and robust for strong shocks, but which does not dominate the SGS dissipation in turbulent regions of shock-free flow. Several LES applications will be presented including decaying compressible turbulence and the Richtmeyer-Meshkov instability produced when a strong shock impacts a perturbed density interface.

The Effect of Topology and Scale Decomposition when using Variational Multiscale LES

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The variational multiscale method developed by Hughes, Mazzei, and Jansen [1] has been extended to make use of a hierarchical basis. This hierarchical basis [2] provides a natural scale separation modeling. Modeling is confined to the effect of a small-scale Reynolds stress, in contrast with classical LES in which the entire subgrid-scale stress is modeled. The model is evaluated on simple flows where it can be directly compared to more traditional approaches like the dynamic Smagorinsky model [3]. Both hexahedral and tetrahedral discretizations will be discussed. We will also consider the relative sizes of the two spaces and the effect this choice has on simulation quality. For example, when considering a hierarchic basis that is complete to order cubic, should the resolved space include linear and quadratic modes or should the resolved space be restricted to linears, leaving the quadratic and cubic modes to fill out the fine scale space where modeling is performed? Smagorinsky models will be shown to be quite effective with this type of modeling though other possibilities will be discussed. Status of more advanced calculations will also be discussed.

NUMERICAL SIMULATION OF TURBULENT FLOWS

SESSION M4D

RANS-LES Approaches to High Reynolds Number Prediction

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There is an increasing interest and use in the application of hybrid schemes for predicting complex flows of technological importance. Most hybrid techniques combine Reynolds-averaged Navier-Stokes (RANS) methods with Large-Eddy Simulation (LES). One of the aims underlying the use of these techniques is an attempt to combine the most favorable elements of RANS and LES, e.g., application of RANS models to regions of the flow not far from their calibration range and LES for resolution of the large-scale structures not well modeled in RANS. An example, and the main focus of this contribution, is Detached-Eddy Simulation (DES), proposed by Spalart et al. (1997). DES has RANS behavior near the wall and becomes a Large Eddy Simulation (LES) in the regions away from solid surfaces provided the grid density is sufficient. The formulation of the base model in DES is developed via a simple modification to the Spalart-Allmaras one-equation model. The method is non-zonal and computationally feasible for high Reynolds number prediction, resolving time-dependent, three-dimensional turbulent structures.

DES was originally proposed as an approach for predicting high Reynolds number massively separated flows, where RANS models of any complexity appear inadequate and whole-domain LES imposes a substantial computational cost. To date, there have been several applications of DES to the massively separated flow around canonical geometries such as an airfoil at high angle of attack, a circular cylinder, and flow over a sphere. These previous applications have been largely successful, typically obtaining more accurate predictions than possible using RANS. In addition, application to more complex configurations, including a full aircraft at high angle of attack, have yielded accurate predictions of quantities such as lift and drag.

These previous applications have been useful for illustrating positive aspects of the method, e.g., its "LES character" in that grid refinement yields more structure, pushing the solution towards the DNS limit. Previous investigations have also confirmed that the computational cost has a weak dependence on Reynolds number, similar to RANS methods. Prediction of massively separated flows are natural applications of the technique since new instabilities rapidly develop in the wake and the error arising from the lack of eddy content in the attached boundary layers is relatively insignificant. An area of current interest is application of the method to flows in which there is stronger coupling between the RANS and LES regions. One example is use of DES for predicting turbulent channel flow at high Reynolds numbers. Computations by Nikitin et al. (2000) have shown that turbulence in the outer layer is sustained even on relatively coarse grids with the flow in the inner layer being relatively smooth. The calculations showed a logarithmic layer with the correct intercept in the quasi-steady RANS region, that connected to an LES region characterized by a higher intercept of the logarithmic layer, corresponding to errors in the skin friction on the order of 15 percent. Improvements in the coupling between the RANS and LES regions within hybrid methods comprises an area of current research interest.

Wall Modeling for LES of Complex Turbulent Flows

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Large-eddy simulations (LES) of wall-bounded flows are extremely expensive at high Reynolds numbers if one attempts to resolve the small but dynamically important flow structures in the near-wall region. As a practical alternative, LES can be combined with a wall-layer model which provides the LES with a set of approximate boundary conditions, often in the form of wall shear stress. This approach removes the severe near-wall grid resolution requirements and thus makes the computational cost only weakly dependent on the Reynolds number.

A brief overview of wall modeling methodologies will be given, followed by discussions of our recent work on wall models based on turbulent boundary-layer (TBL) equations and that based on control theory. In the first approach, the TBL equations with a RANS type eddy viscosity are solved numerically in an embedded near-wall mesh to compute the instantaneous wall shear stresses. The control-based wall model is derived by minimizing the difference between the RANS and LES solutions integrated over an overlapped region adjacent to the wall. The efficacy of the wall models for complex-flow LES is demonstrated via examples of turbulent boundary-layer flows past an airfoil trailing-edge and the flow over a circular cylinder at super-critical Reynolds numbers.

It will be shown that the hybrid LES/wall modeling method predicts the trailing-edge flow well in both attached and separated regions, at a drastically reduced computational cost compared to the full LES with resolved wall layers. The RANS eddy viscosity, when used in the wall-layer equations with nonlinear convective terms, must be reduced to account for only a fraction of the total Reynolds stress. A dynamically adjusted mixing-length eddy viscosity is used in the TBL equation model, which is shown to be superior to the simpler wall models based on the instantaneous log law. Comparable results have been obtained using the control-based wall model without the need to solve the full TBL equations. Simulations of the high Reynolds number flow over a circular cylinder also show promise in that they capture correctly the delayed boundary-layer separation and reduced drag coefficients after the drag crisis. Detailed results and comparisons with experimental data will be presented. Perspectives about the challenges and future directions for wall model development will also be discussed.

Large-Eddy Simulations of Single and Two-Phase Turbulent Flames

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Simulation of turbulent reacting flows in practical systems with sufficient spatio-temporal fidelity is a very challenging task since interaction between chemical and turbulent scales occurs over a wide range. Conventional large-eddy simulation (LES) methods that model the effect of the scales smaller than the grid on the simulated resolved motion fail to accurately capture turbulence-chemistry interactions since combustion process is dominated by small-scale processes that are not resolved on a LES grid. This limitation has been a major problem in developing and implementing reacting LES for practical applications. Additional problems appear when phase change (due to liquid fuel evaporation) has to be predicted accurately. Many features, such as, accurate numerical algorithm, efficient parallel codes, advanced closure for momentum transport, and proper resolution of the small-scale turbulent mixing and reaction-diffusion processes, all have to come together in order to carry out accurate LES of multiphase reacting flows. In this talk, a description of a new subgrid combustion modeling approach that has shown an ability to capture accurately the physics of turbulence-chemistry interactions will be given. It will be shown that by employing appropriate physics-based subgrid models a single LES methodology can be developed to study premixed, non-premixed and spray flames without requiring ad hoc model changes or adjustments. Results obtained using this LES approach will be used to identify the inherent limitations and strengths of this approach. Finally, future development needs to simulate high Reynolds number spray flames in complex domains will be identified and possible strategies will be discussed.

Large-Eddy-Simulation of Turbulent Combustion

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In recent years, Large-Eddy-Simulation of turbulent combustion became a very popular research area. Many studies have, for example, been devoted to a priori testing of the applicability of combustion models, which have

commonly been used in RANS calculations, and also newly developed combustion models as sub-grid scale combustion models in Large-Eddy-Simulations (LES).

Large-Eddy-Simulations have the capability of resolving the major part of the turbulent kinetic energy of turbulent flows. Only the influence of the small turbulent scales on the resolved field has to be modeled. This is particularly interesting for simulations of chemically reacting flows, where an accurate description of mixing is essential and very complex phenomena like turbulent transition and instabilities might be of great importance. However, since chemical reactions in practical systems mainly occur on the sub-grid scales, the combustion process has to be modeled entirely. Although combustion models for LES are therefore often similar to models developed for RANS simulations, LES can provide some advantages. Certainly, the LES predictions of the mean flow fields and scalar fields are expected to be more accurate as compared to RANS. But LES also provides instantaneous and local information on the resolved scales. The main challenge in developing combustion models for LES is to make maximum use of this local and instantaneous information for the sub-grid scale combustion models. This will lead to a better description of the scalar mixing process on the sub-grid scales, and thereby to a more accurate prediction of the entire combustion process.

Examples of LES for different experimental configurations will be shown here.

The final objective here is the development of a versatile model applicable in non-premixed, premixed, and partially premixed combustion situations. We will therefore present models and validation studies for each of these combustion regimes.

First, different formulations of an unsteady diffusion flamelet model for non-premixed combustion are discussed. The application of the models to the Sandia D flame experiment shows that conditionally averaged temperatures and all measured species mass fraction distributions are essentially well predicted. It is also shown that CO can only be predicted correctly if the resolved fluctuations of the local scalar dissipation rate are considered in the combustion model.

For the description of premixed turbulent combustion, a level-set method is formulated for LES. A model for the turbulent sub-grid burning velocity, required in the formulation, is derived from the sub-grid variance equation of the level-set function. The model is applied to a premixed turbulent Bunsen burner. The comparison with experimental data shows that the mean flame front location and the influence of the heat release on the velocity field and kinetic energy is described with good accuracy.

The combination of the models for non-premixed and premixed combustion leads to a comprehensive model, applicable to all combustion regimes. The Combined Conserved Scalar/Level-Set Method is applied in LES of a series of lifted turbulent jet diffusion flames. In these flames mixing of cold fuel and oxidizer occurs in the region close to the nozzle leading to a partial premixed region in which the flame stabilizes. The comparison with experimental data indicates that both the effect of jet exit velocity and the co-flow velocity are well predicted.

Symposium on

Dynamic Fracture

Organizer:
Professor Toshihisa Nishioka
(Kobe University of Mercantile Marine)

DYNAMIC FRACTURE

SESSION W4G

Some Remarks on Dynamic Failure Mechanics

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Advances in experimental techniques and numerical codes have allowed during the last decade for a more detailed analysis of fracture and failure in variety of materials like advanced industrial alloys, composites and ceramics. All domain of dynamic loading of materials, including fracture and failure, can be split into two main branches, that is: *Dynamic Fracture Mechanics* and *Dynamic Failure Mechanics*.

In the case of Dynamic Fracture Mechanics, a discipline relatively well developed, an analysis of already existing crack or a network of cracks in a solid is attempted, where time of loading is relatively short in comparison to the characteristic distance of elastic wave propagation. This relatively short time interval of loading introduces at the crack tips material rate sensitivity, or delay time, and inertia effects.

In the case of Dynamic Failure Mechanics, a discipline in the stage of early development, no initial cracks are assumed. A solid is loaded in a short time interval or by mechanical waves (case of very short time loading, for example explosion), and a more or less uniform plasticity field develops. But after a short time, because of local stress concentrations or even temperature gradients caused by

adiabatic heating, localization of plastic field leading to failure occurs. In this approach the failure is defined as a specific type of fracture, that is creation of free surfaces in a solid developed by specific histories of loading and plastic deformation.

Thus, Dynamic Fracture Mechanics is limited to studies of crack dynamics in brittle or semi-brittle materials within the framework of Small Scale Yielding (SSY). A more general case is the Large Scale Yielding (LSY) of dynamic cracks, whereas the Dynamic Failure Mechanics is focused exclusively on *rate and temperature sensitive plastic materials* with no initial cracks. The specificity in the last case is temperature-coupling plasticity like Adiabatic Shear Banding (ASB) and finally failure.

In this contribution several examples of the Dynamic Failure Mechanics are discussed.

1. Dynamic tensile loading of bars where adiabatic heating leads to instability, localization and failure. At high impact velocities the Critical Impact Velocity (CIV) in tension occurs and the failure is observed near the impact end.
2. Dynamic shearing of a layer where adiabatic heating leads to instability, localization and shear failure. Again, at high impact shearing the Critical Impact Velocity in shear occurs and the failure is observed near the activated layer.
3. Failure by spalling, where combination of high-rate local plastic deformation in tension leads to the local adiabatic micro-bridges and failure. In all three cases the final stage is failure. Thus, the failure criteria based on different physical notions are the last part of this presentation.

Keywords: Dynamic failure; Adiabatic shear bands; Failure criteria; Critical Impact Velocity.

Recent Advances in Dynamic Fracture Studies

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This paper summarizes recent advances in dynamic fracture studies, made by the author and coworkers.

In the section for the experimental studies, explained topics are (1) high-speed photography of laser-caustics for mixed-mode impact fracture, (2) the shapes of propagating crack front and the surface singularities of corner-point, (3) governing criterion of dynamic crack bifurcation, and (4) transonic interfacial fracture.

For the mathematical studies, the following items are briefly explained: (1) asymptotic near-tip fields of unsteadily propagating crack, (2) a unified solution for dynamically propagating interfacial cracks, (3) concept of separated dynamic J integral for dynamic interfacial fracture mechanics, and (4) dynamic interfacial fracture mechanics for piezoelectric ceramics.

For the computational studies, the following recently developed simulation technologies are explained: (1) impact fracture path prediction using a moving finite element method based on Delaunay automatic triangulation, (2) moving finite element simulations of subsonic, intersonic, and supersonic interfacial crack propagation, (3) simulations of dynamic crack bifurcation phenomenon, and (4) simulations of naturally propagating three-dimensional dynamic fracture.

Keywords: Dynamic Fracture; Dynamic J Integral; Moving Finite Element Method; Fracture-Path Prediction

The Intensity of a Singular Near-Tip Field around Three Dimensional Vertex

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Singular stress field around a three dimensional vertex is examined via eigenfunction expansion and finite element analysis. Semi-analytical solution is obtained based upon the separation of variables, and the stress intensity of the near-tip field is calculated with the aid of the two-state M-integral. Numerical examples are illustrated for the vertex formed by a crack-tip line and a free surface of a three dimensional crack, and for three dimensional bi-material interface corners to demonstrate the effectiveness and accuracy of the present scheme.

Numerical Simulations of Unsymmetrical Dynamic Branching Phenomena

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Crack bifurcation phenomena are often observed in the dynamic fracture of brittle materials. In many experiments we have carried out for dynamic crack branching

phenomena, bifurcated cracks propagate asymmetrically, even if the applied loading is symmetrical. In some cases, one of the bifurcated cracks stopped, while other crack was continued propagating. Prediction of the fracture path in such phenomena is very important not only for academic interest, but also to prevent catastrophic failure of structures and to establish a safety design methodology.

The authors have already developed a moving finite element method based on Delaunay automatic triangulation. This method established numerical prediction technology for modeling dynamically kinking and curving fracture phenomena under impact loads. In order to evaluate the dynamic J integral values for dynamically branching cracks, a switching method of the path independent dynamic J integral was derived.

First, in order to clarify the mechanism of unsymmetrical branching phenomena and to estimate various fracture parameters? the generation phase simulation was carried out. In this simulation? the dynamic fracture was 'regenerated' in computer model. The dynamic fracture parameters were satisfactorily obtained, even immediately after crack branching, a region in which the close proximity of the bifurcated cracks tips created experimental measurement difficulties.

Furthermore, in order to investigate the applicability of the crack propagation direction criteria, the fracture-path prediction simulations were carried out for asymmetrically branching cracks. In the fracture-path prediction mode of the mixed-phase simulation, regarding the crack-propagation history (crack-length versus time relation) the propagation direction is predicted in each time-step according to considered propagation-direction criterion.

Keywords: Dynamic fracture, Dynamic crack bifurcation, Moving Finite Element Method, Dynamic J integral

Difraction of Shear Elastic Waves on the Thin Semi-Infinite Inclusion in an Anisotropic Space

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A class of dynamic mixed boundary problem on the diffraction of elastic shear harmonic waves on thin semi-infinite elastic inclusion is considered. It is assumed that the inclusion is located in elastic anisotropic space. In an arbitrary point of the space, a concentrated force is applied. On the surface of elastic inclusion the jumping boundary condition for displacement and stresses are given. Applying the Fourier integral transformation technique, the problem is reduced to the solution of the Winner-Hopf functional equations with the second order f-circulant matrix-function, which components are some transcendent functions. Taking into account the algebraic features of the f-circulant matrix-functions, its factors are obtained in a closed form. Using the Winner-Hopf modernized method (John's method), the Winner-Hopf functional equation is solved, which allows us to obtain the analytical expresions for the solution of the boundary problem. The analytical solutions of boundary problems allow to get: a) stress-strain fields of the elastic ideal anisotropy space; b) find out the influence of anisotropy of space and elastic properties of inclusion to the diffraction of shear elastic harmonic waves. Asymptotic formulas are obtained using of contour integral method and Jordan's lemmas, which, represented in the form of linear combinations of tabulated contour integrals, are convenient for numerical analysis in the proximity of the inclusion.

Keywords: Diffraction, Wave, Anisotropy, Factorization.

Numerical Simulation for Dynamic Elasto Visco-plastic Fracture under Shear Load

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In numerical simulation of dynamic elasto visco-plastic fracture, high strain singularity is observed near a propagating crack tip. Since this moving strain singularity induces various errors in numerical models, the development of accurate solution procedures is required to clarify the mechanism of dynamic elasto visco-plastic fracture. To obtain highly accurate solution, the boundary conditions near newly created crack surfaces have to be satisfied in numerical simulation method.

In this study, to overcome this difficulty, the moving finite element technique is extended to dynamic elasto visco-plastic fracture problems. First, we derive a variational principle to satisfy the boundary conditions near a dynamically propagating crack tip. Using this variational principle, we formulate a moving finite element equation.

Then, based on the large deformation theory and the Delaunay automatic triangulation technique, we develop a moving finite element method for dynamic elasto visco-plastic fracture under large deformation.

Another problem for dynamic elasto visco-plastic fracture is to find out the parameter to characterize the fracture under dynamic elasto visco-plastic large deformation. In this study, the T* integral is used as dynamic elasto visco-plastic fracture mechanics parameter. The T* integral can be used as a unified fracture mechanics parameter, because the T* integral is valid for fracture of all homogeneous materials and it also contains dynamic effects.

Next, dynamic elasto visco-plastic fracture behavior under shear load is simulated using this moving finite element method. An initial imperfection in the specimen thickness is introduced to cause a shear band and crack propagation in the shear band. The strain energy density distributions and the energy flux distributions are visualized. From the numerical results for these distributions and the T* integral, the limits of crack velocity are numerically found for the dynamic elasto visco-plastic fracture.

Keywords: Dynamic fracture; Elasto visco-plastic fracture; Moving Finite Element Method; T* integral

Symposium on

Electro-Magneto-Mechanics

Organizer:
Professor Y. Shindo
(Tohoku University)

ELECTRO-MAGNETO-MECHANICS

SESSION M3P
Magnetoelasticity I

Mechanics and Electrodynamics of New Materials: Magneto-poro-elastics (Penetrable Poroelastic Bodies Filled with Ferro-fluids)

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We consider the mechanical behavior of highly elastic, porous, penetrable bodies filled with a ferro-fluid. The major physical characteristic of materials (such as magnetic rubber) which include magnetic particles is that the phase having high magnetic permeability in magneto-poro-elastic bodies is continuous (due to their permeability). Thus, the total magnetic permeability of such materials remains very high, comparable to the magnetic permeability of ferro-fluids. Meanwhile, these bodies manifest the properties of solids and do not flow in the absence of an external magnetic field. Lastly, we show that magneto-poro-elastic materials can be prepared so that under the influence of a moderate external magnetic field the relative deformation can reach 1-10%.

These properties of magneto-poro-elastic materials make them attractive materials for many technological applications starting from new constructions of valves which could be controlled by external magnetic fields, adaptive optic devices, and even "dolphin skin" for the reduction of the hydrodynamic resistance of moving bodies immersed in a fluid.

In this presentation, we will present a detailed theory of the interaction of magneto-poro-elastic bodies with external magnetic fields based on a modified Frenkel-Biot theory of penetrable fluid filled bodies and discuss the behavior in the presence of an external field of membranes made from these materials.

We will also discuss several possible applications of these materials as elements of sensors, or as actuators.

Nonlinear Magnetoelasticity of Flat Structures Carrying an Electric Current: Foundation of the Theory and Behavior

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A geometrically nonlinear theory of electromagnetically conducting flat plates exposed to a magnetic field of an arbitrary orientation and carrying an electric current is developed.

It is assumed that the electric current vector **J** is parallel to the mid-plane of the plate, and of arbitrary direction in that plane.

It is also assumed that both the elastic and the electromagnetic media are homogeneous and isotropic.

The geometrical nonlinearities are considered in the von-Kármán sense, and the soft ferromagnetic material of the plate is assumed to feature negligible hysteretic losses.

Based on the electromagnetic equations (i.e. the ones by Faraday, Ampere, Ohm, Maxwell and Lorentz), and

elastokinetic field equations, the 3-D coupled problem is reduced to an equivalent 2-D one, appropriate to the theory of plates.

Having in view that the electrically carrying structures are highly susceptible to buckling, by using the presently developed theory, this problem and that of the postbuckling will be investigated. In this context, the problem of the electric current inducing the buckling instability of the plate will be analyzed and ways to enhance its electric current carrying capacity will be investigated. In the same context, the problem of the free vibration of flat plates as influenced by the electrical current is also addressed.

Keywords: Multifunctional materials; magnetoelastic stability; geometrical nonlinearities.

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Three Dimensional Numerical Simulation of Magnetic Microstructure

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In previous works, we have considered the numerical analysis of magnetostrictive materials at the microscopic scale. The associated modelizations are based on the minimization of the total energy functional of the system. The different studies include:

i) the study of existence of solutions both for uniaxial and cubic crystals; these solutions are approximated by combining minimization algorithms (augmented Lagrangian method, conjugate gradient method) with finite element methods [1,2];
ii) some numerical experiments for two-dimensional samples of magnetostrictive materials [3,4]. Corresponding results include computation of hysteresis curves, closure domains and mechanical deformations;
iii) the extension to ferromagnetic materials [5,6,7,8] with cubic crystal. In this case, we have mainly considered the thickness of the walls and their evolution under an incremental magnetic field applied to the cubic crystal as well as the effect of nonmagnetic inclusions. These numerical studies concern two-dimensional samples.

This talk discusses some extensions to:

i) the computation and the representation of three dimensional domains and Bloch walls for ferromagnetic materials;
ii) the case of polycristals: study of the closure domains for two adjacent rectangular or hexagonal crystals whose lines of easy magnetization have different orientations. This study starts with two-dimensional numerical simulations.

Keywords: magnetic microstructure, three dimensional domains, Bloch walls, polycristals.

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A Non-dilute Microstructural Model for Magnetorhelogical Elastomers

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A microstructurally based model for the effective elastic properties of a magneto-elastomeric composite are presented. When these composites are cured in the presence

of a magnetic field the magnetic particles form chains. Results are presented for the absence of an applied magnetic field and the change in elastic properties as a result of an applied magnetic field. In both cases, large volume fractions of magnetic particles are considered and thus the interaction of neighboring chains is considered. Results for the change in elastic properties through the application of a magnetic field are derived by extending the dilute results of Shkel and Klingenberg [1]. Issues pertaining to the microstructural optimization of these composites will also be addressed.

Keywords: homogenization, elastomer, magnetic

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ELECTRO-MAGNETO-MECHANICS

SESSION M4P

Coupled Problems

Finite Element Modeling and Simulation of Magnetostrictive Materials

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Magnetostriction is a nonlinear phenomenon observed in all ferromagnetic materials that couples elastic, electric and magnetic fields. Its industrial applications includes sensors, actuators, adaptive or functional structures, robotics, transducers, and microelectromechanical devices. While many of the aforementioned applications can at present be addressed by rather simple analytical methods, it is expected that in the near future new very small (MMA) or very big devices will require more sophisticated methods of analysis, most likely of computational nature.

In this work we formulate new governing equations, which are fully coupled, 3-D, non-linear (except for material properties), partially dynamic under small deformation and that also incorporate piezoelectric coupling effects. Through the manipulation of the Maxwell equations, it is possible to find appropriate expressions to develop the weak, Galerkin and matrix forms, including completely consistent tangent and inertial matrices.

The only assumed simplification is that the temporal variation of the electric displacement is negligible, due to the low frequencies at which these materials usually work. On the other hand, the principal characteristic of this formulation is the use of a magnetic potential (without clear physical meaning) so that the finite element method is of the displacement type, that is, it uses zero-derivative elastic displacement and electric and magnetic potentials as nodal unknowns.

Important effects, such as Eddy currents responsible for heat generation, can be directly evaluated. If technological developments make it necessary, other effects such as full thermal coupling, elastic dynamics and/or shock waves, and material non-linearity can be added by adapting advanced features from Computational Mechanics.

The formulation is implemented in the research finite element code *FEAP*. In order to validate both the method and the implementation, we present a comparison between numerical and specially developed analytical results for an electromagnetic simple problem with temporal variation. In addition we compare numerical and experimental results for the well-studied magnetostrictive miniactuator Etrema AA-140J. The first comparison agrees perfectly and the second very well.

Keywords: Magnetoestriction, Piezoelectricity, Finite-Elements, Miniactuators.

Mechanics of Cracked Ferromagnetic Plates in a Magnetic Field

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With the development of high-field superconducting magnets, problems involving the fracture and deformation of solids and structures in high magnetic fields have been become important. The stress and strain state in a magnetizable elastic body is caused not only by mechanical loads but also by magnetic fields. If ferromagnetic materials are used in the strong magnetic field, we must consider the effect of induced magnetization. In this paper, the magnetic fracture and deformation of soft ferromagnetic plates is investigated to show this effect. First, the linear magneto-elastic analysis and experimental evidence are presented for a soft ferromagnetic plate of finite length with a through crack under bending. The fixed-end through-cracked plate is bent by a normal line load applied at the center of the plate and is permeated by a

uniform static magnetic field normal to the plate surface. The classical plate bending theory of magnetoelasticity is applied. The moment intensity factor for bending stress loading is computed and the influence of the magnetic field on the normalized values is displayed graphically. A series of experiments are also conducted in the bore of a superconducting magnet at room temperature to verify the theoretical analysis results. Single through-cracked specimens made from ferritic stainless steel SUS430 are used to determine the magnetic moment intensity factor using electrical strain gages. The moment intensity factor is found to increase with increasing magnetic field. Experimental measurements verify the predictions of a theoretical model. Next, magneto-elastic problem for SUS430 double cantilever beam (DCB) specimens is analyzed. The beam-plate theory formulation for magneto-elastic interactions is used to analyze DCB specimens. A simple experimental procedure involving measurement of strain has been also developed to determine the stress intensity factor. A comparison of the stress intensity factor is made between theory and experiment, and the agreement is good for the magnetic field considered.

Keywords: Magnetoelasticity, Mechanical Testing, Soft Ferromagnetic Material, Stress Intensity Factor

Constitutive Modeling of Soft Ferromagnetic Materials

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A robust constitutive model is desirable in order to guide the processing and development of ferromagnetism and for use in the design of ferromagnetic devices. In this paper, both experimental and theoretical work performed on nonlinear constitutive modeling of ferromagnets are presented in this paper, which involve in three aspects:

1. The experimental setup and measured techniques by which the nonlinear deformation of both magnetostrictive and soft ferromagnetic materials subjected to coupled magnetomechanical loading are introduced. And the experimental results will be illustrated and analyzed.

2. Nonlinear deformation behavior of magnetostrictive materials is studied. In addition to an analysis for the Standard Square constitutive model, a Hyperbolic Tangent constitutive relation is proposed to model the magnetic-field-induced strain saturation of magnetostrictive materials. To characterize the moduli in two constitutive relations for one-dimensional problem, a material function is proposed to describe the relation between the peak piezomagnetic coefficient and the compressive pre-stress based on the experimental results. The accuracy of the nonlinear constitutive relations is evaluated by comparing the theoretical results with experimental results of a Terfenol-D rod operated under both compressive pre-stress and bias magnetic field.

3. A phenomenological constitutive model of ferromagnets is developed for general magneto-mechanical loading histories. This general structure for the constitutive behaviour of ferromagnets including soft-ferromagnetic and hard-ferromagnetic materials is similar to classical models of metal plasticity: a convex yield surface can be identified in a stress/magnetic field space, within which the deformation and magnetization are reversible; increments of remnant magnetization and remnant strain are normal to the yield surface. The state of materials is described in terms of the remnant strain and the remnant magnetization which are introduced as internal variables besides stress, strain, magnetic field and magnetization. The evolution equations of the internal variables are subjected to a rate-independent flow theory using kinematical hardening and a quadratic yield surface in a magnetic field and stress space. Such changes in remnant strain and magnetization can only occur when the yield condition is satisfied. The one-dimensional model will be examined by numerical stimulation and the response of the ferromagnetic materials will be discussed in comparison to the experimental results.

Keywords: Constitutive modeling, ferromagnetic material, magneto-mechanical coupling

Coupled Structural-Acoustic-Piezoelectric Dynamic Modeling of High-Frequency Undersea Transducers

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In order to understand the complex structureborne and fluidborne noise propagation physics within various undersea acoustic transducers, three-dimensional nonlinear dynamic Finite Element Analysis (FEA) is utilized in the present paper. Specifically, coupled structural, acoustic and piezoelectric dynamic simulations are carried out for

both Tonpilz-type and conformal 1-3 composite-type marine sonar arrays that model their performance in both (a) the structural and acoustic response resulting from electrical actuation of PZT ceramic array elements and (b) the PZT ceramic array element electrical response due to incident structureborne and fluidborne excitation.

First, the modeling of the noise propagation physics within layered 1-3 composite, half-wavelength resonator transducer arrays for high frequency, broadband underwater applications is presented herein. Various geometric configurations of the individual array layers are examined (e.g., relative PZT element spacing between layers, bond materials, joining layer thickness) to determine their effect on both array performance and structural integrity. The results of the present analyses are compared to experimental data collected on prototype layered 1-3 composite arrays.

Coupled three-dimensional dynamic analyses were also performed for two low-aperture Tonpilz-type transducer arrays designed for a very high-speed underwater research vehicle. Successful self-noise reduction in such high-speed sonar applications requires a precise knowledge of the prominent noise propagation paths within the array early in the design process. Also, laboratory shaker experiments performed in order to validate the modeling are also presented. (Keywords: FEA, Dynamic, Coupled, Piezoelectric)

Propagation of Spin Waves in a Periodic Layered Space

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The propagation of spin waves in the periodic piecewise homogeneous ferromagnetic space is analyzed. It is assumed that the structure is made of two periodic layers with different ferromagnetic properties and thickness. The vectors of an initial magnetization of the layers can be parallel to the applied magnetic field vector or can be antiparallel to it. It is shown that: a) the heterogeneity of the medium can change the character of propagation of spin waves as compare to the similar wave propagating in homogeneous medium; b) the spin waves can propagate in two opposite directions perpendicular to the one of applied magnetic field. Notice that, in the case of half-space the Damon-Eshbach spin waves propagate in a single direction perpendicular to that of the applied magnetic field. In addition, when the initial magnetization vectors are antiparallel, the model of the propagation of the spin waves in piecewise homogeneous antiferromagnetic materials is obtained.

Finally, when thickness of layers are equal to each other it is shown that, the frequencies of the long waves do not depend on the wave number.

Keywords: Ferromagnetic, wave, spin, piecewise homogeneous.

Magnetoelastic Vibrations and Stability of Ferromagnetic Plates and Shells

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On the basis of the theory of magnetoelasticity of ferromagnetic elastic bodies using Kirchhoff-Love hypothesis and applying the solution of asymptotic method for boundary problems of mathematical physics it is obtained the main equation and associated boundary conditions of magnetoelastic vibrations and stability of electroconductive ferromagnetic plates and shells (including cylindrical shells). Describing the behavior of noted bodies in magnetic fields the pertinent linearized problems of mathematical physics are addressed. Concrete problems are solved exploring own and forced vibrations, static and dynamic stability of conductive finite thin-walled ferromagnetic bodies. Note that known works [1] devoted to the problems of own vibrations and static stability of infinite plates. It is shown that:

- As the frequency of own vibrations as the damping coefficient of vibrations essentially depend on the value and orientation of magnetization vector of electroconductive thin-walled body.
- Ferromagnetic plates (cylindrical shells) can lose static stability under the action of constant longitudinal magnetic field. This possibility is shown in the works [2] in the case of transversal magnetic field;
- In thin-walled bodies forced and parametric type vibrations can be generated via time dependent harmonic magnetic field;
- The exception of possibility of parametric type resonant generation (caused harmonic forces) via stationar magnetic field.

The formulas are obtained for the critical values of magnetic field induction when the body loses the static stability, for the determination of the areas of dynamic instability and the amplitude of forced vibrations.

Keywords: Magnetoelasticity; Stability; Ferromagnetic; Plate.

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ELECTRO-MAGNETO-MECHANICS

SESSION T3P

Piezoelectric Fracture and Damage Mechanics

Electroelastic Fracture Mechanics of Piezoelectric Ceramics

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Piezoelectric ceramics have been extensively used in sensors and actuators. The main weakness of piezoelectric ceramics is their brittleness. Stress and electric field concentrations at defects can induce crack initiation and propagation, which will lead to the failure of these piezoelectric ceramics. Therefore, the problems of cracked piezoelectric ceramics have received considerable attention due to practical importance. However, the electrical boundary condition along the crack faces remains a debating issue when studying piezoelectric crack problems. Permeable and impermeable boundary conditions have been proposed for piezoelectric cracks.

The main aim of this paper is to report on recent theoretical and experimental developments which propose enhancement or retardation of crack propagation in piezoelectric ceramics by applied electrical loading. The first section discusses the effects of crack face boundary conditions of the piezoelectric fracture mechanics by analyzing the plane strain electroelastic problem of an orthotropic piezoelectric ceramic strip with a central permeable or impermeable crack. By the use of Fourier transforms, the mixed boundary value problem is reduced to a system of Fredholm integral equations of the second kind which is solved numerically to determine the fracture mechanics parameters such as stress intensity factor, energy release rate and energy density factor, etc. A finite element analysis is also employed to calculate these fracture mechanics parameters. The results for the permeable and impermeable boundary conditions are presented in graphical form and compared for a piezoelectric ceramic P-7. The second section presents the main results of experiments on the electrical loading dependence of cracking of P-7 and then presents the results of the finite element analyses of the piezoelectric specimen. The simulation results are compared to the experimental results.

Keywords: Fracture Mechanics, Finite Element Analysis, Material Testing, Piezoelectric Material

Experimental Study of Fatigue and Fracture of Piezoceramics

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In this presentation, the experimental study of fatigue and fracture of piezoelectric ceramics is introduced. The work consists of two parts, i.e., (1) Study of anisotropic fracture behavior of ferroelectric ceramics subject to combined electromechanical loading by using a moir interferometry technique; (2) Fatigue crack growth in ferroelectric ceramics driven by cyclic electric field:

1. The moiré interferometry was used to measure the strain concentrations near a crack tip and the crack-end open displacement in a PZT-5H ceramics subjected to combined electromechanical loading. The fringes analysis gives insight into the level of toughening related to domain switching. The results show that the strain decreases faster than values predicted by the theoretical analysis as the distance away from the crack tip increases. The strain not only concentrates at the crack tip but also significantly appears along the crack wake due to the in-plane 90° domain switching. Such kind of in-plane 90° domain switching for Specimen II (poled in the Y-axis) can lead to the CEOD decrease with the increase of the applied electric field. For Specimen I (poled in the Z-axis), the electric field seems to tough the material

due to the out-of-plane 90° "a-c" domain configuration. The higher toughness of Specimen I than that of Specimen II indicates an obvious anisotropic fracture behavior of the poled PZT-5H ceramics.

2. The electric-field-induced fatigue crack propagation of the ferroelectric ceramics with through pre-cracks is investigated. The experimental results show that there are two distinct fatigue mechanisms. That is, under low electric loading, the emergence and growth of micro-cracks is major fatigue mechanism, while under a high electric field, the propagation of the main crack is dominant. It was found in experiments that when a positive field is applied, the crack opens, while an applied negative field can make the crack close. The crack grew along the grain boundaries with the grain breakaway, and the main through crack propagates along the middle face perpendicular to the electric field. The crack growth rate is nonlinearly related to the cyclic electric load. Similar to mechanical fatigue, there exists a cracking threshold. When an applied electric field is less than the threshold value, the crack cannot propagate. A steady crack growth occurs after $E = 1.0E_c$. Theoretical analyses are made to predict the cracking threshold. Empirical relations are obtained to describe and predict the crack growth rate in the electric-field-induced fatigue.

Keywords: Electric fracture, Electric fatigue, Piezoceramics, Electromechanical coupling

Coupled Electromechanical Fracture of Electroceramics Subjected to Transient Thermal Loads

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This paper provides a fracture mechanics evaluation method for piezoelectric ceramics under thermal shock environments. The problem is idealized to the case of a plate containing an edge crack or an central crack that is perpendicular to the surfaces of the plate. The plate is initially at a zero temperature environment and is suddenly heated or cooled on their surfaces. The stress and electric displacement histories in an un-cracked plate are calculated. These stresses and electric displacements are added to the crack surface tractions and electric displacement with opposite sign to formulate the mixed boundary value problem. The cracking problem is reduced to two singular integral equations of Cauchy-type, which are solved numerically. Both electrically impermeable crack assumption and electrically permeable crack assumption are considered. The results for stress and electric displacement intensity factors are computed as a function of the normalized time and the crack size. Lower bound solutions are obtained for the maximum thermal shock that the material can sustain without catastrophic failure according to the two distinct criteria: (i) maximum local tensile stress equals the tensile strength of the medium, and (ii) maximum stress intensity factor for the pre-existing representative crack equals the fracture toughness of the medium. The parameters that govern the transient thermal stress and electric displacement level in the medium are identified. The method can be used to explore susceptibility to thermal fracture in piezoelectric materials on condition that it is possible to insert a pre-crack.

Keywords: Fracture; Electromechanical processes; Piezoelectric material; Thermal stresses

An Exact Solution for Doubly Periodic Cracks in Piezoelectric Materials Under Antiplane Shear

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It is well known that cracks which are separated by less than several cracks lengths interact such as to significantly alter the state of stress near the crack tips. The model of doubly periodic cracks is useful in understanding such an interesting interaction phenomenon among regularly distributed cracks. Furthermore, an estimate of the overall properties of damaged materials on the basis of an assumed periodic cracks has broader application and, indeed, provides limiting values for cases where actual periodicity may not exist. Fracture problems in piezoelectric materials have received considerable attention due to the development of a new technology of so-called intelligent materials and structures. However, to our knowledge, the studies have not been reported on coupled mechanical-electrical properties of piezoelectric materials with doubly

periodic cracks.

In this paper, a rigorous and effective method is developed for the problem of doubly periodic cracks in a piezoelectric material under antiplane shear. According to the periodicity and symmetry/antisymmetry of the problem, the boundary condition is exactly determined for a representative rectangular cell with two cracks on its boundaries. By using Jacobi elliptical function $\zeta = \mathrm{sn}(z/A, k)$ as the mapping function, the rectangular cell is transformed onto a complex half-plane and the problem is reduced to a Hilbert one, which results in a closed form solution.

The influence of the row and stack spacings of the cracks (The cracks on the same line are said to form a "row", and a "stack" is formed in the direction normal to the crack faces.) on the generalized stress intensity factors is examined. The numerical results show that decreasing the spacing of the cracks in the row tends to increase the generalized stress intensity factors, but decreasing the spacing of the cracks in the stack tends to decrease them.

The present solution is also used to estimate the effective electroelastic moduli. The electroelastic moduli in the crack line direction remain unchanged (i.e. independent of cracks), but the effective electroelastic moduli in the direction normal to crack faces decrease progressively with increasing the density in the row or in the stack. It is also found that the influence of the density in the row on the effective electroelastic moduli is much stronger than that in the stack.

It is concluded that the coupling mechanics of doubly periodic cracks requires two crack density parameters in the row and in the stack, respectively, instead of a crack density parameter in the case of random distribution of cracks.

Keywords: piezoelectric materials; doubly periodic cracks; stress intensity factor; effective electroelastic moduli

The M-integral Description for Microcrack Damage in Piezoelectric Materials under Combined Mechanical-electric Loading

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This paper deals with the M-integral description for microcrack damage in piezoelectric materials. The basic idea starts from the author's new findings about the conservation laws of the J_k-vector and the M-integral playing an important role in Damage Mechanics in traditional brittle materials (Chen, 2001, *Inter. J. Solids Struct.*, 38, pp. 3193-3212, 3213-3232). The goal of this paper is to extend this description from traditional materials to damaged piezoelectric materials, especially under purely electric loading or combined mechanical-electric loading. Multiple plane microcracks are assumed to be permeable and stationary. The M-integral formulation in piezoelectric materials is established. It consists of two parts. One is associated with the mechanical quantities and the other is with the electric quantities, although both kinds of the quantities are coupled in the constitutive equations of piezoelectric materials. Due to the global-local coordinate translations, the M-integral for multi-cracks is proved to be is divided into two distinct terms. One is induced from the relation between the integral and the field intensity factors (*SIF's* and *EDIF*) at all crack tips. The other is contributed from the local J_k-vector and the coordinates of each microcrack center. The latter is concerned not only with the field intensity factors, but also with the contribution arising from the traction-free and conducting surfaces of each crack. From the work did by Chen and Lu (2001, *Inter. J. Solids Struct.*, 38, pp. 3233-3249), the controversial dependence of the M-integral on the origin selection of global coordinates is clarified. Two numerical examples are given to confirm the derived conclusions. It is concluded that the M-integral analysis, from the physical point of view, does play important role and provide an effective measure in evaluating the damage level of piezoelectric materials with strongly interacting and randomly distributed microcracks.

Keywords: Piezoelectric, Fracture, Damage, M-integral, Microcracking

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ELECTRO-MAGNETO-MECHANICS

SESSION T4P
Modeling and Simulations for
Piezoelectric Material Systems

Damage Evolution Equation of Piezoelectric Ceramics and its Application to Simplified Analysis of Crack Growth

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Piezoelectric ceramics are used in a device of sensor or actuator under mechanical and electrical cyclic load-

ings. Thus, it is important to deal with fatigue of piezoelectric ceramics due to those loadings from the viewpoint of the fracture. In the present paper, damage development in piezoelectric ceramics under fatigue conditions is described by a damage variable based on the continuum damage mechanics, and an evolution equation of the damage variable is formulated. In the formulation, effects of electric field in the opposite direction of poling on fatigue life as well as effects of mechanical and electrical cyclic loadings are taken into account. Furthermore, the damage variable is incorporated into a constitutive equation of piezoelectric ceramics by using the modified cubes model. Then, fatigue life is predicted by using the damage evolution equation and the constitutive equation, and the validity of the formulation is discussed in comparison with experimental results. Finally, the damage evolution equation and the constitutive equation are applied to a simplified analysis of crack growth, which is called the double cantilever beam model. By using the model, analysis of a crack growth in a plate in the steady state is performed based on some assumptions to simplify the analysis. As a result of the analysis, crack growth rate and distribution of stress, strain and damage variable in front of the crack tip are clarified, and effects of electric field on them are discussed.

Keywords: Piezoelectric ceramics, Continuum damage mechanics, Damage evolution equation, Crack growth analysis

On the Nonlinear Behaviour of Dielectric Cracks in Piezoelectric Media

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Unlike traditional crack problems where the crack surface boundary condition is well defined, the electric boundary condition along crack surfaces in piezoelectric materials is still one of the fundamental issues needed to be further studied. There are two typical crack models using different electric boundary conditions, i.e. the electrically permeable and impermeable models. These models represent two limiting cases where the electric permittivity of the crack is assumed to be infinite and zero, respectively. Existing studies indicate that the permeable condition may underestimate the effect of the electric field on the crack propagation and the impermeable model may overestimate its effect. For a slit crack, since the dielectric constant of piezoceramic is much higher than that of the air (or vacuum) filling the crack, the electric boundary condition may be very sensitive to the crack opening caused by the applied mechanical and electric loads. In this case, the problem becomes nonlinear and the crack can be modelled as a dielectric crack filled with a dielectric medium.

It is the objective of the current paper to present a theoretical study of the nonlinear electromechanical behaviour of dielectric cracks in piezoelectric media. Based on the use of the dislocation model of the cracks and the solution of the resulting nonlinear singular integral equations, numerical simulation is conducted to study the effect of the dielectric medium filling the crack and the crack interaction upon the fracture behaviour of the medium. Special attention is paid to the transition between permeable and impermeable crack models with increasing crack opening displacement. Depending on the applied mechanical and electric loads, different deformation modes of the crack are predicted and discussed.

Two-Dimensional Electromechanical Analysis of Piezoelectric Ceramics

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With the development of MEMS microfabrication techniques, piezoelectric ceramics have been gradually used in microsensors and microactuators. The electromechanical coupling in piezoelectric ceramics provides the necessary mechanism in the microtransducers for sensing mechanical disturbances from the measurements of induced electric potential and for altering structural responses via external electric fields. However, piezoelectric ceramics in mechanical behavior are brittle and susceptible to cracking at all scales from microdomains to macrodevices. To improve the structural reliability of piezoelectric microdevices, it is necessary to study the electroelastic interaction in piezoelectric ceramics and the effect of electroelastic coupling on the damage and fracture processes.

The present work uses linear piezoelectric theory to study two-dimensional electromechanical interaction in piezoelectric materials with the consideration of the effect of surrounding dielectric medium, such as air. Integral transforms are used to reduce physical problems to the solutions of a set of integral equations, which lead to closed-form solutions to several specific problems. General expression of stresses, displacements, electric potential and electric displacements for transversely isotropic piezoelectric materials of the hexagonal crystal class 6mm have been obtained. Two special problems are considered here.

The first is the Griffith crack in an infinite piezoelectric material under electric and tension loading. By including electrostatic energy in the calculation of crack driving force, the energy release rate is found to be a third power function of the external load if electric field inside the crack is not zero at the electrode and a simi-inifinite piezoelectric medium. Closed-form solutions to the stresses and electric field distribution are given, in which a square root singularity of normal stress and charge density in the contact zone is found at the edges of the electrode for a plane electrode. Such a stress singularity at the edge of the electrode will even eventually induce the initiation of crack and introduce mechanical and electric instability.

Keywords: Piezoelectric, dielectric, crack, contact, singularity

A Mesoscopic Electromechanical Theory of Ferroelectric Films and Ceramics

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We present a multiscale modeling framework to predict the effective electromechanical behavior of ferroelectric ceramics and thin films. This paper specifically focuses on the mesoscopic scale and models the effects of domains, domain switching and the intergranular constraints. Starting from the properties of the single crystal and the pre-poling granular texture, the theory predicts the domain patterns, the post-poling texture, the saturation polarization and strain as well as the electromechanical moduli. We demonstrate remarkable agreement with experimental data with no adjustible parameters. The theory also explains the superior electromechanical property of PZT at the morphotropic phase boundary. The paper concludes with the application of the theory to predict the optimal texture for enhanced dielectric and piezoelectric constants, coupling factors and high-strain actuation in selected materials.

Eigenvalue Analysis for 2-D Piezoelectric Problems by the Time-Harmonic BEM

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We derive the fundamental generalized displacement solution using the Radon transform of governing equations and present the direct formulation of the time-harmonic Boundary Element Method (BEM) for two-dimensional piezoelectric solids. The fundamental solution consists of the static singular and the dynamics regular parts; the former, evaluated analytically, is the fundamental solution for the static problem and the latter is given by a line integral along the unit circle.

We apply the BEM to the determination of the eigen frequencies of 2-D piezoelectric domains. The eigenvalue problem deals with full non-symmetric complex-valued matrices whose components depend non-linearly on the frequency. We make a comparative study of non-linear eigenvalue solvers: QZ algorithm and the implicitly restarted Arnoldi method (IRAM). The IRAM is faster and has more control over the solution procedure than the QZ algorithm.

The use of the time-harmonic fundamental solution provides a clean boundary only formulation of the BEM and, when applied to the eigenvalue problems with IRAM, provides eigen frequencies accurate enough to be used for industrial applications. It supersedes the dual reciprocity BEM and challenges to replace the FEM designed for the eigenvalue problems for piezoelectricity.

Computation of Electrostatic Fields Around Overlapping Spheres and Cylinders

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The classical method of electrical inversion for an isolated sphere is generalized to composite geometries such as overlapping spheres and cylinders. It is assumed that the two spheres/cylinders intersect at a vertex angle π/n, n an integer, and the electric potential is constant

along the composite geometry. The generalized inversion method is utilized to compute general solutions to the electrostatic problem of a pair of intersecting, conducting spheres/cylinders placed in an arbitrary potential field. This greatly facilitates the solution of problems previously treated by *ad hoc* methods, especially in two dimensions where the method of conformal transformation can be used. Furthermore, the formulae for electric potentials provided here are ready-to-use basis functions and therefore could be used in the calculation of pair (as well as multiparticle) interactions of composite inclusions in electrostatic fields.

Several image systems - consisting of charges, dipoles, higher-order multipoles - are constructed for various electric potentials using the general solutions to demonstrate the power of the method. For the intersecting spheres, the fundamental quantities of interest such as capacity and polarizability (dipole moment) are computed. The polarizability tensor is found to be diagonal with different components for the directions parallel and perpendicular to the line of centers. The analytic results for capacity and polarizability can be very useful in estimating Stokes friction and intrinsic viscosity of macromolecules and also in validating numerical algorithms and codes on path-integration calculation of these physical quantities. An approximation is also proposed for the time-dependent rate of absorption of particles or the time-dependent flow of heat, starting from a uniform initial state of the environment.

Keywords: electrical inversion, capacity, polarizability, conducting spheres/cylinders

ELECTRO-MAGNETO-MECHANICS

SESSION R3P

Piezoelectric Buckling, Stability and Stability and Vibration

Enhancement Flutter and Buckling Capacity of Column by Piezoelectric Layers

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This paper illustrates the use of a pair of piezoelectric layers in increasing the flutter and buckling capacity of a column subjected to a follower force. The column is fixed at one end while the other is free to rotate but constrained transversely by a spring. The mathematical formulation is presented and solved numerically. The effect of the spring stiffness on the capacity and type of instability of the column is first illustrated numerically for the case without any piezoelectric actuators. A transition value for the stiffness can be identified, below which the column fails by flutter and above which the column buckles. Next, an external voltage is applied on the piezoelectric layers bonded on the surfaces of the column, which induces locally a pair of tensile follower force. This has the effect of increasing the capacity of the column as the voltage increases while the transition stiffness remains virtually unchanged for a given size and location of piezoelectric actuators. It is also shown that the capacity of the column increases with longer layers for a fixed voltage. However, the location of the layers along the column determines the transition stiffness and hence has an effect on the type of failure for a fixed spring constant. Positioning towards the fixed end increases the flutter capacity whereas positioning away will result in an increase in buckling capacity.

Dynamics of a Coated Piezoelectric Composite Bar

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Within the linear theory of piezoelectric materials which find use in intelligent structures, a system of one-dimensional equations is consistently developed to govern the dynamics of a laminated piezoelectric composite bars. The bar with rectangular cross section comprises of perfectly bounded N layers, each with a distinct but uniform thickness and electromechanical properties, and is completely coated with conducting electrodes on its faces. First, the fundamental equations of piezoelectricity are expressed by the Euler-Lagrange equations of a unified variational principle by the authors [Int. J. Engng. Sci., 34(7): 769-782,(1996)]. Then, by use of the principle, the system of piezoelectric bar equations is constructed in differential and variational forms for the case when the mechanical displacements and the electric potential of each layer vary linearly across the layer thickness. The system of equations accounts for the extentional, thickness shear, flexural, torsional and coupled motions of piezoelectric bar at low frequencies [Mindlin, R. D., Int. J. Solids Structures, **12**, 27-49,(1976)]. The significant electrical and mechanical effects in each layer, the interaction between layers and the electrodes are considered. Finally, the uniqueness is examined in solutions of the system of bar equations.

The results are shown to agree with and to recover some of the earlier ones[e.g.,Yang, J. S., Int. J. Appl. Electromagnetics Mech., **9**, 409-420,1998; Lee, H-J and Saravanos, D. A., AIAA Journal, 34(6), 1231-1237, (1996), the authors, Int. J. Nonlinear Mech., 37(2):225-243,(2002)] and emphasis is placed upon special cases. (Supported in part by TÜBA).

Keywords: Piezoelectric composite bars, vibrations of bars, uniqueness of solutions.

Equations of High-frequency Vibrations of Porous Piezoelectric Plates

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The aim of this paper is threefold: (i) to express the fundamental equations of a porous piezoelectric continuum with voids which adequately describe the physical behaviour of piezoceramics and alike, [e.g., Ciarletta, M. and Scalia, A., Meccanica, **28**, 303-308 (1993)], in variational form, (ii) to derive a system of 2-D equations for vibrations of porous piezoelectric plates and (iii) to investigate the uniqueness in their solutions. First, a porous field vector, that is, the gradient of the change in volume fraction, is introduced as a new concept which is analogous to the electric field or thermal field vectors [e.g., the authors, Int. J.Non-linear Mechs., **37**, 225-243 (2002)]. With the new concept, the principle of virtual work is expressed for the continuum and a three-field differential variational principle is obtained, and then it is augmented through Friedrichs's transformation and a unified variational principle is developed. Next, by use of the unified variational principle together with the series expansions of the mechanical displacements, the electric potential and the porous field vector in the thickness coordinate, the system of 2-D equations accounting for all the types of low- and high-frequency vibrations is established in invariant, differential and variational forms. Lastly, the results are shown to agree with and to recover some of earlier ones [e.g., the authors, Thin-Walled Structures, **39**, 95-109 (2001) and references therein] and the uniqueness is investigated in solutions of the system of plate equations. (Work supported in part by TUBA).

Keywords: porous and piezoelectric plates, variational principles, uniqueness of solutions

Computer Simulations and Design Optimizations of Piezoelectric Resonator

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In this work the design, analysis, and simulation of piezoelectric cantilever resonator are introduced. The piezoelectric cantilever was studied in order to create a micro-machined chemical sensor, which could be reliable and inexpensively mass-produced. The electrically driven cantilever resonant will have a chemo-selective polymer tip, which senses chemicals through the change of resonant frequency due to mass landed at the polymer tip. The quality factor, Q, measures the efficiency of a dynamic system and is defined by the total energy over the dissipated energy. Low Q values implies large amount of energy loss and also tend to produce noise interference in the signal. The purpose of the structural design is thus aiming at achieving highest Q value subjected to the constraints due to the function, size and strength requirements. Large-scale commercial programs such as MSC/NASTRAN and ABAQUS, were employed in this work for the mechanical and electromechanical analyses. Analysis-based design optimization process involves the structure with various shapes and dimensions while the 4 layers of thin films: SiO_2, Platinum, PZT, and Platinum and their thickness are kept fixed. Normal modes simulations give the natural frequencies and the vibration modes, while piezoelectric analyses predict the performance of the designed structure with the deflections and stresses under electrical loading. From the simulation results of the frequencies, deflections, and stresses, the best design is found. Also, the effects of the electric field, the dimension and the geometry of the structure on the performance of the resonator have been obtained.

Frequency Stability of Piezoelectric Resonators

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Piezoelectric crystal resonators are essential components for radios, telephones, missiles, satellites and other equipment for timing, frequency control, and communication. Ideally, piezoelectric resonators are supposed to work at a particular resonant frequency. This operating frequency must be designed and maintained with very

high precision. However, the frequency, and hence the performance of resonators, can be affected by various environmental effects that act as biasing fields in resonators. For example, a temperature change in the working environment causes initial biasing deformations in resonators. These deformations induce frequency-shifts in resonators. In addition, accelerations can cause frequency-shifts in resonators through mechanical biasing fields due to inertial forces. Such accelerations are relevant when resonators are mounted on moving objects such as missiles. Frequency stability analysis has been one of the major issues in resonator design and optimization. For resonators used in timing and frequency control frequency shifts are to be minimized. On the other hand, frequency shifts can be used to design sensors for detecting various biasing fields. After a brief review of the topic, this paper summarizes our recent work on the analysis of the frequency stability of piezoelectric resonators. This includes the analyses of frequency-shifts due to relatively large constant linear accelerations, frequency-shifts due to rotations at constant angular rate, and frequency-shifts under dynamic biasing fields. Some remaining issues that require further study are pointed out.

ELECTRO-MAGNETO-MECHANICS

SESSION R4P

Smart Sensors and Actuators

Control of Transient Deformation in a Heated Intelligent Composite Disk

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The problem of sensing and controlling the temperature-induced response of a composite circular disk is studied. The disk consists of a transversely isotropic structural layer onto which two piezoelectric layers of crystal class 6mm are perfectly bonded (Fig. 1). The middle piezoelectric layer acts as a sensor to measure an ambient transient temperature distribution on the free surface of the structural layer. Control of the elastic displacement distribution on the surface of the structural layer is achieved through application of a distribution of electric potential across the top piezoelectric layer. The analysis thus entails two parts: (i) solution of an inverse problem for the determination of an unknown transient heating temperature distribution based on measurement of the induced electric potential in the sensor layer; and (ii) solution of a control problem in which the distribution of the electric potential applied to the actuator layer is determined, such that the resultant displacement at the free surface of the structural layer has a desired distribution. The resultant response of the disk represents a superposition of the responses obtained from the inverse and control problems. Solutions to both problems are derived using potential functions and a finite difference approximation with respect to the time variable.

Numerical results are presented for an initially stress-free disk in which the structural layer is a graphite/epoxy composite, and the piezoelectric layers are cadmium selenide. The "measured" distribution of the induced electric potential is taken to be that obtained by solving a corresponding direct problem; i.e., a problem in which the transient heating temperature is specified. Numerical results for the resultant thermal, elastic and electric fields are presented graphically. Fig. 2, for example, shows the resultant radial distributions of the transverse displacements at layer interfaces when the control objective is zero displacement at the free surface of the structural layer.

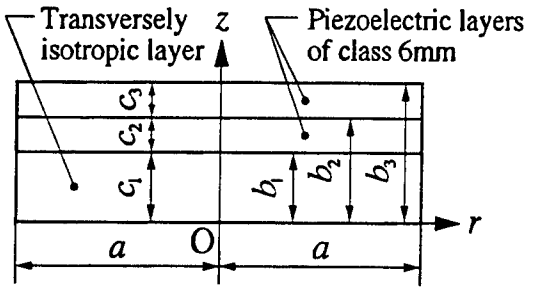


Fig. 1.

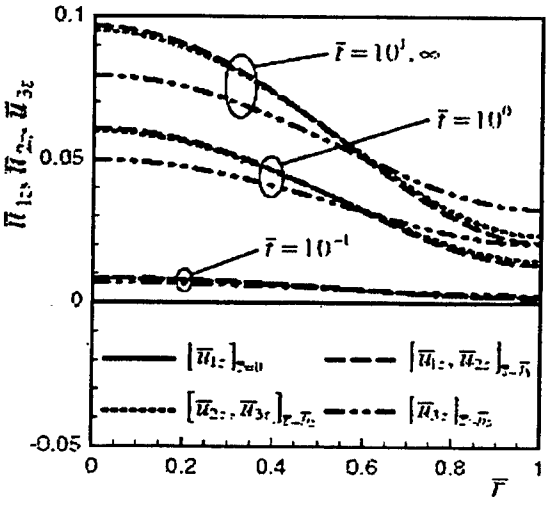


Fig. 2.

Keywords: Piezoelectric, control, thermal, composite disk.

Ultrasonic Imaging of Structural Damage Using Integrated Sensor Signals

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Piezoceramic sensors/actuators have shown the potential to receive/induce high frequency wave propagation in structures to which they are attached. The induced wave propagation from the actuators can be used for the online health monitoring of structures in conjunction with properly arranged sensors. The quantitative identification of possible damages requires detailed understanding of the distribution of the mechanical property of the structure. In spite of the fact that extensive studies on the global response of electromechanical structures have been conducted, much less has been accomplished in determining the localized behaviour of them. The current research work provides a theoretical study of the ultrasonic imaging of damages in elastic materials using a migration technique for identifying cracks. Unlike the traditional ultrasonic technique for damage detection based on the Pulse-Echo measurement, the current method includes the use of the detailed procedure of wave propagation in structures based on integrated sensor signals and a migration process. Numerical simulation indicates that the current technique can be used successfully to identify the position, length, orientation and shape of embedded cracks based on sensor signals obtained from the surface of the structure.

Keywords: Damage detection, Ultrasonic imaging, Wave propagation, Health monitoring

Active Vibration Suppression of a Gossamer Spacecraft

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Inflated space-based devices have become popular over the past three decades due to their minimal launch-mass and launch-volume. Once inflated, these space structures are subject to vibrations induced mechanically by guidance systems and space debris as well as thermally induced vibrations from variable amounts of direct sunlight. Controlling the vibrations and shape of space-based structures is critical to ensuring their optimal performance. Inflated materials, however, pose special problems when testing and trying to control their vibrations because of their extremely lightweight, flexible, and high-damped properties.

In this study, we showed that Macro-Fiber Composite (MFC) patches, which is recently developed at the NASA Langley Center and can be integrated in an unobtrusive way into the skin of the torus, could be used as sensors/actuators in order to find modal parameters. The data measured with the MFC patches has a good agreement with the measurements with an accelerometer. Further, it is obvious during the tests that the MFC excitation produced less interference with suspension modes of the free-free torus than excitations from the conventional shaker.

In order to control and reduce vibrations of the torus, we used positive position feedback methods since they are fairly robust to parameter uncertainties. Both separate sensor/actuator combination and self-sensing actuators have been used for vibration control. Our experimental results clearly indicate that this control strategy and actuators can reduce vibration, and provide the potential of smart materials for use in the dynamics and control of inflated structures.

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Micro-Actuators for Structural Control

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A compact, long stroke inertial actuator is developed to enhance the precision control of ground and space based structures. The goal is a compact actuator capable of producing 4.5 N of force over a frequency range from 5 - 1000 Hz. Scalable actuation materials and methods are investigated along with micro-electro-mechanical systems (MEMS) and microsystem fabrication techniques to produce a state of the art inertial actuator.

Three actuation candidates are piezoelectric materials, shape memory alloys (SMAs), and electrostatic forces. Piezoelectric materials are limited by total expansion, but have an actuation bandwidth typically exceeding 10 kHz.

SMAs have larger stroke capabilities than piezoelectric materials, but are limited by the material transformation rate, which restricts actuation to 30 Hz or lower. Electrostatic actuation methods scale down well; however, they must be formed into complex arrays to generate large forces and strokes.

Compared with meso-scale systems, scalable actuators offer a host of design benefits, including reduced system volume, increased heat dissipation, thin actuator elements, and risk reduction (multiple actuators vs. a single monolithic actuator). Fabrication of a scalable, compact, high force, low frequency actuator requires the use of high-aspect-ratio microstructures (HARMST), which allow the development of structural components able to withstand the stress and strain of moving a proof-mass. HARMST methods, such as thick photoresist techniques, lithographie galvano-formung, abformung (LIGA), and deep reactive ion etching (DRIE) are candidate fabrication processes.

A microactuator system arranged to yield increased stroke and force is presented. Using off the shelf materials, an inertial actuator is developed that produces 4.5 N from 16 - 1000 Hz. Other means to increase the stroke of this concept are being investigated to help achieve the 5 Hz design goal.

Keywords: MEMS, inertial actuator, proof mass

Formulation of Inertial Sensors based on the Classic Linear Plate Theory

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Recently, due to the needs of space navigation for satellites, precision targeting and mining positioning, miniature solid-state inertial sensors are highly demanded. Several techniques have been developed and commerciali zed, such as, ring laser sensors, hemispherical resonator gyro (HRG), fibre optical gyro (FOG), etc. Each one has its advantage and disadvantage. One common problem is that manufacturing of those devices is very difficulty, especially for HRG. The advantage of HRG, for instance, it has no any magnetic field and can still works even electric power be cut off in extreme environment with rapid temperature changes. It is fundamental component of precision war-head.

To make the inertial sensors smaller, light, affordable and reliable, the new concept sensors should be proposed. This paper has investigated possibility of using piezoelectric plate for vibratory inertial sensors. The G force has been founded based on the rotation perturbation of vibrating plate. All the formulation is based on classical theory of plate and gyro theory. It is hope that this plate-type inertial sensor can replace HRG in some applications.

Effects of Static Electric Field on the Fracture Behavior of Piezoelectric Ceramics

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The presentation provides an overview on experimental observations of the failure behavior of electrically insulating and conducting cracks in piezoelectric ceramics. The experiments include the indentation fracture test, the bending test on smooth samples, and the fracture test on pre-notched (or cracked) compact tension samples. For electrically insulating cracks, the experimental results show a complicated fracture behavior under electrical and mechanical loading. Fracture data are greatly scattered when a static electric field is applied. Statistically based fracture criterion is likely required. For electrically conducting cracks, the experimental results demonstrate that static electric fields can fracture poled and depoled lead zirconate titanate ceramics and that the concepts of fracture mechanics can be used to measure the electrical fracture toughness. Furthermore, the electrical fracture toughness is much higher than the mechanical fracture toughness. The highly electrical fracture toughness arises from the greater energy dissipation around the conductive crack tip under purely electric loading, which is impossible under mechanical loading in the brittle ceramics.

Piezoelectric Passive Distributed Controllers for Beam Flexural Vibrations

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Recent technological developments made available efficient bender transducers based on piezoelectric effect. In this paper an electrical circuit analog to Timoshenko beam is synthesized using a Lagrangian method and by paralleling capacitive flux linkages to rotation and transverse displacement. A PEM beam is conceived by uniformly distributing piezoelectric transducers on a beam and interconnecting their electric terminals via the found analog circuit, completed with suitable resistors.

The high performance features of the synthesyzed novel circuit include: i) the circuit topology is extremely reduced, the used components are all but one two terminal

elements, and the only two port network needed is an ideal transformer; ii) one and the same dissipative circuit assures a multi resonance coupling with the vibrating beam and the optimal electrical dissipation of mechanical vibrations energy; iii) for a prototype PEM beam the design of the analog circuit is possible and the obtained nominal values of the circuital elements assure they can be technically realized without any external feeding.

The insertion of resistors in the analog circuit is determined according to optimality criteria, based on specific engineering needs.

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Symposium on

Mechanics of Thin Films and Other Small Structures

Sponsored by
ASME Electronic Materials Committee

Organizer:
Professor Zhigang Suo
(Princeton University)

Dr. Rui Huang
(Princeton University)

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION M2D
Deformation, Fracture, and Mass Transport A

Mechanics of Propagating Buckle Delaminations

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Thin films subject to compressive stress are susceptible to buckle delamination wherein an initially debonded region of the film buckles away from the substrate supplying elastic energy to drive the interface delamination. This type of film failure is widely observed and generic to many film/substrate systems. The shapes of the propagating buckles takes a number of forms, including shapes that are circular, straight-sided and the intriguing telephone cord morphology. Recent observational work on the morphologies using atomic force microscopy and focussed ion beam slicing will be discussed along with some new theoretical simulations of the telephone cord blisters. The underlying mechanics explaining the relative frequency of the telephone cord morphology relative to other shapes will be presented. Experimental and theoretical results on the role of substrate curvature on the propagation of the blisters will also be presented. The work has been done in collaboration with A. G Evans, H. M. Jensen and M. Moon.

Keywords: Delamination, thin films, buckling, instabilities

A Mechanism for the Premature Failure of Cyclically-Loaded Polycrystalline Silicon Thin Structural Films

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Based on the generally accepted fatigue mechanisms for brittle and ductile materials one would not expect single and polycrystalline silicon to be degraded by cyclic stresses. However, recent work has established that thin, micron-scale, films of single- and poly-crystalline silicon are susceptible to premature failure under cyclic loading conditions. Silicon films subjected to stress amplitudes of approximately one half of the single-cycle fracture strength exhibit lives $\sim 10^9$ cycles. However, the mechanism(s) of such failures have remained a mystery. In this presentation, we describe a mechanism for the fatigue of thin-film LPCVD polysilicon based on extensive stress-life fatigue testing and high-voltage transmission electron microscopy. It is proposed that the fatigue process is "surface dominated" and involves the mechanically-induced thickening of the native oxide film, followed by environmentally-assisted subcritical cracking of the thickened film.

Compressed Elastic Islands on a Viscous Layer: Expansion, Wrinkling, and Fracture

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A technique has been developed recently to fabricate SiGe film islands on a glass layer, which in turn lies on a silicon substrate. The islands are initially under an in-plane compressive strain. Upon annealing, the glass flows and the islands relax. The resulting strain-free islands can be used as substrate to grow epitaxial optoelectronic devices. This paper models the annealing process. A small island relaxes by inplane expansion. Because of the viscosity of the glass, the relaxation starts at the island edges, and moves toward the island center. A large island wrinkles before the inplane relaxation reaches the center. After some time, the wrinkles may disappear when the inplane relaxation arrives. Alternatively, the wrinkles may cause tensile stress in the island, leading to fracture. We model the film island by the von Karman plate theory, and the glass layer by the Reynolds lubrication theory. The solid and the fluid couple at the interface by traction and displacement continuity. The inplane displacement and the vertical deflection evolve simultaneously. A combination of experiments and calculations describes the conditions under which the islands relax by inplane expansion without significant wrinkling and fracture.

In-situ TEM Observations of Cracking of Interfacial Films

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Microelectromechanical systems are ideal tools for conducting fatigue experiments on small structures. When integrated with electron microscopy techniques, microelectromechanical testing systems provide unique platforms for investigating micromechanisms of fatigue crack propagation along interfacial thin films. We present two examples from our recent work where piezoelectrically actuated microelectromechanical systems were built to examine fatigue crack growth along interfacial thin films. The first example investigates fatigue cracking of the grain boundary film in a polycrystalline ferroelectric ceramic where field-induced cavitation and ligament bridging played a significant role. The second example examines fatigue crack growth in a metallic thin film confined by the rigid substrates, where the stress-induced voiding of the thin film was the dominant fatigue crack growth mechanism. Mechanics of piezoelectric driving force for the crack growth in the microelectromechanical systems will be given and analyses of the pertinent crack growth mechanisms will be discussed.

Models for the Nonlinear Switching of Ferroelectrics

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Ferroelectric ceramics such as lead-zirconate-titanate (PZT) and lead-lanthanum-zirconate-titanate (PLZT) are used as transducers in sensing devices and as actuators in active control systems. Actuation displacements and forces are generated by the piezoelectric effect, but ferroelectric/ferroelastic depolarization occurs when the forces generated become too high, thereby destroying the actuation of the device. Measurements of the processes of polarization, depolarization and switching for a polycrystalline ceramic have provided insight into the combined electromechanical response of ferroelectric ceramics. This response is modeled as the average of the domain wall motion controlled repolarization behavior of individual grains. The result is a constitutive law for the single crystal switching behavior of ferrolectric materials. Based on experimental results and a domain-averaged model of polycrystalline materials, a nonlinear constitutive law is developed for ferroelectric ceramics that accounts for switching. This model is phenomenological and contains internal variables representing the degree of strain and electrical polarization as well as their principal directions. There is a close connection to kinematic hardening laws in the plasticity of metals. The driving force for switching is phrased in terms of applied stress and field with critical conditions depending on the current state of polarization. Switching saturation occurs when all possible domains have experienced reorientation. The resulting

constitutive law is useful in finite element calculations of the response of a ferroelectric ceramic in critical locations in devices such as at crack and electrode tips. Examples are given of switching zones around electrode and crack tips.

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION M3G

Microelectronics, MEMS and Coating A

Thermo-mechanical Challenges of Cu/Low k Interconnects

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As the interconnect scaling down to deep submicron regime, it begins to dominate overall RC delay of the device. This makes the transition of dielectric materials from SiO_2 to low-k essential. The drastic deterioration in mechanical properties of low-k materials has led to serious process challenges in both integration and assembly. As a result, the thermo-mechanical stability has emerged as a major reliability concern with interfacial delamination and ILD cohesive fracture being the leading failure modes. Another fundamental change of low-k ILD films is their tensile intrinsic stresses in comparison of compressive ones enjoyed by conventional SiO_2 based materials. This paper will review mechanical properties of low-k materials, describe a set of thin film characterization metrologies and review their merits based on low-k and ULK data. In addition, potential failure modes relevant to current interconnect feature size will be discussed along with some scaling trends moving forward.

Material and Reliability Issues of Copper/Low k Damascene Interconnects

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Copper/low k interconnects is needed to replace the aluminum/silicon dioxide metallization beyond the current 130nm device generation. In spite of the extensive effort from the semiconductor industry, the implementation of low k dielectrics has been delayed for about three years. The basic difficulty arises from the weak thermomechanical properties of the low k dielectrics. This will be examined focusing on the correlation of dielectric polarizability and bonding characteristics and the tradeoff between dielectric constant and mechanical properties. The development of porous low k materials is discussed and its challenge is highlighted by recent results obtained on the porosity effect on material properties of porous organosilicate films. The impact of material properties on reliability will be examined and recent results obtained on thermal stresses and electromigration for Cu damascene structures will be discussed.

Chemistry at Interfaces and Adhesion

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Interfacial adhesion plays a significant role in determining the overall reliability of many technologically important devices. For microelectronics, in particular, adhesion can determine the overall mechanical integrity of the structure especially when considering processes such as CMP. However, it is not only mechanical reliability that may be affected by the adhesive properties of interfaces but also the electrical robustness of the device in such processes as electromigration. This work reports on progress made at understanding how adhesion and overall device reliability are related.

Mechanics of Stress Voiding in Thin Films

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Stress voiding in metals is critical to the reliability of interconnect structures in semiconductor devices. It is a wearout mechanism of diffusion process driven by the stresses that arise from the mismatch in thermal expansion of metal and dielectric used in the structures. In the last three decades considerable advances have been made to understand the stress voiding in aluminum, and most recently, focus has been shifted to copper in modern advanced interconnects. In the former case aluminum is isotropic while in the latter copper is anisotropic. Our understanding of stress voiding in aluminum encapsulated in an oxide dielectric cannot be translated to copper in the same dielectric or low permittivity dielectrics being introduced to enhance interconnect circuit performance. In this talk we present the mechanics of stress voiding in an anisotropic metal film that consists of various grains with different orientations. Because of the anisotropy

stress voiding highly depends on film textures, and it is enhanced by grain boundary sliding due to the elastic mismatch across grain boundaries. The results are discussed and compared with experiments in the context of nucleation and void growth in both copper and aluminum thin films capped with various dielectrics.

Current-Induced Fatigue in Chip Level Interconnects

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Aluminum interconnects on silicon-based substrates have been tested using high current density a.c. cycling. Joule heating within the lines induced temperature cycling over ranges of approximately 29-177 K during low frequency (100 Hz) testing at rms current densities in the range 6-14 MA/cm^2. Differential thermal expansion between the aluminum and the substrate resulted in a cyclic total strain amplitude in the range 0.06-0.35%, and corresponding biaxial cyclic stress amplitudes of approximately 61-368 MPa. We will present observations of damage and lifetime behavior in these interconnects that are partially consistent with conventional fatigue approaches to damage evolution. For instance, damage during early stages of cycling showed site selectivity, with surface offsets being confined to individual grains. Continued cycling increased the severity of damage, as well as the proportion of surface area damaged, with final failure occurring in the form of open circuit. This happened at locations where the interconnect thinned down excessively, presumably due to localized plasticity and melting. Some observations are not easily described by conventional fatigue concepts as applied to bulk metals, such as lack of lower energy dislocation arrangements after millions of cycles, absence of microcracking, and the formation of whiskers. Effects of current density, interconnect geometry, and encapsulating materials will be discussed. We suggest that thermomechanical fatigue may pose an important reliability problem for copper-low-k dielectric interconnect systems in the context of low frequency operation, energy-saving modes, and power cycling.

Keywords: ac electromigration, interconnect reliability, thermomechanical fatigue, thin film fatigue

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION M4G
Nanostructures and Nanomechanics A

Semiconductor Nanostructures: Phase Separation, Self-Assembly, and 3D Quantum Dot Crystals

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Recently, semiconductor nanostructures have shown significant promise for a wide range of electronic, optoelectronic, and photovoltaic applications. In this talk, I will discuss various methods for synthesizing semiconductor nanostructures, including phase separation-induced alloy nanostructures and strain-induced self-assembled quantum dots. I will show how we have used these nanostructures for fundamental studies of the mechanisms of amorphous-crystalline transitions and alloy phase separation, as well as the first direct atom level measurements of very short interdiffusion and segregation lengths [1,2]. I will also present a novel scheme for the design and synthesis of three-dimensional quantum dot crystals.

[1] B. Lita, R.S. Goldman, et al, Appl. Phys. Lett. 75, 2797 (1999).

[2] B. Lita, R.S. Goldman, et al, Surface Review and Letters 7, 539 (2000).

[3] This work is supported in part by NSF, DOE, AFOSR, ARO, DARPA, TRW, and ACS-PRF.

Stable Islands by Height-Constrained Stranski-Krastanov and Lithographically-Induced Self-Assembly

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We present theoretical studies of two methods to produce stable island arrays. In height-constrained Stranski-Krastanov growth, we show that placing a ceiling above

a thin film during annealing can reverse the role of elasticity, which normally causes the islands to coarsen. With elastic and surface energies providing refining and coarsening actions, respectively, it is possible to obtain equilibrium island sizes. In lithographically-induced self-assembly, the two competing forces are electrostatic and surface energies. Motivated by experimental observations of stable island arrays, we present an explanation for the stability. The electrostatic energy serves as the refining force while surface energy remains the usual coarsening agent. The two theories suggests a few experimentally controllable parameters that can be tuned to obtain the desired stable island diameters.

Formation of Nanocrystal Islands During Heteroepitaxial Growth

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Growth of nanocrystal islands by heteroepitaxy techniques has attracted the attention of many researchers recently due to the potential applications of the nanostructures. The islands are generally fabricated under the Stranski-Krastanow (SK) growth mode where a film first grows layer by layer on a substrate and then evolves into three-dimensional islands/structures. It was commonly observed that the morphology of the three-dimensional structures as well as the kinetic pathways of the formation process could vary significantly even for similar material systems and growth conditions. The causes of the differences, however, are still an open question, indicating limited understanding of the formation of islands during the SK growth. In this paper we present our theoretical investigation on this issue, based on a continuum model for the SK heteroepitaxial systems. Of particular interest here are the effects of the energetic forces in the systems on the island formation process. The energetic forces include the mismatch strain between the film and the substrate, the film surface energy, and the film-substrate interaction. The effects are determined by energy analyses for the islands and by three-dimensional simulation for the morphological evolution during the SK growth. The results are compared with the experimental findings, revealing possible explanations for the different island formation processes in the experiments.

Keywords: Nanocrystal, Island Formation, Heteroepitaxy, Stranski-Krastanow Growth.

A Continuum Description of the Evolution of Stepped Surfaces in Strained Nanostructures

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As a departure from the many continuum analyses of stability and evolution of surface shape that have been reported for crystalline materials, this paper provides a description of surface evolution based on the physics of the main feature imposed by the discrete nature of the material, namely, crystallographic surface steps. It is shown that the formation energy of surface steps depends on the sign of extensional strain of the crystal surface, and this behavior plays a crucial role in surface evolution. The nature of this dependence implies that there is no energetic barrier to nucleation of islands on the growth surface during deposition, and that island faces tend toward natural orientations which have no counterpart in unstrained materials. The continuum framework developed is then applied to study the time evolution of surface shape of an epitaxial film being deposited onto a substrate. The kinetic equation for mass transport is enforced in a weak form by means of a variational formulation. It is found that islands evolve with the features that were identified from the energy arguments. The implications of the calculations are shown to be consistent with the behavior observed during deposition of semiconductor materials in recently reported experiments. The parameters in the continuum description are obtained from atomic scale simulations.

Critical Layer Thickness in Stranski-Krastanow Growth of Ge on Si(001)

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The physical factors that control the critical wetting layer thickness in Stranski-Krastanow growth have re-

mained unresolved. Here, we report results of density-functional calculations that demonstrate a key role played by the surface reconstruction of the initial layers. We show that, in the prototype Ge/Si(001) system, the assumption that the (2 × 1) reconstruction of the Si(001) substrate is preserved during the growth leads to an underestimation of h_c. Proper inclusion of (2 × N) reconstruction and buckling as stress-relieving mechanisms, however, leads to delayed islanding with h_c equal to the experimental value of three monolayers.

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION T2D

Deformation, Fracture, and Mass Transport B

Modeling Plasticity in Polycrystalline Gold Thin Films on Silicon Substrates

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Modeling plasticity in gold thin films on silicon substrates is discussed with particular reference to the evolution of stresses during thermal cycling. Following the work of Kobrinsky and Thompson, we show that plasticity of unpassivated Au films is dominated by constrained diffusional flow of matter from the free surface of the film to the grain boundaries. This diffusional effect depends strongly on film thickness, as expected. The presence of a 10 nm thick passivation layer of W inhibits these diffusional relaxation processes and causes the stress evolution in the film to be dominated by dislocation flow. It is shown that a simple kinematic strain hardening law for plasticity, suggested by Suresh, together with a temperature dependent elastic modulus, provides a good phenomenological account of the stress-temperature curves for passivated films. Using this modeling approach it is possible to draw a distinction between the yield strength of the film and the strain-dependent flow stress. Models of multiple misfit dislocation formation, developed separately by Willis and Freund, are used to rationalize the linear kinematic hardening laws used in this modeling. Efforts to model the stress-temperature behavior of unpassivated films by combining the effects of diffusional relaxation and dislocation mediated strain hardening will be reported.

In-situ Nanoindentation, a Novel Method for exploring thin film Mechanical Behavior

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Nanoindentation has become the primary method for quantifying the mechanical properties of thin film materials. However, a mechanistic understanding of the phenomena occurring during nanoindentation of thin films is still lacking. We report results from our development of a new technique, that of in-situ nanoindentation within the transmission electron microscope. With this technique, we can observe in real time and at high spatial resolution deformation behavior and, in most instances, correlate this with quantitative load – displacement characteristics of the indentation. In our experiments, a relatively sharp diamond is positioned at the edge of an electron transparent thin film using a combination of mechanical and piezoceramic actuation. The actual indentation is performed in a voltage-controlled manner, through piezoactuation alone. In this presentation, we will detail the necessary steps required to obtain accurate, reproducible quantitative information, with particular attention paid to issues related to load frame compliance and the actuation characteristics of the piezoceramic. Results from the indentation of aluminum films on silicon will demonstrate the utility of the technique. We find that in aluminum the onset of plastic deformation is accompanied by the sequential nucleation and propagation of geometrically necessary prismatic dislocation loops into the material, which act to accommodate the volume of the diamond within the material bulk. Additionally, we will present results on the the effect of grain size and proximity of the indenter to grain boundaries on indentation behavior.

Discrete Dislocation Plasticity for Small Scales

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Continuum descriptions of plastic deformation have found applications from the length scale of large-scale structures down to the length scale of grains in a polycrystalline material. At small length scales, it is necessary to account for the discreteness of slip systems inside individual grains, but the plastic part of deformation is still modeled in a continuum sense. With continued miniaturization, a limit to the applicability of continuum descriptions of plastic flow is reached. At sufficiently small sizes, the discrete nature of dislocations induces a length scale of the same order of magnitude as the size of the component or of the wave length of the deformation or stress field.

Discrete dislocation plasticity provides a description of plastic flow in which dislocations are treated individually, as line singularities in an elastic continuum. Determining the stress and deformation field of a body with dislocations essentially is an elasticity problem; but a very complex one, due to the singularities and the presence of boundaries. A methodology has been developed that decouples these two difficulties and allows arbitrary boundary-value problems to be solved. The physics of dislocation motion, annihilation, generation and pinning at obstacles is supplied in terms of relatively simple rules: the constitutive equations. This paper will first summarize the approach, with an emphasis on the implementation for three dimensional problems. The role of boundaries and the accuracy of satisfying the boundary values are highlighted. Next, the application of dislocations in a quantum dot is discussed, in order to address the issue of the critical size for dislocation nucleation. Also, a few two-dimensional applications are presented, including the problem of stress relaxation in a thin film.

Crack-Like Grain Boundary Diffusion Wedges in Thin Films on Substrates

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We have been studying a new class of defects called the grain boundary diffusion wedges in polycrystalline thin films. These diffusion wedges are formed by stress driven mass transport between the free surface of the film and the grain boundaries during the process of substrate-constrained grain boundary diffusion. The mathematical modelling involves solution to integro-differential equations representing a strong coupling between elasticity and diffusion. We show that the solution can be decomposed into diffusional eigenmodes reminiscent of crack-like opening displacement along the grain boundary which leads to a singular stress field at the root of the grain boundary. We find that the theoretical analysis successfully explains the difference between the mechanical behaviors of passivated and unpassivated copper films during thermal cycling on a Si substrate.

An important implication of our theoretical analysis is that dislocations with Burgers vector parallel to the interface can be nucleated at the root of the grain boundary. This is a new dislocation mechanism in thin films which contrasts to the well known Mathews-Freund-Nix mechanism of threading dislocation propagation. Recent TEM experiments at the Max Planck Institute have shown that, while threading dislocations dominate in passivated metal films, parallel glide dislocations dominate in unpassivated copper films with thickness below 400nm. This is fully consistent with our theoretical predictions.

Interfacial Failure of Thin Epoxy Films

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Interface adhesion is a key factor in controlling the reliability of thin films. It is particularly important in components with thin polymer films on metal substrates where changes in composition and structure during processing and service can lead to interfacial failure. There is also a move to thinner bond lines than we have used before. Nevertheless, our understanding of interfacial failure in these systems is limited. We have therefore begun a program to determine the fracture susceptibility of Epon 828/T403 on aluminized glass substrates. The films were spin coated onto aluminized substrates to four thicknesses ranging from 24 nm to 11.8 mm. Nanoindentation test techniques were combined with deposition of highly stressed overlayers to induce delamination and blister formation from which interfacial fracture energies

were obtained using mechanics-based models. The resulting fracture energies decreased with film thickness and approached a lower limit for films less than 200 nm thick. However, this limit is significantly higher than the true work of adhesion for this film system. This suggests that inelastic or plastic dissipation processes operate even in the thinnest films we can test. In this presentation, the test and analysis techniques will be discussed and used to show that practical works of adhesion can be obtained for the very thin polymer films used in this study.

This work supported by U.S. DOE Contract DE-AC04-94AL85000.

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION T3Q

Microelectronics, MEMS, and Coating B

Pull-in Voltage of a MEMS Microphone

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A useful configuration for a MEMS transducer intended to convert acoustic signals into electric signals is a parallel plate capacitor. One plate of the capacitor is rigid, or nearly so, and the other plate is sufficiently flexible to respond to acoustic pressures in the audible range. The two plates are closely spaced with an air gap between them, and the rigid plate is typically perforated with many holes to avoid pressure buildup in the gap. A fixed bias voltage is maintained between the plates. As the pressure is applied to the flexible film, the gap changes size and a current is induced in order to maintain a fixed bias voltage. The plates of a capacitor are oppositely charged, so they exert an attractive distributed force on each other. This pressure depends locally on the gap spacing, and it acts to reduce the gap dimension from its initial value. This is a strongly nonlinear attractive force with the potential for inducing an instability, with the capacitor plates collapsing together. This occurs at a voltage level called the pull-in voltage, a critical system parameter for design. Nonlinearity in the elastic response of the solid can be a significant stabilizing influence. Estimates of the pull-in voltage in terms of material and geometrical parameters of typical systems are discussed.

The Mechanics of Thick Deposited Layers and Their Implications for Practical MEMS

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MEMS devices are being developed with high mechanical, thermal and electrical power densities. These "Power MEMS" are being considered for portable electrical power applications as alternatives to battery technology. The mechanical power densities that can be achieved are directly proportional to the strength of the materials that are used as the prime movers. Furthermore, for a given power density, the total power available scales with the volume of material under stress. These system requirements drive towards the creation of high strength materials and structures with scales which push the upper limits of what can be realized by traditional microfabrication technologies. Deposition processes are attractive means of creating such structures, however there are significant mechanics issues associated with their use. In particular the control of residual stress is key. The presence of residual stress affects the ability to control down stream processes, such as planarization and wafer bonding and in extreme cases can lead to fracture of the deposited material.

Experimental results are presented from two material development efforts, for silicon carbide and silicon dioxide. In both cases chemical vapor deposition processes were used to create layers in the range 10-100 μm thick on silicon wafers. Wafer curvature measurements at varying temperatures were used to quantify the thermal and "intrinsic" components of the residual stress. Microscopy and elemental analysis were used to identify the factors affecting the residual stress levels and this information was utilized to achieve process control. For the case of silicon oxide, a systematic study of the thickness dependence of film cracking was also carried out. The implications of these material and process development activities on the MIT Microengine will be discussed.

Design of Multilayered Polysilicon for MOEMS Applications

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A mechanical analysis of a multilayered polysilicon laminated system, constructed by alternating deposition

of low-pressure chemical vapor deposition (LPCVD) polysilicon at two different temperatures is presented. The different crystallization behavior at the two temperatures results in misfit strains that can be exploited to control the radius of curvature of released structures. We describe a semi-empirical method for estimating the nonuniform misfit strain distributions associated with the two temperatures, and using these to design laminated systems for prescribed curvature.

The Mechanical Behavior of LIGA Ni Structures for MEMS applications

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LIGA (a German acronym for lithography, electroplating and molding) is a micromachining technology used to produce MEMS devices from metals, ceramics or plastics. Electroplated LIGA Ni structures offer higher aspect ratios and greater functionality than traditional vapor deposited thin films. LIGA Ni structures have been found to have an attractive balance of room temperature properties, but these properties have been found to be extremely sensitive to processing parameters. This variation in properties is closely tied to the fact that the underlying microstructures are deposited far from their equilibrium condition. Our current understanding of the effect of electroplating parameters on these non-equilibrium microstructures is currently rather limited, and this point is exacerbated by the fact that thermal exposure can lead to significant changes in both microstructure and properties. These points will be illustrated in a structure-properties case study of LIGA Ni structures that were considered as candidate materials for a MEMS safing/fuseing and arming device. Microsample tensile, creep and fatigue test were conducted to measure a full range of mechanical properties, and microstructural observations were used to explain the observed mechanical behavior. Variations in Young's modulus of 15% have been measured and related to variations in crystallographic texture caused by changes in the current density used to deposit the LIGA Ni structures. Dramatic variations in room temperature tensile strength have also been related to significant reductions in grain size as a result of process variations, and the elevated temperature strength of this material has been found to be compromised by microstructural coarsening at relatively modest temperatures. Prospects for alternative elevated temperature LIGA materials will be discussed.

Plasticity in LIGA Nickel MEMS Structures: Size Effects and Dislocation Substructures

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This paper presents the results of a combined experimental and theoretical study of plasticity in LIGA Ni MEMS structures. Experimental techniques and theoretical approaches are presented for the measurement of plasticity length scale approaches associated with stretch and rotational strain gradients. These include nano-indentaiton/micro-bend techniques, and dislocation mechanics models. Dislocation substructures associated with known strain gradients and stress levels are also compared with those in undeformed specimens and tensile specimens in which there are no applied strain gradients. The implications of the results are then discussed for the development of dislocation.

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION T4Q
Nanostructures and Nanomechanics B

Strain-Induced Morphologies and Compositional Modulations in Compound Semiconductor Thin Films

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Our work centers on understanding the morphological and compositional evolution, as well as the strain relaxation and defect formation in lattice mismatched compound semiconductor thin films. 3D roughening will occur in lattice mismatched films above some critical thickness. 3D islands and surface ripples have been shown to relieve strain to some degree. Theory shows that pits are even slightly more efficient at relieving strain than islands, but experimental evidence of pit nucleation has only appeared recently. This work presents a detailed study of the

morphological evolution of In0.25Ga0.75As alloy layers on (001) GaAs substrates (lattice mismatch $\gg$ 1.8%) as a function of thickness and growth conditions and shows that pit nucleation is an additional mechanism for ripple formation.

Another area of interest is in lateral composition modulation, i.e.; controlled phase separation in multilayer structures. By and large, phase separation is undesirable and has been avoided in device structures. However, reproducibly obtaining regular and robust arrays of phase-separated material is a promising way to acquire low dimensional structures such as quantum dots or wires. We have achieved such arrays by the deposition of short period superlattices, where each layer is on the order of one or two monolayers thick. We have demonstrated lateral composition modulation in several different materials systems, such as GaAs/InAs, AlAs/InAs, and GaSb/GaAs. We have shown that the appearance of lateral composition modulation is correlated to roughening of the surface front. Also, the microstructure is largely dictated by the relative lattice mismatch between the individual superlattice layers. These results are consistent with continuum perturbation models that predict the coupling of morphological and compositional instabilities under the appropriate circumstances.

Forces that Drive Nanoscale Self-assembly on Solid Surface

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Experimental evidence has accumulated in the recent decade that nanoscale patterns can self-assemble on solid surfaces. The ability to pattern nanoscale structures guarantees a continuation in the miniaturization of functional devices and the devolvement of novel devices. We investigated the roles of several configurational forces in molding solid nanostructures, their collaborative actions, and their responses to external modulation. Based on our continuous phase field model, we developed the numerical technique and performed large-scale simulation of the process of formation and evolution of nanostructures on a solid surface. The simulation reveals remarkably rich dynamics and suggests a significant degree of experimental control in growing ordered nanoscale structures.

Keywords: nanostructure, self-assembly, surface stress, phase field model

Modeling of Nanostructure Patterning

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Computational nanotechnology is an emerging field of research aimed at developing nanoscale modeling and simulation methods to enable and accelerate the design and development of functional nanometer-scale devices and systems. A major challenge in nanodevice technology is how to fabricate patterned nanostructures with precise size and position control, and a predictive computational modeling can guide and accelerate experimental development in nanostructure patterning. Even though accurate quantum and atomistic simulation methods are available, they are limited to very small systems (thousand to billion atoms) and very short simulation time (nano to micro seconds). A promising approach is to develop multiscale modeling methods using continuum and atomistic simulation methods to investigate the nanostructure patterning processes during epitaxial growth on solid surfaces. A detailed atomistic understanding on the role of surface stress field, temperature, growth rate, and surfactants will facilitate the optimal design of patterned nanostructures. For this purpose, we use continuum theories to model the length scales determined by competing mechanisms of epitaxy, surface stress, surface energy, and strain energy. We apply kinetic Monte Carlo and quantum simulations to simulate nanoscale self-organization processes for creating controlled nanostructures on strained surfaces. In this talk, we will discuss about our multiscale modeling investigation on patterned growth of nanoparticles guided by surface strain modulation and its application to magnetic nanostructure patterning.

Keywords: Computational nanotechnology, nanostructure patterning, controlled self-assembly, atomistic simulations

Collaborators: Bruce Clemens and Bill Nix (Stanford University)
Support: NSF - EEC-0085569

In-plane and Out-of-plane Self-organization of Heteroepitaxial Islands in Superlattices

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During epitaxial growth, a strained film may relax its strain energy by surface roughening. Recently this mechanism has attracted significant attention since it can be potentially used to grow self-organized quantum dots. A great deal of experimental effort has been devoted to achieving uniform and regular quantum dots, and has revealed tremendous complexity and richness of the processes. Yet to achieve uniform and regular 3D quantum dot arrays through self-organization is still a challenging issue.

We have developed a 3D finite element method to simulate the morphological evolution of a strained film via surface diffusion, with an aim to understanding the self-organization, shape transitions and stability of quantum dots. We model deposition of films on a large lattice mismatched substrate. The film surface diffusion is driven by the gradient of the surface chemical potential, which includes the elastic strain energy, elastic anisotropy, surface energy anisotropy and the interaction between the films and the substrate. For in-plane growth, our simulations reveal that both surface energy anisotropy and elastic anisotropy have a strong effect on the self-organization and shape transitions of the quantum dots. With properly chosen surface energy form, the islands may self-organize into a meta-stable state with relatively uniform island size and spacing. With strong elastic anisotropy, the dots may align up along specific directions. For out-of-plane growth, our simulations demonstrate that the spacer layer thickness and interruption time are crucial for achieving different stacking schemes of quantum dots. In particular, with properly chosen system parameters, after a few layers of growth, the top dots self-organize into an almost perfectly uniform and regular array. Finally the simulation results are compared with experimental results and the potential ways in achieving uniform and regular quantum dot arrays are discussed.

A Phase-Field Model for Coherent Microstructure Evolution in a Thin Film Constrained by a Substrate

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A three-dimensional phase-field model has been developed for studying the stability and evolution of coherent microstructure evolution in thin films constrained by a substrate. Elastic solutions are derived for both elastically anisotropic and isotropic thin films with arbitrary domain structures, subject to the mixed surface stress-free and substrate constraint boundary conditions. Electric field in the film is calculated taking into account the long-range electric dipole-dipole interactions under short-circuit, open-circuit or mixed electric boundary conditions. A specific example of a [001] orientated PbTiO3 film heteroepitaxially grown on a [001] cubic substrate is considered. We investigated the effect of substrate constraint, temperature and depolarization on the volume fractions of ferroelectric domain variants, domain-wall orientations, surface topology, domain shapes, and their temporal evolution for a cubic-to-tetragonal ferroelectric phase transition. It is shown that the shapes of a-domains with tetragonal axes parallel to the film surface are significantly different from those of c-domains with tetragonal axes perpendicular to the film surface. For the substrate constraints and temperatures under which both a1- and a2-domains coexist, both types of a-domains are present with their tetragonal axes perpendicular to each other, and the domain wall orientations deviate from the 45 degree orientation generally assumed in thermodynamic analyses. It is demonstrated that a substrate constraint results in sequential nucleation and growth of different tetragonal domains during a ferroelectric phase transition. The effect of depolarization on the domain shape and domain variant volume fraction will be discussed.

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION W2D

Deformation, Fracture, and Mass Transport C

The Stiffness of Metallic and Ceramic Thin Films

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The modulus of a thin thin metallic (Cu, Ag, Cu/Ag multilayers; polycrystalline) or ceramic (alumina; amorphous) films has been measured by differential thermal expansion on an elastic substrate, and by tensile testing in a specially designed microtensile tester [1]. The differential thermal expansion technique has been used as well to monitor the evolution of the modulus in situ during vapor deposition [2].

Possible origins of the lower stiffness which these films compared to their bulk counterparts are reviewed: amorphization, texture, porosity, anelasticity, microplasticity and microcracking [3, 4]. In many cases several factors contribute together. In the case of alumina, the loss of stiffness is attributable to amorphization as well as porosity (measured by adsorption porosimetry). In the case of the metals, the contribution from dislocation anelasticity has been identified from stress relaxation measurements in the tensile tester [5].

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Stress and Structure Evolution During Formation of Polycrystalline Films

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We have used both conventional cantilever and new micro-machined microelectromechanical devices to make high-sensitivity measurements of the bending forces exerted on substrates during nucleation, pre-coalescence growth, coalescence and post-coalescence growth of polycrystalline films have been made. Measurements of stress evolution as a function of substrate temperature and deposition rate have been made at all stages of growth. Measurements of stress evolution during interruptions of growth have also been made at different stages of film formation and thickening, and for interruptions of growth that have been carried out under different steady-state conditions.

We find, as others have in other systems, that Cu films are in an apparently compressive state prior to, and in the early stages of, coalescence, and evolve into a tensile state during coalescence. These films evolve back into a compressive state during post-coalescence thickening. We also find, as have others in other systems, that growth interruptions during post-coalescence thickening lead to reversible tensile relaxations. We argue that the reversible stress evolution that occurs during growth interrupts is associated with differences in the shapes of the grain surfaces during growth and during growth interruptions. This argument is supported by simulations of the morphological evolution that occurs during growth and during growth interruptions, and by analyses of the effects of shape evolution on forces exerted by the deposit on the substrate. These models are consistent with a wide range of data, both in prediction of the magnitudes of the stress changes, and in predictions of the kinetics of stress evolution.

The Mechanical Properties of Electroplated Cu Thin Films

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The microstructure of electroplated Cu thin films has been investigated using texture analysis. It is found that film thickness has a significant effect on the texture of the films, both as deposited and after annealing. Thin films

tend to have a sharp < 111 > fiber texture. As the film thickness increases, the volume fraction of < 111 > component decreases and other texture components such as the < 100 > and the < 110 > fibers become more apparent.

The mechanical properties of these electroplated Cu films have been determined by measuring the deflection of Si-framed, pressurized Cu membranes. The membranes were deformed under plane-strain conditions, which makes it possible to convert the pressure-deflection data into stress-strain curves by means of simple analytical formulae. Both yield stress and Young's modulus increase with decreasing film thickness and correlate well with changes in the microstructure and texture of the films.

Effects of Microstructure and Solute Content In Pt Thin Films

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This presentation will explore the effects of microstructure and Ru solute content in Pt thin films. The relative strengthening effects of grain size, film thickness and solute fraction were evaluated using a combination of techniques including substrate curvature and nanoindentation. Comparison between experimental results and simple models show that solid solution strengthening can have a large effect on the mechanical behavior of thin Pt films. Closer examination of nanoindentation data for pure Pt also clearly shows the influence of grain boundaries on loading curve behavior. The results of these studies should also be relevant for other FCC materials such as Cu and Al.

Keywords: thin film, mechanical behavior, nanoindentation, solid solution strengthening

Relaxation Kinetics of a Compressed Film on a Viscous Substrate

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One mechanism for producing large single crystal films for which lattice-matched substrates are unavailable is to grow a very thin film on a substrate with a small mismatch, bond the free surface to a glass layer, remove the substrate and anneal the structure above the glass transition temperature in order to relieve the misfit strain. Due to in-plane expansion, the stresses relax and the relaxation process propagates from any free edge towards the center of the film. However, when the displacement of the expanding film reaches a critical value, the film can also separate from the substrate and a delamination crack can propagate. A simple model for the kinetics of stress relaxation and the rate of crack growth is derived for a misfitting film bonded to a non-Newtonian viscous substrate. A competing mechanism for stress relaxation of a compressively-stressed elastic films on a finite-thickness viscous substrate is a buckling instability which relieves stresses but destroys the planarity of the film. A linear-stability analysis determines the onset, rate of growth and wavelength of this instability. Unlike the free-standing film, the growth of the buckle instability occurs slowly with a characteristic time set by the viscosity of the glass. An approximate non-linear theory predicts the saturation of the buckling instability at intermediate times, followed by a long time coarsening of the buckling wavelength and a decrease of the stress within the film. Based on these results, the length and time scale over which one or the other relaxation mechanism dominates is estimated.

Keywords: Viscous, Delamination, Buckling, Stability

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION W3Q
Microelectronics, MEMS, and Coating C

On the Mechanics of Thermally Grown Oxides and Thermal Barrier Systems

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A substantial research effort has been devoted to the investigation of mechanisms that dictate the durability of thermal barrier coatings (TBCs) used to protect metallic components in gas turbines. TBCs are widely used, with demonstrated performance attributes, but are susceptible to delayed failure by way of cracking, buckling and delamination. These coating systems are complex materials, comprising multiple layers having disparate thermoelastic properties, and experiencing severe cyclic ther-

mal exposure. Residual stresses that develop due to microstructural evolution, oxide growth and thermal mismatch are the principle drivers for failure. The continuous growth of an oxide layer during service is of key importance. The compressive stresses that develop in this layer, and interaction with morphological features, motivate the damage evolution. For a particular TBC system, failure occurs by a displacement instability in the thermally grown oxide (TGO). Experimental observations characterizing the damage evolution and failure mechanisms for such a system will be discussed. Indentation test protocols are used to quantify fracture characteristics of the multi-layer TBC structures. The mechanisms controlling the growth of the TGO is of particular interest. Key issues include the overall oxide growth rate, the location of new oxide formation, the influence of surface preparation and oxidation environment, and the resulting microstructure. Systematic studies of oxide growth under varying conditions are discussed, with emphasis on how the details of the oxide growth effect the mechanics of damage evolution. A novel mechanics-based test methodology providing insights into oxide growth mechanisms will be described. The experimental findings are correlated with simulations to capture and quantify the important parameters affecting durability. Implications of the research for the design of thermal barrier systems with improved durability will be discussed.

Fracture Mechanics Applied to TBC Failure , Experiments and Analysis

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Thermal barrier coatings (TBC's) are ceramic coatings applied to internally cooled gas turbine components to reduce the metal temperature by up to 150 C in order to realize important improvements in both part life and system performance. Such coatings almost universally are made of yttria stabilized zirconia. Such coatings are used on nearly all current generation aviation gas turbines and their use is rapidly increasing in inductrial turbines.

Unfortunately TBC's eventually fail by spallation. There are a wide variety of failure mechanisms and each different TBC system and load history is it's own specific case. In the present paper we will briefly describe the failure mode of a specific system (PtAl bondcoat EB-PVD coating, Single Crystal superalloy substrate). In this particular system there is a 10X scatter in the failure life for nominally identical samples. In the present paper we will show that of the several failure mechanisms considered previously, one of them provides a quantitative explanation for the 10X variation in failure life. In addition it will be shown that the proposed failure mechanism is quantitatively consistent with fracture mechanics. In order to apply fracture mechanics to this problem, parameteric solutions for two different interface fracture problems were developed. The solutions were for elongated edge in a thin layer on an elastic quarter space and for an interface cracks in a pre-compressed film on a cylinder and sphere. In ordxer to use fracture mechanics on this particular problem the available strain energy was determined experimentally using a combination of oxide thickness measurement and oxide stress measurement based on photo luminescent piezospectroscopy (PLPS). Consideration of PLPS measured stresses lead to a conclusion that accurate knowledge of the strain energy available to drive spallation at present is best obtained by measurement and that energy calculated from standard properties can be in error by as much as a factor of 4. Experimental determination of strain energy value is recommended in future studies of spallation mechanics. Progress in the ability to predict oxide stress evolution in such systems is needed.

Toughness Degradation in Thermal Barrier Coating Systems

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A principal concern with thermal barrier coatings (TBCs) is their loss of adhesion during service, leading to coating spallation. In this research, an indentation test is used to quantify decreases in interfacial toughness of TBC systems as a function of the duration of isothermal or cyclic high-temperature exposures in dry air or in the presence of water vapor. The indentation test involves penetration of the TBC and the oxide layer below it, inducing plastic deformation in the underlying metal bond coat and superalloy substrate. This plastic deformation induces a compressive radial stress away from the indent, which drives an axisymmetric delamination of the TBC and oxide layers. Test results are presented tracking the "apparent" loss of toughness (that could include changes in the TBC system that contribute to adhesion loss independent of interfacial damage) for EBPVD TBC

systems as a function of isothermal exposures from 1100 C to 1200 C. These results indicate a significant loss in apparent toughness occurs at a fraction of the total TBC system life. Apparent losses in toughness are correlated with observations of increasing oxide thickness and TBC sintering. Further analyses and tests are presented which quantify the relative importance of oxide thickening, TBC sintering and interfacial damage in decreasing apparent TBC system adhesion in these tests. A select group of tests are used to show the importance of as-processed interfacial toughness in determining the rate of toughness loss with exposure and in determining TBC life. Results are also presented that give insight into the importance of steam exposure and cyclic thermal loading, compared to results for isothermal loadings in dry air.

Phase Transformation and Transformation Strain in Thermally Cycled Platinum Aluminide Bond Coats

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Thermal barrier coatings (TBCs) are multilayered systems, composed of four components: ceramic top coat, thermal growth oxide, bond coat and the superalloy substrate. Each layer in the system is dynamic and all interact to control the systems durability. The chemistry and microstructure of the bond coat is believed to be crucial, because of its influence on the mechanical and physical properties of bond coat and thereby on the state of stress in the whole TBC system. Recently a martensitic transformation has been found in thermally-cycled platinum aluminide bond coats. In situ TEM observations and high temperature X-ray analysis will be presented to demonstrate that the transformation is reversible and that it occurs on each thermal cycle. The L10 martensite is stable at lower temperatures and the B2 parent phase at elevated temperatures. The phase transformation is associated with a jump in volume and a quantitative measurement indicates that the atomic volume of the B2 phase is approximately 2% smaller than that of the martensite. Thus, the phase transformation produces about 0.7% strain, which has been incorporated into FE model of the TBC system. During heating, the transformation strain is accommodated by plastic deformation and creep. During cooling, because the transformation temperature is below the ductile-brittle transition point of the bond coat, the transformation strain cannot be completely dissipated by nonelastic deformation and significant stresses appear to develop in the system.

Coupled Diffusion and Creep in Multiphase Coatings

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The microstructure of a multiphase coating evolves during service. Processes include oxidation, phase transformation, evaporation, diffusion and deformation. We first consider an internal region of a single phase, away from boundaries of various kinds. Diffusion induces a dilatation field, which is incompatible, driving the alloy to deform plastically. since Darken's one-dimensional theory has been used widely to interpret diffusion experiments, it is desirable to extend his theory into a three dimensional theory with minimum tinkering. Following Darken, we neglect elastic strain, compositional strain, and vacancy concentration change. The governing equations, formulated in the Eulerian space, simultaneously evolve concentration field and creep velocity field. We then examine the conditions at phase boundaries, oxide-metal interfaces, and vapor-metal interfaces. We apply the theory to analyze several cases.

This work is done in collaboration with D. Kubair, D.R. Clarke, V. Tolpygo, A.G. Evans, and G. Meier

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MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION W4Q

Nanostructures and Nanomechanics C

Coalescence of Ductile Metal Surfaces: When Solids Can Behave Like Liquids at the Nano-Scale

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Much is known about the fundamental mechanisms of material failure, such as fracture and crack propagation, but much less about the reverse effect of material formation, i.e., how bulk materials form or consolidate via the

coalescence of their constituent molecules, nanoparticles or surfaces as occurs during material processing or crack healing. Using the Surface Forces Apparatus (SFA) force and various optical, microscopy and x-ray imaging techniques we have studied how gold and platinum films "sinter" or "cold-weld" at the nano-scale to form continuous bulk films when two initially rough surfaces (composed of 5-10 nm asperities) are pressed together. We find that coalescence of these ductile materials occurs abruptly, like a first order phase transition, once a critical local pressure or interparticle separation is reached. Simple thermodynamic reasons are given for this apparently general effect which suggest that it may be a more general phenomenon for ductile materials interacting at the nano-scale, where high local curvatures, extremely small sizes and confinement effects produce large local forces, and where rapid molecular rearrangements (short equilibration times) can occur even at low diffusion rates. We also make some qualitative comparisons with the very different behavior observed with hard, brittle materials.

Keywords: ductile nanoparticles, cold-welding.

Deformation and the Origins of Strength in Metallic Multilayers

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This presentation will focus on (1) the effects of length scale and interface on the mechanical properties, and (2) mehcanical and thermal stability of the nanoscale structures in several model metallic multilayered systems. We have utilized conventional, analytical, and high resolution transmission electron microscopy to establish an atomic scale description of the microstructure, deformation structure, and local composition profile. The mechanical behavior has been characterized by nano- and micro- indentation, and by micro-tensile testing. Calorimetric measurements were made to determine the amount of strored energy on the degree of deformation. A strong scale effect on the mechanical behavior including the deformation structure, hardness, and fracture characteristics has been observed. In addition, both cold rolling and annealing of self-supported samples were performed to characterize the mechanical and thermal stability of metallic multilayers. The unusual stability of the layered structure and texture that was observed reflects the operation of new kinds of deformation mechanisms. Atomistic simulations have been carried out to examine slip behavior in coherent and semicoherent layered systems. The results reveal complex interfacial structure in response to applied stresses, and shed light onto the unusual deformation processes.

This work has been conducted at Los Alamos National Laboratory under the support of DOE Office of Basic Energy Sciences, Division of Materials Sciences and Engineering.

Deformation Behavior of High-strength Nanoscale Al/Al3Sc Multilayers

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Micro- and nano-structural features within thin films and multilayers control their resistance to plastic deformation. In the present work, we investigate the relationship between microstructure and strength of multilayered thin films composed of Al and Sc. The Al/Sc system is currently receiving a great deal of attention due to the significant strengthening effect of Sc in Al alloys. Thin film deposition processes allow the synthesis of multilayered thin films of arbitrary compositions. We have used this to advantage to create high-quality polycrystalline multilayered films consisting of soft Al layers (6-100 nm thick) separated by thin (0.5-5 nm) layers of Al_3Sc. We have produced volume fractions of Al_3Sc far in excess of those possible by traditional casting techniques. Nanoindentation and wafer curvature tests have revealed that the multilayer films are extremely strong, with increases in hardness as much as 3-4 times the rule of mixtures value. Characterization, via FIB, High Resolution TEM and X-ray diffraction, has shown these layers to be coherent, providing a simple (and ideal) test system for investigating the strengthening behavior of metal multilayers. We find that the strength of these materials increases markedly with decreasing bilayer period, as expected, but these increases are smaller at very small bilayer periods. We present a model based on misfit dislocation creation and propagation in coherent multilayers as an attempt to explain the observed strengthening behavior.

Computer Simulations and Experimental Observations of Dislocation Motion in Nanoscale Multilayer Films

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A predominant attraction of nanoscale multilayer thin films is the ability to specify the phases and interfacial structure, so that dislocations are constrained to propagate in individual layers. This ability to constrain slip is cited as a primary reason why multilayer thin films display such extraordinary hardness. However, constrained slip is not always possible. In particular, many multilayer systems exhibit a critical layer thickness, below which the hardness either reaches a plateau or even decreases. This critical layer thickness occurs due to the inability of interfaces to contain dislocations as layer thickness is decreased. This presentation is three-fold. We will present transmission electron micrographs from in-situ straining tests to first identify important dislocation propagation and transmission modes. Next, we will discuss continuum and atomistic simulations of dislocation tranmission across interfaces, to identify the important features that control dislocation transmission across interfaces. Finally, we will incorporate the experimental observations from the microscopy and important features of the dislocation transmission studies into a 3D dislocation model. The 3D dislocation model is used to study the response of both threading and interfacial dislocation segments as a macroscopic biaxial tension is applied to the multilayer. The results shed light on how the choice of phases, layer thickness, and interfacial structure serve to contrain crystal slip and thus provide extraordinary plastic strength.

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[2] PMA gratefully acknowledges the support of Los Alamos National Labs while on sabbatical as Bernd T. Matthias Scholar in the Materials Science and Technology Division.

Experimental Results on Free Standing Nanoscale Al Films

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We present a new methodology, based on MEMS (micro electro mechanical systems) technology, that allows to apply known forces on material samples of free standing thin films (20nm and higher) and measure corresponding displacements of the samples in-situ in SEM or TEM. We demonstrate the methodology by carrying out two experiments: (a) uniaxial tensile experiments on 30-200nm thick, 20μm wide and 200m long free standing aluminum samples. A unique feature of this experimental approach is that the sample and the loading instrument are co-fabricated so that the alignment of sample and loading is within 10E-5 degrees - a critical concern in a uniaxial test particularly at small scale. The stress strain response of the samples indicates: (1) the modulus of elasticity is in the range 62-75GPa, lower values for thinner samples, (2) yielding occurs at 327MPa, 710MPa, 328MPa and 250MPa in 200nm, 100nm, 50nm and 30nm thick samples showing negative Hall-Petch behavior, (3) after yielding, there is a short strain hardening regime followed by an almost ideal plastic behavior for thicker films, whereas for thinner films (30 and 50nm) the behavior is nearly brittle. (b) Bending experiments on 100-200nm thin Al films to explore the effect of strain gradients on strain hardening of nanocrystalline materials. It is found that the length parameter related to the strain gradient theories proposed in the literature approaches zero when the film thickness approaches 100nm, but for 200nm film, it is around 4 micro meter.

Keywords: MEMS, uniaxial tension, strain gradient, aluminum

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION R2D
Deformation, Fracture, and Mass Transport D

A Volume to Surface Length Scale for Thin Film Mechanics

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Previous determinations of a volume to surface area length scale associated with the indentation size effect has been extended to thin film deformation. Further application of this same length scale to thin film delamination has resulted in an R-curve dependence for crack growth. By using both normal indentation and scratch modes of delaminating copper and gold thin films, crack initiation and arrest conditions can be determined. The cusp point of overlapping delamination regions in a sliding contact is found to delineate the initiation region for crack growth in the scratch mode. Using this it is possible to define both the initiation and crack arrest strain energy release rates. The inherent assumption is that the scaling constants for initiation and arrest are the same for different film thicknesses. The initiation value can be predicted by the tangency of the strain energy release rate to the R-curve. After each subsequent delamination at arrest, the resistance curve at arrest can be found utilizing the length scale as interpreted from indentation. The initiation and arrest curves define an oscillating "frictional" contact during the sliding and grooving of a conical diamond tip into Cu and Au films 50 to 3000 nm in thickness. The oscillating lateral force curves tend toward relatively constant values of initiation and arrest after approximately 5 to 10 discontinuities. Two detailed examples of this in 100 nm and 250 nm thick gold films on silicon wafers are discussed. In the thinner case, the steady state strain energy release rate at initiation is 2 N/m and at arrest is 1.3 N/m. For the thicker film, the respective values are 8.3 and 3.4 N/m.

Keywords: length scales, thin films, nanoindentation, delamination

Strength of Surface Nano-Crystalline Layers

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A dislocation-based model on the strength of a surface nano-crystalline layer is presented. The strength of a surface layer is assessed as the strength under multiple-asperity indentation loading. When the crystallite size is large, the hardening and the plastic slip depend on obstacle strength and dislocation pile-up mechanisms. In this size range the cooperative slip processes are mainly internal and the Hall-Patch relation is satisfied.

On the other hand, as the crystallite size becomes small in nanometer scale, a dislocation glide generated by a source is limited by the size of the crystallite and the cooperative slip processes are mainly external. The scale-dependent mechanism transition of plastic deformation from obstacle-limited plasticity to single-glide-limited plasticity is analyzed for the strength of surface nano-crystalline layers. In addition, another possible mechanism transition from single-dislocation-limited plasticity to source-limited plasticity is also discussed.

Interfacial Force Microscopy Studies of γ-APS on Glass and SiO_2

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Swadener et. al. (1999) have shown via X-ray photoelectron spectroscopy (XPS) and atomic force microscopy (AFM) that mixed-mode fracture near a glass/epoxy interface left a 3 nm layer of epoxy on the glass surface. Such a cohesive crack path helped explain why the high intrinsic toughness of the interface was 20 times higher than the thermodynamic work of adhesion of the glass/epoxy interface. Other studies of glass/epoxy interfaces (Drzal,

1986; Winter and Houston, 1998) have indicated the presence of an interphase region where polymer properties are affected by the substrate so that there is a transition from the substrate to the bulk behavior of the polymer. Presumably, the subinterfacial fracture noted by Swadener et. al. (1999) took place in such an interphase region. The traction-separation law of this region was extracted in an iterative manner via a combination of crack opening interferometry and finite element analysis. The objective of this work is to make more direct assessments of traction-separation laws of interphase regions. One promising instrument for these purposes is the interfacial force microscope (IFM). The IFM is unique in that it employs a self-balancing, force feedback sensor which allows force profiles (load vs. displacement data) to be obtained while the sensor remains rigidly fixed in position throughout the measurement (Joyce and Houston, 1991; Houston and Michalske, 1992). In this study, the (IFM) was first used to probe the nanomechanical properties of hydrolyzed g-aminopropyltriethoxysilane (g -APS) films fabricated by spin coating on soda glass and SiO2 surfaces. The g-APS is widely used as a coupling agent for fiberglass-reinforced composites and as a primer for adhesive joints with thicknesses ranging from a few nanometers to hundreds of nanometers. It was found that the modulus of 50 nm thick g-APS films on glass were a quarter of those on SiO2. XPS analysis revealed that leaching of Na^+ ions from the glass into the g-APS destroyed cross-links, making it softer. In order to have more control on polymer film thickness, a self-assembled octadecyltrichlorosilane (OTS) monolayer adsorbed on SiO2 substrates is being used as a model fracture surface. Its nanomechanical properties are now being probed using the IFM so that comparisons can be made with the g-APS results. Once this is understood, epoxy on glass fracture surfaces will be examined in a similar way.

Keywords: Interfacial fracture, interphases, nano-indentation, spectroscopy

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Measurement of Mixed-Mode Interfacial Failure in Thin Films Using Laser Induced Stress Waves

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Thin films are critical components in a wide range of multilayer microelectronic and optical devices, but the size scales and dissimilar nature of the constituents present challenges with regard to thermomechanical integrity and reliability. A particular challenge is the design and implementation of test procedures that measure thin film interface properties. In the current work, laser induced stress waves are used to characterize intrinsic interfacial strength of thin films under mixed-mode conditions. Laser pulse absorption generates high amplitude, short duration stress wave pulses that can be used to load the interface between a film and a substrate. Gupta and co-workers have reported extensively on a laser spallation experiment to determine the intrinsic tensile strength of planar interfaces. We explore the use of laser pulse induced shear waves to obtain a range of mixed-mode and pure shear failures of thin film interfaces. The laser-induced compression pulse is allowed to mode convert at an oblique surface, and the resulting shear wave to impinge upon the interface to be tested. A careful series of experiments and analysis is carried out for development of the mixed-mode loading method. Interfacial strengths and failure modes obtained for Al films loaded in pure shear and mixed mode are compared with those obtained for the same films loaded by a tensile wave.

On the Mechanics of Foreign Object Damage

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Foreign Object Damage (FOD) occurs when small hard particles are ingested into aircraft jet engines. Particles impacting turbine blades at velocities up to about 300 m/s produce small indentation craters which can become sites for fatigue crack initiation, severely limiting the lifetime of the blade. FOD imparted to a thermal barrier system can cause delamination cracks extending away from the impact in the thermal barrier coating (TBC) adjacent to

the interface. In this paper, a framework for analyzing the mechanics of FOD is established and its implication to fatigue cracking and TBC delamination is elaborated. Finite element analysis is used to determine the residual stresses and geometric stress concentration resulting from FOD. A non-dimensional analysis is presented that allows the impact and material variables to be grouped into the smallest possible parameter set needed to characterize FOD. This parameterization provides explicit results for the stresses and displacements that arise as the projectile characteristics and material properties are varied over a range applicable to FOD in gas turbines. The second step in the analysis focuses on the potency of cracks emerging from critical locations at the indents. The results have been used to address the question: When and to what extent do the residual stresses and stress concentration caused by FOD reduce the critical crack size associated with fatigue threshold? For deep indents, it is found that elastic stress concentration is the dominant factor when the applied cyclic load ratio is large, otherwise the residual stresses are also important. For FOD in a thermal barrier system, a scaling relation has been derived from the stress field and the penetration that relates the length of the interface delamination to the impact and material variables. Comparisons with a set of experiments conducted in parallel with the theory show that the numerical approach can account for various phenomena observed in practice.

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION R3Q
Microelectronics, MEMS, and Coating D

CGS Interferometry as a Full-Field, Real-Time, and In-Situ Wafer Inspection and Reliability Tool

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As the semiconductor/integrated circuit industry retools for the processing of larger diameter (300 mm) wafers with smaller circuit features (0.13μm or less), the need for accurate full-field, in-situ and real-time inspection and reliability analysis tools becomes imperative.

In this presentation we discuss the development of a vibration insensitive interferometric method designed especially to meet these new inspection and stress management challenges. Coherent Gradient Sensing (CGS) interferometry is discussed in relation to wafer planarity issues that arise throughout the entire wafer processing cycle. In particular, we discuss CGS as a means of measuring the non-uniform curvature tensor evolution of entire wafer surfaces in real-time during the cycle, as an in-situ process diagnostic. Issues presented include a) the use of CGS during film deposition as a means of continuously monitoring film uniformity and coverage within a deposition reactor, b) its use in conjunction with elaborate stress analysis tools for the measurement of stresses on thin films and lines during wafer processing or thermal cycling and, c) its ability of mapping highly non-uniform, non-linear deformations and curvature bifurcations that become important as wafer sizes scale up.

Throughout the presentation emphasis is given to the suitability of the method as an in-situ process diagnostic. Other applications of the technique, which include deformation measurements in the die and packaging levels and the study of large deformation and gravity effects and wafer support design in large, thin, wafers are also briefly discussed.

Keywords: Curvature, Full-Field, Real-Time, In-Situ

Cladding Layer Thickness Effect on Optical Performance in Ridged Waveguide

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Planar optical waveguides are key elements for integrated optical devices and semiconductor lasers.Stresses in waveguides, caused either by CTE mismatch or by different processing and doping conditions, have a significant effect on optical performance of photonic devices.In this study, our focus is on silicon based ridge waveguide, as shown in Fig. 1. This waveguide is consist of a square or rectangular core (Si) surrounded by a cladding (SiO2) with lower refractive index than that of the core.



Fig. 1: A ridged waveguide structure, and stress distribution in the waveguide.

For a cladding of 0.5 μm, FEA results show that stresses in the waveguide result in a 10^{-3} refractive index change. This index change will have significant impact on optical

performance. In order to reduce stress level in the waveguide, a lower processing temperature to form the cladding layer, i.e., plasma-enhanced chemical deposition, and a thinner cladding layer are recommended. For a waveguide structure with an Al coating on the top of the cladding layer, the cladding layer thickness has a significant effect on the optical performance. The Al layer thickness is 0.3 μm, and is formed at 380oC and then cooled down to 25°C. The SiO_2 layer is formed at 800°C and cooled down to 25°C. As shown in Fig. 2, there exists an optimized cladding layer thickness.

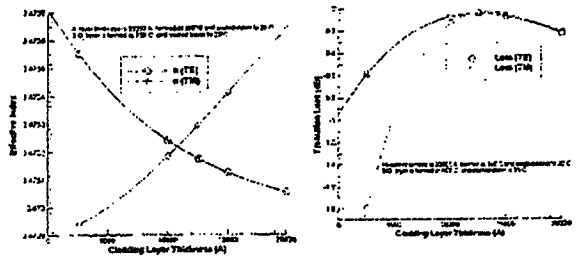


Fig. 2: Cladding thickness effect on effective index and transition loss.

The above results show stress effect on optical performance in photonic components and integrated photonic devices is much stronger than that in microelectronics, where there is no significant effect on electric performance as long as the stresses do not cause delamination or cracking. In the future photonic integration, we have to overcome or compensate the stress effect by material selection, processing and design.

Optimal Design of Microclips for Mounting of Optical Fibers in Silicon V-Shaped Grooves

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The use of single mode optical fibers in telecommunications is widespread. However, current laser pig-tailing methods employing either glue or weld to secure the fibers in place are costly and there are inherent problems such as initial fiber mis-alignment and movement during bonding. An innovative mechanical solution using silicon or silicon nitride clips has recently been proposed to address the issue. The fabrication process is simple, with one or two lithographic steps required on a thin film deposited on a silicon substrate. Single mode optical fibers are inserted and held in position in V-shaped grooves etched in silicon substrates by the cantilever clips protruding from the edges of the V-grooves. As the fiber core is in general either level with or above the silicon surface, the clips are deflected by the fiber and act as springs holding the fiber kinematically in place. However, the design of the microclips is faced with apparent contradicting constraints: on the one hand, they need to be sufficiently flexible for fiber connections and disconnections; one the other hand, they need to be sufficiently stiff so that the clamping force exerted on the fibers is reliable. Additional problems that must be addressed in designing the clips include substrate spalling and interfacial debonding due to stress concentrations at the clip/substrate joint. In this work, the optimal thickness, mass and shape of clips are first studied with an effective optimization procedure, Metamorphic Development (MD). This procedure aims at finding structural shapes and topologies of the clips that minimize their structural compliance and weight subject to stress and deflection constraints. The paper then analyzes the mechanical properties of such clips, with special focus placed on crack initiation and propagation due to excessive loading. The orientation of the initial crack as well as crack growth processes are discussed.

A Comparison Study of Ti/GaAs Ti/Si Fracture

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Thin Ti film is commonly used as an adhesion-promoting layer for different metallization schemes, Cu/Ti/SiO2, Au/Ti/GaAs to name a few [1]. This research reports results on a comparison study for Ti/Si vs. Ti/GaAs adhesion measured by means of the superlayer indentation test [1, 2].

The thermodynamic work of adhesion for any thin film will depend on the condition of the substrate surface at the time of deposition. Most often sputter clean cycle is used prior to film deposition. Unlike monoatomic substrate such as Si, compound substrate surface compositions can be significantly altered by sputter cleaning. We propose a mechanism by which such a process can lead to significantly reduced adhesion for the Ti/GaAs interface.

A 1 μm thick compressively stressed superlayer of TiW was deposited on top of Ti films of varying thicknesses, sputtered under various conditions on Si and GaAs wafers. Blister size along with materials elastic properties, residual and indentation stresses provide a basis for calculating thin film practical work of adhesion [2].

While Ti films on Si wafers provided consistent adhesion values, Ti film adhesion on GaAs scattered as high

as 100 J/m^2. In order to understand the discrepancy several blisters of TiW/Ti films have been removed from substrates with an adhesive tape. Fracture surfaces were characterized with SEM. Opposite to Ti films on Si, where cracks initiated in Si and then spread to the interface, Ti/GaAs fracture started at the interface, kicked into the GaAs substrate and then back again to the interface, leaving chips and pieces of GaAs on the debonded Ti surface. Opposite to Si, there were distinct radial cracks present in the GaAs substrate. GaAs fracture toughness is three times less than that of Si, which makes it more susceptible to radial cracking. There is a competition between the interfacial adhesion of Ti to GaAs and the fracture toughness of GaAs itself, which has caused large scatter in adhesion measurements.

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Effects of Adhesion on Deformation Behavior of Thin Metal Films on Substrates

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The thermomechanical behavior of thin metal films on silicon substrates can be dramatically influenced by changes in the chemistry at the interfaces between the films and adjacent barrier and passivation layers. By adjusting interface chemistry, large changes in stress levels and in the shape of stress temperature curves can be seen. Phenomena including strong stress asymmetry (higher flow stresses in tension than in compression), negative yielding (compressive plastic deformation during tensile unloading) and very large anelastic recovery effects can be induced. These behaviors are consistent with variations in the ability of interfaces to constrain deformation in thin films. We suggest that mechanisms such as the spreading of dislocation cores into the interface and other local interface sliding events may account for the observed behaviors. The role of the interface in constraining deformation in films and the effect of reduced adhesion, here defined as resistance to local interface sliding, will be discussed.

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION R4Q
Nanostructures and Nanomechanics D

Depth-dependent Hardness

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The present study investigates the depth-dependent hardness observed in nanoindentation tests. The depth-dependent hardness may be caused by deformation within the bulk of the indented material and/or by deformation at the surface of the indented material. The plastic work done by an applied indentation load is divided into plastic bulk work and plastic surface work. The plastic surface work represents the energy dissipated at the surface during nanoindentation. Consequently, an apparent surface stress is defined as the energy dissipated per unit area of the surface. The plastic surface work is necessary for the deformation of a solid surface to form an impression, which relates to the apparent surface stress and the size and geometry of an indenter tip. Good agreement is found between the first order approximation of the theoretical results and the available data of depth-dependent hardness, indicating that the apparent surface stress may play an important role in the depth-dependent hardness. The apparent surface stresses extracted from the nanoindentation tests at room temperature are much higher than the corresponding surface energies at elevated temperatures.

An Atomistic Modeling of the Mechanical Behavior of Carbon Nanotubes

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Carbon nanotubes exhibit remarkable mechanical, thermal and electrical properties. These properties, combined with their low density and high aspect ratio, make carbon nanotubes an ideal candidate for reinforcing composites with superior mechanical and physical performance. However, because of the difficulties in experiments and theoretical analyses due to their extremely small size,

there is still a lack of the fundamental knowledge regarding the strength and failure behavior of carbon nanotubes.

In this paper, we present an innovative method for modeling the deformation of carbon nanotubes. Fundamental to this method is the notion that carbon nanotubes are geometric, cage-like structures where the load-bearing members are connected at a number of joints. It seems then a logic approach to modeling the deformation of carbon nanotubes at the atomistic or molecular level by emulating the approach in engineering structural analysis. The primary bond between two nearest-neighboring atoms forms the load-bearing member whereas the individual atom acts as the joint of the related load-bearing members. We term this approach the "molecular structural mechanics" method.

This paper reports the following aspects of the mechanical behavior of carbon nanotubes. First, the molecular structural mechanics method has been applied for the prediction of elastic modulus of carbon nanotubes. The results are in good agreement with those of more computationally intensive methods, such as molecular dynamics simulation, tight-binding model and density functional theory. Next, this method enabled us to model the strength of single-walled carbon nanotubes with or without Stone-Wales defects. Finally, we applied this method to analyze the compressive buckling of carbon nanotubes. The complete load-displacement relationship including pre-buckling and post-buckling has been obtained. The effects of tube diameter and chirality on the buckling have also been examined.

Surface Wrinkling of Two Mutually Attracting Elastic Bodies due to van der Waals-like Forces

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Very recently [1], a new type of surface instability has been observed for compliant rubber-like elastic films interacting with a rigid flat plane through van der Waals-like forces. The flat surface of the elastic film is found to be morphologically unstable when the interaction exceeds a critical value, and the wavelength of the instability mode is determined by the thickness of the elastic film, independently of its elastic modulus and the details of the interaction. This surface instability is elastic in nature and essentially different from other known surface instabilities due to surface compressive stress or stress-assisted surface diffusion. Motivated by some physical problems of current interest, a novel method is suggested to study this surface instability for two mutually attracting elastic films [2], and an elastic film interacting with a suspended elastic plate [3]. One major new result of [2, 3] is that the system consisting of two elastic layers could admit more than one metastable instability mode, in contrast to the unique instability mode of an elastic film interacting with a rigid flat surface. It is anticipated that this non-uniqueness of the metasbale instability modes could cause complex surface patterning phenomena, such as snap-through between two distinct instability modes, and even chaotic behaviour under dynamic conditions.

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Spontaneous Correlation of Crystallographic Orientations in Crystallite Aggregation

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Self-organization of microstructures in interfacial growth has been intensively studied in the past decades. Ordered structures can be spontaneously generated in the interfacial growth by stress-induced instability. Yet up to now most researches concentrate on two-dimensional systems such as thin films. In crystallization, spontaneous alignment of crystallites and hence ordered crystallite aggregate can be observed, yet the mechanism remains unclear. One example is the spherulite growth, in which crystallites are continuously twisted or titled. Another example is the aggregation of NH4Cl crystallites in agarose gel, where the orientation of each crystallite becomes closely correlated. Ultimately branches with regular zigzagged microscopic features are formed. By changing the driving force of crystallization, aggregate with spatial periodic roughening transition on the surface can be observed, which arises from the regular change of crystallographic orientation of the crystallites (part of these results have been published in Phys. Rev. Lett., 80, 3089 (1998); J. Crystal Growth, 208, 687 (2000)). Here we report an in-depth study of the origin of the long-range correlation of the crystallographic orientations in the aggregate investigated by means of micro-X-ray-diffraction, atomic force microscopy and in-situ optical observation.

It is shown that the topographic regularity of the aggregate originates from the consecutive rotation of the crystallographic orientation in the nucleation-mediated growth. This effect may occur when nucleation takes place in a region with inhomogeneous surface tension. It may help to clarify the long-range orders observed in our experiment and possibly the spherulite growth in general.

Characterization of Indentation Damage in Boron Carbide/DLC Nanocomposite Coatings

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Sputtering processes which take place in the presence of reactive hydrocarbon gases will produce coatings consisting of sputtering target compounds embedded in amorphous hyrogenated carbon (a-C:H). The a-C:H matrix is also commonly known as diamond like carbon (DLC). For processing with low levels of acetylene flow, coatings with enhanced hardness have been produced. For higher levels of acetylene flow tribological investigations have shown decreased friction coefficients. Coatings with the best wear properties are those which optimize hardness, strength, and friction coefficient.

To investigate the fundamental nature of the coating hardness, adhesive strength, and cohesive strength, indentation experiments have been performed with four different Boron Carbide/DLC coatings on steel substrates. Coatings were were approximately 1.5 microns thick and have been characterized with SEM, TEM, and Raman spectroscopy. Indentations were made at nano, micro, macro loads. Nano and micro-indentations provide information relating to the hardness and modulus of the different coating compositions. This information was used interpret crack patterns produced by higher load micro and macro-indentation. Observations were made with optical microscopy, optical profilometry, and SEM.

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION F2D

Deformation, Fracture, and Mass Transport E

Mechanical Properties and Stresses in Two Thin Film-Substrate Systems

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A study of material characterization and mechanical property measurements of two representative thin film coating systems will be discussed in this talk. The first system consists of thin gold films up to 2 microns thick deposited on a silicon substrate. Both microtensile tests of free-standing thin gold films and nanoindentation tests of the thin gold films attached to the silicon substrate have been carried out. A crystal plasticity model of the gold films is calibrated via the simulation of the microtensile tests of free-standing samples. Then the nanoindentation tests of the gold films on a silicon substrate are analyzed to assess the effects of both the film texture and internal stresses on the nanohardness numbers. The second system studied consists of a thin anodic oxide coating on a metal substrate. In-situ tensile stretching of the film coating system under an optical microscope, a scanning electron microscope and an atomic force microscope has been carried out in an effort to better measure the fracture property of nanoscale thin film coatings and the interfacial strength of the coating-substrate interface. A nonlinear finite element analysis of the coating-substrate system is used to extract the mechanical properties of the nanoscale anodic oxide coatings (tens to a few hundreds nanometers) on aluminum alloy substrates.

Microtensile Testing in the Scanning Electron Microscope

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A technique for tensile testing of very small specimens of thin films has been developed and applied to metals, a polymer, and a ceramic-like material. This technique

is straightforward and able to reveal clearly the different behaviors of the different types of materials. Since the gauge section is 10 by 180 micrometers in plan, the behavior of the aggregate film, including grain interiors and grain boundaries, is sampled. The specimen preparation techniques used to date have relied on photolithographic patterning and removal of a sacrificial substrate. Tensile tests of physical-vapor-deposited (PVD) films of several different specimen materials have been conducted within the scanning electron microscope (SEM). Our scheme is similar in principle to the apparatus originally reported by Greek et al. For our current specimen sizes, typically 10 by 180 micrometers, the principal benefit of testing in the SEM is its greater depth of focus.

The complete procedure for testing is as follows. Specimens are formed by photolithography and freed by etching away the sacrificial substrate beneath the tensile section and the moving end. By etching to a depth of 50 micrometers beneath the specimen, we are able to avoid interference between the probe tip and the substrate. Force is sensed indirectly via the displacement of flex plates that support the probe holder, measured using a non-contacting eddy current sensor. The displacement of the gauge length is measured using digital image correlation to analyze 100-500 SEM images acquired during the test. Temperature is varied by placing a heated stage beneath the substrate, and by a resistive winding on the probe holder. This testing scheme has been applied to pure aluminum films deposited in our laboratory, aluminum films made in a commercial CMOS fab facility, polyimide films, and polysilicon films. The differences among the stress-strain curves for these very different materials were as dramatic as would be expected.

Theoretical Treatment of Void Nucleation Due to Coupling of Mechanics and Vacancy Composition

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We present a coupled continuum formulation of mechanics and composition applicable to polycrystalline microelectronic and semiconductor structures. The formulation is thermodynamically-based and accounts for atomic transport, creation and annihilation of species, and the interactions of these processes with local stress and strain. Coupled constitutive field equations are obtained for composition and mechanics by standard thermodynamic arguments. They are incorporated in balance laws, and various boundary value problems for metal self-diffusion and dopant diffusion in silicon can be solved [1,2]. Electromigration is also treated. More recently, we have tried to address the question of void nucleation. We consider metal self-diffusion and choose vacancy concentration as our composition variable. Allowing the elastic moduli to vary with vacancy concentration via a simple rule-of-mixtures introduces a double-well shape to the Gibbs free energy density. A minimum at low vacancy concentration corresponds to the equilibrium value usually observed: about 7–8 orders of magnitude below the lattice site concentration at room temperature in aluminum. However, a second, deeper minimum also exists for vacancy concentration equalling the lattice site concentration. A large energy barrier exists between these states and, under most regimes of temperature, stress, electric field strength etc., the barrier is not surmounted. We have examined situations under which this barrier is reduced or made to disappear altogether. The implications for stability of the structure and for void formation are examined. The study is analytic and computational, and coupled boundary value problems have been solved in the regimes of interest.

[1] A Lattice-based Micromechanical Continuum Formulation for Stress-driven Mass Transport in Polycrystalline Solids, K. Garikipati, L. Bassman and M. Deal, *J. Mech. PhyS. Sol.*, **49**, 1209–1237, 2001.

[2] Atomically-based Field Formulations for Coupled Problems of Composition and Mechanics, K. Garikipati and L. Bassman, in *Materials Research Society Symposium*, **vol 653**, Z9.6.1–Z9.6.6, 2001.

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Multiscale Simulations of Interface Separation in Pre-Stressed Thin-Film Structures

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Near-tip plasticity is a significant and sometimes dominant contributor to the overall adhesion properties of multilayer thin film structures. In many technologically relevant interconnect structures, the plastically deforming layer is separated from the crack-tip by a thin elastic barrier layer. We employ multiscale simulations of such debonding by modeling a region around the crack tip where we apply local asymptotic fields as boundary

conditions. The salient parameters governing interface fracture resistance (barrier layer, plastic layer and cohesive zone properties) are explored systematically. Of particular interest in the present study is the effect of high residual stresses in the layers on local fracture processes. These stresses have a variety of origins such as thermal mismatch strains and epitaxial stresses induced by island growth. We explore the effect of such pre-stresses on the decohesion process with particular attention to the relationship between the sign of the pre-stress in the plastic layer and the resulting macroscopic fracture energy. It is shown that the pre-stress can significantly alter the local debond tip deformation behavior and influence the macroscopic fracture energy. We propose simplified models to account for this effect.

Critical Crack Lengths for Debond-Resistant Bimaterial Layers[1]

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Bonded layers of dissimilar materials form the basis for a number of engineering applications, such as thin films and coatings, layered microelectronic devices, and a variety of solid freeform fabrication or layered manufacturing processes. In many such applications, differential expansion stresses can give rise to initiation of debonding at free-edges and subsequent interface crack extension. As such, methods are required for designing "debond-resistant" bimaterial systems. To this end, design guidelines have recently been developed based on both initiation of debonding at free-edges and subsequent steady-state interface crack extension [1],[2]. However, a gray area exits between the two approaches, in which a short interface crack exists in the vicinity of the free-edge. Depending on the bimaterial configuration and crack length, such cracks may or may not be susceptible to subsequent delamination.

In this study, the susceptibility to debonding of short interface edge-cracks is investigated for the general global problem configuration of a bimaterial strip with a uniform edge load applied to the top layer (a general model of differential expansion). The goal of this study is to determine the critical crack length L below which interface crack extension is inhibited, or more specifically, for which the mode I component of the interface stress intensity factor is negative. This is equivalent to a maximum allowable flaw size, which is of substantial interest to both designers and inspectors of bimaterial systems. The critical crack length L has been extracted from parametric finite element analyses of the global problem configuration over a wide range of bimaterial combinations using the commercial software package ABAQUS. The numerical results indicate that L increases with both the relative stiffness and thickness of the top layer, and may represent a significant inspectable flaw size for a variety of practical bimaterial configurations.

[1] Klingbeil, N.W. and Beuth, J.L., "On the Design of Debond-Resistant Bimaterials, Part I: Free-Edge Singularity Approach," *Engineering Fracture Mechanics*, Vol. 66, 93-110.

[2] Klingbeil, N.W. and Beuth, J.L., "On the Design of Debond-Resistant Bimaterials, Part II: A Comparison of Free-Edge and Interface Crack Approaches," *Engineering Fracture Mechanics*, Vol. 66, 111-128.

[1]This work has been supported by the Wright State University Research Council. The authors also wish to thank Jack Beuth and Paul McKeown for their thoughts and insights related to this research.

MECHANICS OF THIN FILMS AND OTHER SMALL STRUCTURES

SESSION F3D

Microelectronics, MEMS, and Coating E

In-Situ Study of the Growth Stress and Stiffness of Alumina Thin Films during Vapor Deposition

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The evolution of the growth stress and stiffness of amorphous alumina thin films was studied in-situ during electron-beam evaporation on Si and sapphire substrates in the temperature range 170-400°C. The curvature of a cantilevered substrate was measured from the spacings between multiple laser reflections. In the initial stage of the deposition, a tensile growth stress develops immediately and has a constant value from the onset of deposition. No transient regime is observed. The value of the tensile stress decreases with increasing deposition temperature. The microstructure results from island growth, but the differences in tensile stress with temperature can not be explained by differences in island size according to the Nix-Hoffman coalescence mechanism, nor by stoichiometry or density, which remain the same. No stress

change occurs during annealing at the growth temperature following deposition, reflecting the absence of changes in microstructure or surface structure. All films deposited at 3 Å/s, and those thinner than 0.30 mm deposited at 6 Å/s, had a biaxial modulus of 200 GPa, which is 0.4 times that of polycrystalline corundum. The greater compliance is attributed to a combination of structural (atomic coordination) and microstructural (17% closed porosity) effects. In films deposited at 6 Å/s, the biaxial modulus decreased continuously for thicknesses greater than 0.30 mm. This is attributed to the development of partially interconnected, open cylindrical pores, to an overall porosity of 27%, as determined by adsorption porosimetry. The ratio of the average growth stress to the average biaxial modulus is similar in all films, both with constant and with variable growth stresses, and only depends on temperature. A constant tensile growth strain may therefore be a fundamental characteristic of the deposition process.

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Multiscale/Multi-physics Modeling of Void Evolution on Narrow Interconnect Lines

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Semiconductor devices, such as static and dynamic random access memory, use thin metal interconnect lines to electrically link different parts of a microcircuit. Downward scaling of these interconnects introduces severe concerns about the performance and reliability of the chip. One of the most compelling problems is void nucleation and growth, which degrades the electrical conductivity and eventually severs the interconnect line rendering the device inoperative. Void nucleation and growth result from mass transport and deformation. Thermal stresses and electric current are the main driving forces for void nucleation and subsequent growth.

In this paper we introduce a formulation to describe the evolution of defects driven by electromigration and thermal stresses on narrow interconnect lines. The methodology is based on a mixed discrete/continuum formulation, which merges a local Monte Carlo scheme with a finite difference one. In agreement with experiment, simulations show that for an initial defect in a perfect crystal: (temperature effects only) the defect rounds and vacancies are absorbed into the lattice; (electromigration and temperature) the defect shape is altered due to the competition of surface diffusion driven by electromigration and thermal effects; (thermal stresses, electromigration and temperature) cracks appear at the defect surface inducing a region of high stress concentration, promoting further crack growth. The current methodology offers the ability to analyze the behavior of defects subjected to individual driving forces as well as the coupled scenarios.

Dislocation Activities in Semiconductor Thin Film Systems

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Microstructural dislocation defects play a central role in the fabrication, performance and reliability of microelectronic devices. A discrete dislocation dynamics model is developed to establish the equations of motion for three-dimensional interacting dislocation loops in the semiconductor thin film - substrate system. The film is assumed to be an elastic thin layer and is perfectly bonded with another elastic substrate. The stress fields of threading and misfit dislocation loops are first calculated as an essential ingredient in the dislocation dynamics method. Dislocation loops are discretized into segments, each of which is represented by a parametric space curve of specific shape functions and associated degree of freedom. The simulation of dislocation activities is applied to several issues related to threading dislocation growth, interaction of dislocation loops with surface and interface. Comparisons between the present prediction and experimental observation are also presented.

Keywords: dislocations, stresses, semiconductors, thin films.

Delamination of Wear-Resistant Coatings

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Diamond-like carbon coatings (DLC) are of interest as wear-resistant coatings. Mechanical milling of the substrate material, which promotes film adhesion, typically produces a parallel array of milling tracks on the substrate surface. Residual stresses from the deposition process in conjunction with thermal expansion mismatch result in compressive stresses in the film that can exceed 1 GPa.

Failure of these coatings frequently begins with a delamination at the film-substrate interface directly above a convex undulation as a result of the large compressive stresses in the film. Milling tracks are unidirectional and approximately semi-cylindrical. The delamination crack spreads over the cirfumference of the wear track and then tunnels along its length. This cracking sequence finally leads to partial spallation of the coating which greatly reduces the overall wear life of the component. Buckling dominates the cracking behavior if the delamination crack is larger than about ten film thicknesses. The solution for such long cracks is well developed. However, the width of a typical wear track in a DLC coating system is on the order of the film thickness. In this paper a solution for circumferential tunnel cracks whose width is comparable to the film thickness is presented and used to investigate the failure of DLC wear-resistant coatings.

A Study Of Experimental Determination of Interface Toughness With The Mixed Mode Flexure Specimen

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Technologies that make use of thin layers of dissimilar materials for different functional requirements are fast developing. As interfacial debonding of the thin films within can severely affect the reliability of devices, the subject of interface toughness has become a crucial point of investigation. The sandwich configuration of UCSB mixed mode flexure specimens is widely used for experimental determination of interface toughness. Commonly used as the closed form solution for the energy release rate in such a specimen was derived by assuming that the contribution of the sandwich material to the total energy release rate is negligible, and hence ignored. In this paper, a finite element simulation employing a fully implicit iteration scheme and incorporating the sub-structure method, was carried out to study if this assumption is detrimental to results obtained by experimental techniques. The traction separation law of the Embedded Process Zone (EPZ) model (Tvergaard and Hutchinson (1992)) is used to model the fracture process while plastic response is characterized by the J2 flow theory. It is found that the assumption tends to yield values significantly larger than the J-integral values obtained from the finite element simulations. A correction factor taking into account of the elastic behaviour of the sandwich material is subsequently introduced in this paper.

Keywords: Interface; Experiment; Crack Growth; Closed-Form Solution

GENERAL SESSIONS

SESSION W2P
ANALYSIS OF PIEZOELECTRIC MATERIALS

Interfacial Cracks Between Piezoelectric and Elastic Materials Under in-plane Electric Loading

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We have recently developed a technique to conduct accelerated fatigue crack growth tests using piezoelectric actuators, which can reduce the time required for a typical fatigue experiment of 10^7 cycles from weeks to minutes. The key to the validity of such technique is the equivalence between results using piezoelectric loading and that using conventional mechanical loading. Evaluation of crack tip driving force for interfacial cracks between piezoelectric actuators and elastic substrate is crucial to successful applications of such technique. Here the behavior of an interfacial crack between a piezoelectric material and an elastic material under in-plane electric loading is studied. The displacement mismatch along the bonded interface due to electric potential change is modeled by an array of uniformly distributed dislocations along the interface. Using Fourier transformation method, the governing equations are converted to an integral equation, which is then converted to a standard Hilbert boundary problem. A closed form solution for stresses, electric field, and electric displacements along the bonded interface is obtained. The results agree very well with that from numerical simulations using the finite element method. The results show that the closed form solution is not only accurate for far field distributions of stresses and electric variables, but also accurate for the asymptotic distributions near the crack tip. The solution also suggests the likelihood of domain switch for piezoelectric material near the crack tip.

Observation of Inner Hysteresis Loops of BaTiO3 Single Crystals Under Electrical-Mechanical Loadings

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BaTiO3 single crystals have recently been demonstrated to display massive electrostriction under coupled electrical-mechanical loadings. The strains generated are many times that of commercial PZT. This behavior of BaTiO3 is generated by domain wall motion, and is consequently nonlinear and hysteretic.

Using a novel experimental setup by Burcsu, Ravichandran and Bhattacharya, which applies constant compressive stress and cyclic electric field to suitably oriented single crystals, we explore the interior of the hysteresis loops of BaTiO3. The crystal is simultaneously monitored using insitu polarized light micr oscopy. These inner loops help us to explore the kinetics and mobility of domain walls.

Our experiments show that, the shape of the inner loops strongly dependent on E, the amplitude of the electrical field, and they collapse to limit loops as E decreases. We also observe the evolution of the inner loops. The teachings of these results in terms of domain wall mobility, and the implications for the design of novel micro-actuators are discussed.

Keywords: Ferroelectrics, hysteresis, domain wall mobility, electrostriction

Saint-Venant End Effects in Multilayered Piezoelectric Laminates[1]

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Evaluation of the decay length and the characteristics of stress decay in a piezoelectric laminate is essential in strain measurement and designing a smart structure. In this work, the Saint-Venant end effects and stress decay in multilayered laminates of piezoelectric materials are examined. A simple yet rigorous approach is developed on the basis of the state space formalism for composite laminates in the context of generalized plane strain. By means of matrix algebra and the transfer matrix, the electromechanical fields and decay rates in self-equilibrated piezoelectric strips and laminates are determined through an eigenvalue problem. Their elastic counterparts are included as special cases. It is shown that a 2-D formulation for piezoelectric strips without accounting for the antiplane field variables is invalid for electroelastic analysis even when the piezoelectric strip or laminate is subjected to a 2-D electromechanical loading. The characteristic decay lengths of various electromechanical modes for typical piezoelectric materials are evaluated. Comparisons of the internal fields with and without piezoelectric effects show that electromechanical coupling has significant effects on the internal fields, and the Saint-Venant end effects are significant and decay length far reaching in piezoelectric strips and laminates.

Keywords: Saint-Venant's principle; Stress decay; Piezoelectric materials; Electromechanical coupling

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Thermal Fatigue of Piezoelectric Thin Film due to a Laser Pulsed

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Piezoelectric thin film materials operating in many structural components are more or less ineluctable subjected to thermal cycling. The thermal fatigue of piezoelectric thin films induced by a single or continuous pulsed laser is theoretically studied in this paper. Thermopiezoelectric problem induced by a laser beam for a piezoelectric thin film is analytically solved by integral transform technique and piezoelectric potential function method. The effects of laser beam parameters such pulsed width, repetition frequency and cycle times on the thermal fatigue of the film are investigated. The numerical results for piezoelectric thin film PZT-6B deposited on crystal silicon substrate induced by Gaussian or doughnut laser beam show that the failure of the film is in the period of cooling.

Keywords: Piezoelectric thin film, thermal fatigue, laser beam, potential function method

Keywords: Nano-indentation test, interfacial fracture toughness, ferroelectrics thin film, dependence of indentation depth

Two Variants of Self-consistent Scheme Applied to Micromechanic Predictions of Piezoelectric Composites. Some Comparisons with the Homogenization Technique

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In the present work, the self-consistent micromechanic theory is extended to consider the coupled electroelastic behavior of piezoelectric composite materials. Homogeneous matrix phase with fibers randomly distributed in the matrix is considered. The constituents of the composite are ideally elastic (matrix phase) and transversely isotropic piezoelectric medium (fibers). Two variants of the self-consistent scheme, the Effective Field Method (EFM) and Effective Medium Method (EMM) are applied to calculate effective material properties, such as, effective dielectric, piezoelectric and elastic properties of the piezoelectric-composites. Explicit and closed-form expressions are given for each variant of the self-consistent methods. The universal relations of Schulgasser are satisfied for both set of formulae. Numerical results are presented to illustrate the effect of concentration of volume fraction of the fibers on the effective properties. A comparison with the asymptotic homogenization method (AHM) is carried out. Good theoretical results between them are obtained. Some applications to ultrasonic transducers are shown.

Assessment of Interfacial Adhesion of PZT Ferroelectrics Thin Films by Nano-Indentation Test

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Interfacial adhesion is becoming a critical material property for improving the reliability of multiplayer thin film structures. Nano-indentation testing techniques were used to quantitatively assess the adhesion of PZT ferroelectrics thin film-substrate systems. In the test, the effect of residual stress on the interfacial fracture toughness was considered. The nano-indention fracture of PZT ferroelectrics thin films deposited by metal organic decomposition (MOD) and solution-gelation chemistry (sol-gel) were studied using a cube corner indenter. The residual stresses in the ferroelectrics thin films were estimated by continuous sharp nano-indentation method. The interfacial fracture toughness was determined by testing relationship of load and indentation depth as well as the radius of the thin film delamination. The experimental results show that the interfacial fracture toughness was not a constant and it was dependent on the indentation depth.

Irreversible Thermodynamic Modelling of Phase Transition in Ferroelectric Ceramics Under Large Mechanic or Electric Loadings

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Our objective is to describe the irreversible thermodynamic processes that are observed in the application of piezoelectric ceramics such as PZT actuators and sensors. Typically, such processes involve nonlinear thermo-electro-mechanical coupling. Such "smart" components exhibit the following characteristics: nonlinear dielectric hysteresis, Ferro elastic hysteresis, butterfly hysteresis, phase transition and depolarization etc. In this paper, a thermodynamic model that is based on the hybrid framework of extended irreversible thermodynamics (EIT) and internal variable theory (IVT) is presented to describe PZT behavior beyond the linear approximation region. At each instant, the local state is described by both a set of classical state variables and a set of extended non-equilibrium state variables (non-equilibrium thermodynamic fluxes). The classical set of state variables includes temperature, strain (or equilibrium stress), and electric displacement (or equilibrium electric displacement). Extended non-equilibrium thermodynamic fluxes are heat flux, non-equilibrium stress field, non-equilibrium electric displacement. A phase transition model is used to account for all the hysteresis phenomena. To describe polarization reversal, the mass volume fraction for each phase (two phases with opposite polarization) is chosen as an internal state variable. The nucleation fluxes for each phase are the non-equilibrium thermodynamic fluxes that describe the non-equilibrium fluctuations of phase transition. In this model, a coupling between thermal, electric and mechanical fields exists in (traditional) equilibrium fields and

non-equilibrium fields. The energy balance equation governs the energy conversion between electric, mechanical and thermal fields. The determination of PZT energy dissipation can be very important in the design and application of intelligent systems.

SESSION R4R
APPLICATIONS OF FINITE ELEMENT METHODS I

Hygro-Mechanical Deformation of Cardboard: A Numerical Study

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The paper and wood industries are very important for Canada. One concern of these companies is the in-service transient warping of their products when subjected to ambient humidity changes. A research project, funded by the Canadian company Cascades, has been initiated to better assess the deformation behavior of cardboard sheets subjected to such changes. The purpose of this paper is to briefly describe the model, the analysis process, and the results of this study.

The in-plane dimensions of the sheet are 70X100 cm. The cardboard is a 3-layer 0.506 mm thick unsymmetrical laminate. The orthotropic properties of each layer are summarized in Table 1, where M, R, and T designate respectively the machine, transverse, and thickness directions. Values for the Poisson's ratios are not provided. Difficulties in the measurement of these coefficients have been experienced and will be described.

Table 1. Mechanical properties of each layer

Layer	Direction when applicable	Thickness (m)	Density (kg m^{-3})	E (GPa)	G (GPa)
Top	M	59^{-6}	1373	5.9	2.36
	R,T			1.5	
Middle	M	405×10^{-6}	578	1.9	1.17
	R,T			0.8	
Bottom	M	42×10^{-6}	833	4.2	1.46
	R,T			1.4	

Layer	Diffusion coefficient $D(m^2\ s^{-1})$	CME Desorption $(mm^{-1}\ \%^{-1})$	CME Adsorption $(mm^{-1}\ \%^{-1})$
Top	5.7×10^{-11}	1.0×10^{-4}	0.9×10^{-4}
		5.3×10^{-4}	7.2×10^{-4}
Middle	5.7×10^{-11}	1.2×10^{-4}	$1,8 \times 10^{-4}$
		$4,7 \times 10^{-4}$	5.8×10^{-4}
Bottom	5.7×10^{-11}	1.8×10^{-4}	1.9×10^{-4}
		5.4×10^{-4}	11.0×10^{-4}

It is assumed that: 1) the sheet is in moisture equilibrium at t=0; 2) it is resting on an horizontal surface; 3) gravity acts in the thickness (T) direction; 4) the sheet is initially stress free; 5) Water exchange occurs only through the top face of the sheet; 5) Initial paper moisture content (M) is 9%; 6) at t=0, ambient humidity is raised to 18% and maintained at this value up to t= 20000 s; 7) ambient humidity is lowered to 9% at t=20000 s and maintained at this level up to t=40000 s;

To study the evolution of the deformation process, a finite element model has been set up in ABAQUS. A fully coupled solution procedure of the transient diffusion and 3D equilibrium equations at a series of automatically chosen time steps is used to solve for the corresponding moisture levels and displacements.

Results of moisture content gradients and overall sheet deformation will be presented. It will be shown that, due to the difference in the coefficients of moisture expansion (See CME values in Table 1), residual deformations are present in the cardboard even when ambient conditions have returned to their original value.

Keywords: cardboard, laminate, deformation behavior, numerical modeling

Numerical Simulations of Dynamic Fracture Process in Brittle Materials

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Brittle structures often develop complex fracture and fragmentation patterns. The fragments sizes and distributions of a brittle structure depend on the material properties and the loading conditions. Within the context of the finite-element method, the cohesive model theories have enjoyed a wide success in explicitly modeling crack initiation and propagation.

In this paper we investigate numerically the dynamic crack propagation process in brittle materials. After a review of popular cohesive element models and existing techniques for dynamic insertion of cohesive elements, we will present two fully three-dimensional simulations: (a) the dynamic bursting (fragmentation) process of a rotating ceramic ring, and (b) the dynamic crack propagation within a long strip. Experimental data of these problems have been collected from the literature. The presented simulations are perfect candidates to investigate the numerical feasibility and challenges of using cohesive theories of fracture.

In the simulations, we highlighted the influence of stochastic variations of the material strength on the formation of micro-cracks. In essence, these variations shine

light on the influence on the numerical results of initial defects and microstructural configurations. The dependency of the crack propagation patterns and velocity profiles on the numerical meshes is also discussed. To conclude, we will correlate the cohesive element material parameters to crack branching, crack velocity and fragment size. The results of the simulations agree with the experimental observations.

Keywords: Brittle material; Dynamic fracture and fragmentation; Finite Elements; Cohesive elements

On Modeling Bonds in Fused, Porous Networks: 3D Simulations of Fibrous/Particulate Joints

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Fused, fibrous networks are used in Li-ion and NiMH battery electrodes containing porous carbon or metallic substrates, gas filters comprised of sintered metal fibers, and open space trusses manufactured of cast metals. Mechanical behavior of these porous network materials is largely governed by the strength and behavior of the network bonds. Model 2D stochastic networks (Figure 1a) have been shown to be accurate in modeling both transport and mechanical properties and their variances in real materials[1,2,3]. Here, we model the response of geometrically complex 3D joints under load, in order to inform 2D network simulations on appropriate joint properties.

Failure of these joints is hypothesized to be ductile, and we therefore model the geometry and response of bonds among cylindrical fibers (inset of Figure 1a) as containing a fillet at the joint (Figures 1b and 1c) to eliminate stress singularities. We define a degree-of-intersect (d.o.i.) as d.o.i.=d/T to quantify interpenetration of the cylindrical segments (L_1,L_2); volume of the two original segments is conserved with selection of the radius of curvature of the fillet, R.

We present finite element simulations of the local stresses in two cylinder assemblies with aspect ratios ($[L_1+L_2]/d$) of 100, 0.5<d.o.i.<1.0, and intersection angles of 45°, 60°, and 90°. The maximum joint stresses in the 3D simulations were shown to increase significantly with decreasing d.o.i. for all ratios of segment lengths (L_1/L_2) studied. For example, for intersection angle 90° and $L_1/L_2 = 1$, the ratio of maximum joint stress in the 3D versus 2D simulations were 3.2, 1.7, and 1.3 for d.o.i. of 0.52, 0.55, and 0.65 respectively. Further, for any given combination of d.o.i. and length ratio, the ratio of maximum 3D joint stress to the maximum joint stress obtained via 2D simulation increased with decreasing intersection angle. For example, for d.o.i.=0.65 and $L_1/L_2 = 1$, the maximum joint stress in the 3D simulations were found to be 3.9, 2.3, and 1.7 times the joint stress of the corresponding 2D simulations for intersection angles of 45°, 60°, and 90°, respectively.

The results of these 3D simulations underscore the dominance of joint behavior in network response, as well as the dependence of this response on the details of the geometry of the joint. The results also demonstrate the feasibility of adaptation of the results of more tractable 2D simulations of stochastic networks to capture the stress-enhancing effects of the actual 3D joint geometry of microscale materials.

Keywords: network, fiber, stochastic, damage

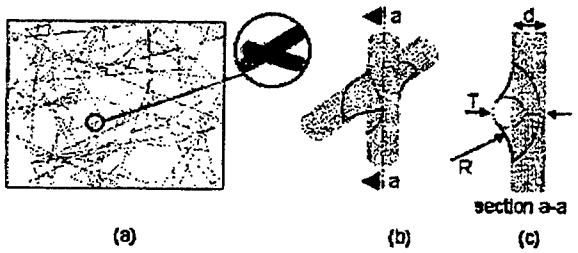


Figure 1. Network (a), and element (b,c) models for 3D analysis.

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Fractal Interpolation in Solid Modelling and Meshless Structural Analysis

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A method based on fractal interpolation is proposed to remove shape imperfections for curve and surface generation. The concept of fractal dimension of an object,

assumed as numerical descriptor of its tortuosity, allows geometrical comparisons for different profiles. Considering a set of contractive affine transformation, by the combination of a rotation and scaling or resizing, we are in condition to transform the components of a given point in order to obtain the vertical scaling factor d_i, a numerical descriptor of the relative roughness of that part of the object, as compared to the rest. Being d_i computed for interval of two points, $\Sigma|d_i|$ is the vertical scaling factor for the whole data set of points. If N is the number data points of a shape and D the fractal dimension of the corresponding geometrical object, the above factor must satisfy the condition:

$$\Sigma|d_i| = N \qquad \textbf{(D-1)}$$

From an applicable viewpoint, introductory numerical examples of fractal dimension for spline, triangular patch, triangular mesh, sweeping solid, are proposed in solid modelling and in the patch test for meshless structural analysis. In the case example of triangular patch, in order to remove shape imperfections in the mesh generation, due to different fractal dimension of mesh lines, we turn to account the fractal dimension of such surface introducing local fractal control subpolygons for smooting needy mesh lines. A similar procedure is proposed in solid modelling, where the digitized data points manifests typical problem in the solid generation process; reinserting the data points from fractal dimension of the "feature", the "protusion" modelling of the smoothness surface appears to be feasible. Fractal interpolation of node-points appears to be a promising way in the translation to FEM (finite element method), introducing proposal for further investigations on meshless methods.

Keywords: Fractal, solid, modelling, meshless .

Two Dimensional Finite Element Analysis for Cantilever Beam

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In the present work, it is aimed to analyze the cantilever beam, using two-dimensional Finite Element Method. An eight node isoparametric quadrilateral element has been employed to perform stresses, strains and deflections at any point on the beam under different loading and support conditions.

Based on Quick Basic language a computer program has been developed and employed to perform Finite Element calculations. The numerical results showed good agreement when compared with the theoretical results.

More Readable, Manageable and Extensible Codes for Finite Element Analysis Using JAVA

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Throughout the history of computing, the innovations and advances in computer language design have been driven by the perpetual need to handle the increasing complexity of software. The programming language JAVA was developed by refining the object-oriented programming paradigm of C++ to provide a platform independent language that would be readily portable across a variety of architectures. Object Oriented Programming (OOP) in JAVA allows the programmer to remain close to the higher-level physical model of the real-world problem through the use of data abstraction, encapsulation, inheritance and polymorphism. The present paper attempts to demonstrate the unique programming capability and versatility offered by JAVA for writing more readable, manageable and expandable object-oriented codes for computational finite element analysis. The paper presents illustrative user code fragments of an object-oriented program that was developed in JAVA for finite element analysis of a structural system with the purpose of highlighting the relative advantages of using JAVA in object-oriented programming of large-scale scientific codes for finite element analysis. The user-code segments are accompanied by a commentary that is intended to provide more detailed directions to civil engineers who wish to adopt JAVA and the OOP paradigm in the development of computer programs for finite element analysis. The paper describes the salient advanced features of JAVA that can be advantageously employed in computational finite element methods. The paper also provides a brief theoretical background on the important basic elements of JAVA for the orientation of civil engineering professionals who are new to the concepts of JAVA and OOP. The paper includes a review of the evolution in computer programming languages over the past few decades that elucidates why JAVA and its generation may be the programming languages of choice for scientific codes in the future.

SESSION F2I
APPLICATIONS OF FINITE ELEMENT METHODS II

Effect of Heat Sink on the Final Fatigue Life of Flip-Chip Packages

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Numerical studies are conducted to investigate whether the final fatigue life of flip-chip solder interconnections are affected by the ways to mounting solder balls and the heat sink. Two finite element models, the heat sink model and non-sink model, are used to simulate the effect of the processing mechanics and sequent cycle thermal loads on mismatch. This paper models the bonding process and sequent cycle thermal loading. Simulation results show that heat sink can extend thermal fatigue life of electronic packages in two ways. One is in thermal load, heat sink can lower the upper limit of thermal load, and fatigue life gets nearly 5% increase with 1% temperature decrease. The other is in construction, heat sink can counteract thermal deformation and stress caused by different CTEs. The predicted deformation values of the flip-chip package obtained from the numerical analysis are compared with the test data obtained from the laser moir interferometry technique. The displacement contours of the flip-chip package samples obtained from the test show similar distribution patterns compared with those modeled by the finite element method.

Homogenization Techniques to Include Plasticity Effects in Materials

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To describe the behavior of materials and structures accurately, it is essential to compute the eects of materials at dierent hierarchical scales spanning many orders of length scales, from atomic level (in nano meters), through grain level (in micro meters) to macro level (in tens of millimeters). Dierent computational tools specic to a given scale such as, molecular dynamics codes, crystal plasticity codes, and nonlinear nite element codes are employed in modeling the behavior of solids at disparate scales. Though these tools are currently being used for many scientic investigations, and perhaps even engineering applications, their use are usually isolated and disconnected. In order to combine their capabilities in solving critical engineering problems, certain basic mechanics, physics, materials and computational issues need to be clearly resolved. The purpose of the present paper is to examine a few steps in this hierarchical approach with special reference to one of the processes pertinent to ductile rupture, namely, the plastic deformation of a single-crystal.

Here we attempt to link heterogeneous grain level micro structural behavior to continuum scale by using mathematical homogenization theory [3]. This is achieved by decoupling the heterogeneous body ε into a continuum scale homogeneous body X and a meso scale (Y scale) polycrystal Θ (see Fig. 1(a)). A methodology for multiscale simulation is proposed by employing a two scale asymptotic expansion [1] for the displacement and eigenstrain elds to describe the material heterogenity and inelastic strains (plastic defor- mation). The inelastic strain or eigenstrain evolution is obtained from from a mesoscale, micro-mechanical model based on crystal plasticity [2]. The microstructure at Y-scaled enoted by Θ is assumed to be made of ensemble of 216 grains (see Fig. 1(b)) and is periodic. For linear problems a unit cell or a representative volume of microstructure (Y domain) characters needs to be evaluated only once for the given loading. On the otherhand for nonlinear history dependent systems, features of Y domain has to be solved at every load increament and at each macroscopic gauss point. The above formulation will be implemented in nite element schemes to solve boundary value problems.

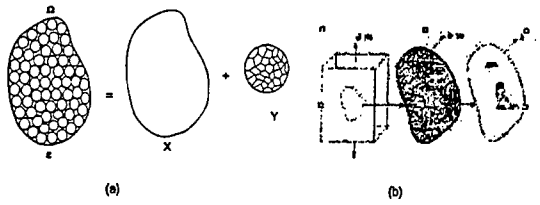


Figure 1: (a) Heterogeneous body e with an homogenized body in X and a representative unit cell T in Y with 216. (b) Micromechanical model of a polycrystal for eigenstrain evolution

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Incomplete Constitutive Relationship in Computer Simulation in Manufacturing Processes*

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The purpose of this work is to present novel alternatives to IMCR-the incomplete material constitutive relationships among process variables employed in the analysis of material processes in manufacturing, mainly machining and forming. Processes include variables such as Sij (stress tensor), Eij (strain tensor), dEij (incremental strain tensor), Ëij (strain rate tensor), 1/T (homologous temperature), and Q(activation energy). Applications of IMCR in manufacturing processes result in errors when one use computational simulation by Nonlinear Finite Element Analysis. In addition one observes miscalculations that can rise from computer CPU and application software errors. In the present one might note the increase and all spread application of non-FEA in manufacturing industries vastly. Critics to these computer practices proclaim someone in more errors. One reason relays on the dependence on some materials process manufacturing from the continuous mechanic's viewpoint, it means: if solid mechanics or/and fluid mechanics. From the nonlinear solid mechanics originate more questions if material's or geometrical dependence occurs. Nevertheless, non-FEA deals quite nicely in these nonlinear solid continuous mechanics. The great questions arise from fluid mechanics approach. First, one must deal with Newtonian or non-Newtonian related to thermal-viscous-elastic-plastic behavior. It appears that someone must deal within rheological problem fields. To these types of fluid mechanics problems, the experts show the use of non-FEA but CFD-Computational Fluid Dynamics computer codes. Due to damage and instabilities in solid mechanics one should use the Damage Mechanics approaching near the deformation limits. Linear and nonlinear plastics behaviors require the use of deformation theories or flow theories in the analysis, it means in non-FEA or CFD type of computational analysis. What is theoretical relationship between Sij and dEij? Is it a forth rank tensor? Is it a not symmetrical tensor? This is our master problem nowadays. The results from the application of these complexes' methods are all spread in literature. The join all of above and related them to fourth rank unsymmetrical tensor will be the great technical purpose in the future. A possible resolution to theses problems would be to enclose the constitutive relationship inside a generalized Hill type energy formulation. Cases from actual scope of this work are presented and discussed.

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Finite Element Limit Formulation for Dynamic Simulation of Structural Members

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Structural members of a vehicle are designed to increase the energy absorption efficiency and thus to enhance the safety and reliability of a vehicle. The crashworthiness of each member needs to be done at the initial stage of vehicle design for good performance of the whole design process. As the dynamic behavior of structural members is different from the static one, the crashworthiness of vehicle structures has to be assessed by numerical impact analysis considering dynamic response related to the inertia and strain-rate hardening effects. Impact simulation is usually carried out with the elastic-plastic finite element analysis code such as PAMCRASH or LS-DYNA3D. However, it inevitably requires tremendous time and efforts to estimate the crashworthiness of structural members even with the explicit methods. Impact simulation with finite element limit analysis considering dynamic effects is an alternative to reduce the computing time and efforts dramatically for the crashworthiness assessment of structural members.

The conventional limit analysis method seems seldom applied to real complicated structural problems probably because of the limitation of the method. However, a burst of development in limit theories and computer technology enables limit analysis applied to complicated structural problems. Especially, the limit analysis concept has extended to a class of work-hardening materials from its long conjecture of perfectly plastic materials. In this paper, the limit analysis concept is extended

to consider the dynamic equilibrium condition considering the inertia and strain-rate effects instead of the static equilibrium. A dynamic formulation for the limit analysis has been derived for incremental analysis dealing with time integration, strain and stress evaluation, strain hardening, strain-rate hardening and thermal softening. The time dependent term in the governing equation is integrated with the WBZ-α method, which proposed by Wood, Bossak and Zienkiewicz. The dynamic material behavior is modeled with the Johnson-Cook relation in order to consider strain-rate hardening and thermal softening as well as strain hardening. Simulations have been carried out for impact analysis of structural members and numerical results are compared with elastic-plastic analysis results from ABAQUS/standard and LS-DYNA3D. Comparison demonstrates that the dynamic finite element limit analysis can predict the crashworthiness of structural members effectively with less computing time and effort than the commercial codes compared. The crashworthiness of the structure with the rate-dependent constitutive model is also compared to the one with the quasi-static constitutive relation for demonstration.

Keywords: Finite element limit analysis, Dynamic formulation, Structural impact, Strain-rate hardening

Finite Element Simulation of Impact to a Kevlar Vest Worn by a Human Thorax

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The Army Research Laboratory licensed access to the 1999 version of the WSU thorax model (WSTM99), a 3D finite element (FE) model developed by Kevin Wang and his thesis advisor, Professor King Yang. The model was originally developed for automotive applications, and we are applying it to problems involving body armor. Our goal is to develop an FE-based design methodology for body armor.

For our initial application, we used WSTM99 and LS-DYNA to simulate tests performed at the Armed Forces Institute of Pathology. In these tests, a 9-mm-diameter lead bullet impacted at 425 m/s a Kevlar (fabric) vest worn by human thoracic tissue. Endevco accelerometers were surgically implanted at four locations: the posterior sternum, the carina of the trachea, the ligamentum arteriosum, and the spinous process of the T7 vertebra. In the tests the vest stopped the bullet, but the thorax nevertheless underwent shock loading and subsequent large displacements.

HyperMesh was employed to add an FE model of the vest to the exterior of WSTM99. We discuss constitutive modeling of Kevlar. We present FE results for velocity contours throughout the thorax and accelerations at the four locations for which data were obtained. Guided by acceleration comparisons with experiment, we draw conclusions regarding instrumentation and we propose modifications to WSTM99.

SESSION F3I
APPLICATIONS OF FINITE ELEMENT METHODS III

A New Finite Element Method Integrating Extrinsic And Intrinsic Cohesive Zone Models

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Cohesive Zone Model (CZM) is increasingly being used as a method to model fracture processes because it eectively appeals to both physics and mechanics. CZM eliminates the presence of a singularity in the stress field and manages to maintain a mathematical continuity in displacement and traction across the separating surfaces. CZM can model not only crack initiation (as in most of the fracture mechanics approaches), but also crack propagation without invoking any ad-hoc external criterion. The constitutive model for CZM is prescribed through a traction-displacement relationship motivated by experimental observations. The shape of the traction-displacement response is believed to be the cumulative eect of several micromechanical dissipative processes occurring both in the forward and the wake regions of the crack. The main advantage of CZM lies in its ability to be implemented within a numerical scheme like finite element method with relative ease.

Two different approaches have been followed in the numerical implementation of CZM, extrinsic and intrinsic. In the extrinsic type, an external fracture criterion is required for crack initiation and when the crack is allowed to propagate, then the scheme does not conserve energy. Here the stresses in the normal and tangential directions at the midside node of the interface is compared with an ad-hoc fracture criterion, and upon satisfying the crack propagates following the extrinsic cohesive law. In the intrinsic type no external fracture criterion is needed and the surfaces separate as a consequence of the traction-separation law. However, in this case separation of the elements takes place not only at the crack tip region (with steep stress gradient) but also at the regions where the stresses are not so high. This is just a consequence

of the fact that separation ± occurs for all non-zero values of traction T , the amount of separation depending on the magnitude of the traction. Obviously this does not represent the physics of the problem where regions far away from the tip are governed by material constitutive law and not the cohesive law. Thus both the approaches have shortcomings. To overcome the problem of using external fracture criterion (extrinsic) and element separation at all loca-tions (intrinsic), a new unified (and modified) CZ element is proposed in this paper. The new element while incorporating the advantages of both the extrinsic and intrinsic models avoids their pitfalls. In the new approach, illustrated in the figure below, cohesive zone elements will be modeled as three layered element assembly. The central element will have zero thickness and is based on intrinsic CZM while the outer two layers are based on constitutive model of the bounding material. Once the energy in the outer elements reach the value given by the forward region in the T ± curve, then the element will be allowed to separate thereafter following the post-peak behavior. Some illustrative examples will be presented to validate the accuracy of the proposed element.

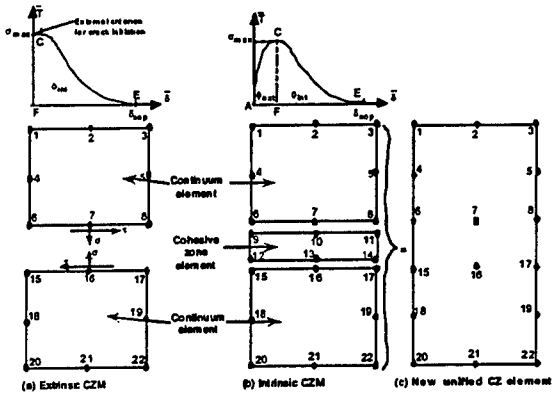


Figure 1: Extinsic, Intrinsic and Unified Cohesive Zone Models

Finite-Element Line-of-Sight Jitter Performance Under Gunfire Vibration

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This paper discusses the finite-element approach to predicting the structurally induced line-of-sight (LOS) jitter variation for a housing component under gunfire loading. The housing is cast from A356 aluminum material prior to final machining and utilizes sophisticated optics and electronic assemblies. The analysis approach is described from beginning to end whereby a CAD/CAE model is taken and meshed with NASTRAN finite-elements. Optical sensitivities are included in the finite-element model and code is written into the finite-element data file to predict the LOS jitter performance. An appropriate level of damping is assumed for the overall structure. Properties are assigned and boundary conditions are applied to the model in order to first perform an eigenanalysis to determine the modal frequencies and mode shapes of the structure. The eigenanalysis is saved into a database in preparation for a modal transient analysis that utilizes the mode shapes of the structure as modal coordinates and applies the time history loading as a transient. This assumes that a sufficient number of modal frequencies and associated mode shapes are retained in order to accurately represent the dynamic characteristics of the structure. The LOS jitter performance is produced from the transient loading as a response to the applied loads in the form of a time history. The effect of including or ignoring the rigid-body modes is discussed. RMS values of the LOS jitter response are calculated and presented.

Radial Boundary Node Method for Elastic Problem

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FEM and BEM are widely used in solving partial differential equations for elastic problems. However, it is time consuming for both to trace conditions varying with time by changing element information. Applying the moving least-square (MLS) approximation, the boundary node method (BNM) removes elements and can adapt the moving boundary easily. Unfortunately, BNM inherits the deficiency of MLS, in which the shape functions lack delta function property, so implementation of essential boundary conditions is difficult for BNM. Furthermore, the present BNM uses flat integration cell, which cannot accommodate curve boundary.

This paper proposed a radial boundary node method (RBNM). Using improved interpolation and integration technique, it retained the dimensional attribute of BEM and BNM in decreasing dimension of problem. Simultaneously, by using radial basis functions, its interpolation functions exactly hit nodes, and thus the shape functions possess delta property. The shape parameters were studied in detail for multiquadric (MQ) and exponential (EXP) basis functions. In addition, a quadratic integral procedure was introduced in RBNM. Finally, Some examples

were studied to verify if RBNM were generally suitable for two-dimensional elastic problems.

Results obtained from numerical examples showed that shape parameters used in RBNM should be selected carefully, or else the calculating results would fluctuate violently. For EXP basis, in a range from 0.03 to 0.1, the error is steady and low with varying b value; For MQ basis, in ranges from 0.96 to 0.99 and 1.01 to 1.05, the error is acceptable with varying q value. From the case studies, it was also proved that RBNM has comparable or even higher accuracy contrasted with BEM.

The results suggested that the current RBNM could be robust and thus applicable. The appropriated ranges of parameter b for EXP basis and parameter q for MQ basis were suggested according to the results.

Saint-Venant and Almansi-Michell Problems for a Prismatic Beam with a GEneral Cross-Section

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A solution procedure is presented for the Saint-Venant and Almansi-Michell problems for a prismatic beam, whose cross-section is general in terms of its shape and the number of distinct, perfectly bonded, linearly, elastic anisotropic materials. Recall that Saint-Venant's problem dealt with a beam with a free lateral surface and applied tractions on the ends whose resultants are axial force, bending moments, torque and transverse forces, while the Almansi-Michell problem accommodated body forces and lateral surface tractions applied to this beam that are expressed as a power series in the axial coordinate. Such solutions, which are based on three-dimensional elasticity, enable an evaluation of all simplifying kinematic hypotheses of structural beam theories and demarcation of their ranges of applicability.

A semi-analytical finite element formulation is used and the kinematic fields for the different loading conditions in terms of an unknown set of kinematic coefficients are stated at the outset. Finite element analyses are used to establish cross-sectional warpages and particular solutions. Then, by enforcing global equilibria, these unknown kinematic coefficients are defined. Some examples are given to show this procedure. The same system of governing equations can be used to extract end solutions in the form of a complete set of eigendata. Such data is used to represent end conditions that are different from those of the relaxed Saint-Venant and Almansi-Michell solutions, thus quantifying Saint-Venant's principle.

An Economic Efficient Stable Algorithm for Damped Coupled Thermal-Structural Problems

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An efficient unconditionally stable numerical algorithm for the analysis of damped dynamic coupled thermal-structural problems using the finite element method is presented in this paper. The time integration of the semi-discrete finite element equations is performed using an implicit scheme. The algorithm proves to be effective and versatile in thermal and stress wave propagation analysis. Computer implementation aspects are discussed and a typical case study is presented to demonstrate the effect of material damping on thermoelastic analysis of structural problems. It is found that the thermal stress shock wave has inverse proportionality to the material-damping coefficient. Also, the implementation shows at lest memory saving more than thirty percent of the other techniques, which is saving on the computational time.

Keywords: Damped thermal Structure, Dynamic thermal-structural, coupled thermal-structural problems, implicit time-domain integration, finite element analysis.

Hybrid Scheme of Finite Element Method in the Problems of Calculation of Layered Shells and Plates with Regard for Possibility of Weakening or Breaking the Interlayer Contacts

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The modern stage in mechanics of the composite plates and shells, variational problems and finite element methods are analyzed and actuality of the interphase contact problem with damages such as delaminations and sliding zones is emphasized.

The discrete layers' description the basic cases of mathematical models are systematized and the correspondent energy functionals are given when the interlayer damages are being taken into consideration. The nonideal interaction assumes the jumps of the value of displacements with continuity of stresses on interphase surfaces. The

summarized principle of potential energy by Lagrange's multiples method for the kinematic contact conditions is generalized. The calculatory schemes based on the m,n-approximation method for all elasticity equations of an anisotropic layer by series on Legendre polynoms are constructed. In this case the displacements on interface surfaces depend on the displacement of middle surface as well as the contact stresses. As a result the functional have the second degree of contact stresses. Such approach is more preferable than the models within the framework of the classic hypothesises like the Tymoshenko's shear theory. The mixed finite element method in the form of generalized displacements of layers and contact stresses is proposed.

The next part of work contains the theoretical results as to the development of the solution method. The peculiarities of the statement of the variational problem have been investigated. The saddle point theorem and the existence of the unique solution are proved. For symmetric but not positively-determined system of linear algebraic equations with block structure the asymmetric scheme of factorization is constructed and on its base the special iterative algorithm for calculation of the contact stresses and jumps in the damage zones is proposed. The general object-oriented approach concerning the program's realization is developed.

Analysis of finding solutions of series problems of bending two- and three-layered plates, cylindrical and spherical shells with ideal and nonideal interphase contact shows a perspectivity of such given approach to evaluation of contact strength of layered structures on designing stage.

SESSION W3G
ARTERIAL FLOWS IN HEALTH AND DISEASE

A Blood Particle Residence Time Model for the Evaluation and Design of Femoral Bypass Grafts

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Mounting clinical and laboratory evidence shows that excessive blood particle interaction with a dysfunctional vascular surface triggers and sustains a cascade of biological processes which may lead to stenotic developments and/or thrombus formation ultimately resulting in vessel occlusion. A thorough understanding of blood particle motion, particularly in the near-wall region, is critical to identify regions susceptible to hyperplasia formation in branching blood vessels (e.g., bypass graft-end configurations) and for the prediction of vessel failure due to thrombosis.

Previous blood particle simulations in complex geometries have widely ignored the hemodynamic effects of the wall on particle motion and assumed that particle adhesion occurs at the point of surface contact. Inclusion of the lubrication force and lift force in the equation of particle motion results in more accurate near-wall particle trajectories, especially in the wall-normal direction. Still, a number of physico-biological particle-to-surface interactions remain elusive, which is the rational for the more probabilistic, near-wall residence time (NWRT) model.

In conjunction with the widely accepted wall shear stress (WSS) based hemodynamic parameters, e.g., regions of low WSS, the NWRT model shows a high correlation to measured cell deposition data and hyperplasia development. Considering regions of vessel wall dysfunction in conjunction with the probability for particle attachment, branching blood vessels may be more accurately evaluated to identify sites of potential stenotic developments. As a specific case study, selected current designs of the distal femoral bypass graft-end will be evaluated. Resulting from this comparison study will be design recommendations for future graft-end configurations that may generate high sustained patency rates.

Weighted Temporal and Spatial Smoothing for the Inverse Problem of Electrocardiography

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We present a straightforward method for incorporating temporal smoothing into the estimate of epicardial potentials from body surface potential data. Our algorithm employs a different spatial smoothing parameter, chosen by the CRESO criteria, at each time step in the sequence. The total spatial smoothing term is then simply partitioned between temporal and spatial smoothing. The algorithm appears to be quite robust with regard to this partitioning. In examining the match between estimated and measured electrograms, or the match between estimated isopotential maps and measured isopotential maps, the estimates

constructed using the new temporal smoothing algorithm produced consistently smaller relative errors than those constructed using a quasi-static algorithm or those constructed by post-processing the quasi-static estimate with a moving average filter.

This work was supported in part by the National Science Foundation grant BES-0001315.

Viscous Drag of Deformed Vesicles in an Optical Trap: Numerical Simulation and Experiments

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Traditionally, Stokes-Einstein theory is applied in the calculation of the maximum lateral (drag) force induced by an optical trap acting on a rigid sphere. Experimental results show that the spherical vesicle is deformed to a more cylinder-like shape by the pressure gradient inside the laser trap. Moreover, such a vesicle, traveling in liquid medium, is naturally deformed by flow hydrodynamics force, and thereby the drag force will deviate from that of a rigid sphere. Thus, it is critical to elucidate whether a discrepancy in the calculated drag force exists when the trapped vesicle is deformed under flow. In this study, optical tweezers is applied to interrogate the shape transformation of a moving unilamellar vesicle, and finite different method combined with elliptic grid generation technique is developed for calculating drag coefficients. The results show that the shear stress distributions on the vesicle surface are reduced for a deformed vesicle in the laminar Stokes flow regime. The drag coefficient deviation can be up to 38.3% even for a slightly deformed vesicle. Overall, this study provides new insights into the mechanics of suspending model cell under flow and interpretation of lateral drag force of deformable vesicle.

Keywords: Optical tweezers, Cell mechanics, Hydrodynamics forces, Stokes flow

Chaotic Onset of Sickle Cell Blood Flow Crises

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Existing Lagrangian-based formulations of sickle cell blood flow in capillaries have been extended. A novel Eulerian-based model [Apori-Harris model] that includes the oxygen concentration, red blood cell average velocity, cell stiffness, and plasma viscosity as dependent state variables has been used to investigate the chaotic onset of sickle cell blood flow crises in capillaries. In canonical form, the Apori-Harris model is a set of coupled, non-linear equations in which the velocity-viscosity and viscosity-cell stiffness relationships dominate the physics of the model. The equation set is investigated to determine its chaotic properties with respect to control parameters representing the specific rheology of the sickle cell erythrocytes. A mathematically rigorous definition and a clinically acceptable definition of sickle cell crises onset in capillaries have been derived and are based on the eigenvalues of the equation set in 4-dimensional phase space. Results of chaos tests proved positive for a range of the selected control parameters. The results include (a) continuous patterns found in the Poincare section, (b) spectral broadening of the Fourier power spectrum, (c) fractal dimension, and (d) positive Lyapunov exponent values. The mathematical prediction of chaotic onset of sickle cell blood flow crises in capillaries based on the Apori-Harris model coincides with the change from a clinically healthy person to a clinically defined crisis state for sickle cell disease. Our findings identify new ways to prevent and to treat crises and point to specific clinical trials.

Keywords: biofluid mechanics; chaos; sickle cell disease; Lyapunov exponent

SESSION R4D
BIFURCATIONS AND NONLINEAR DYNAMICS IN FLUIDS

Three-dimensional Simulation on Flow Bifurcation in a Plane-symmetric Channel with Sudden Expansion

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Flows in sudden expansion are classical examples of many aspects of fluid flow phenomena. The inherent nonlinear flow transition from symmetric to asymmetric states with increased Reynolds number makes the problem become complexity and attraction. In this study, direct numerical simulation were performed three-dimensionally to conduct the flow simulation. In a careful and extensive

computational study, we observed that when the channel aspect ratio exceeds a critical value, the well-known step-height (pitchfork) bifurcation evolves with different symmetry breaking orientations on the left and right sides of the channel in the spanwise direction. For the channel aspect ratio less than the critical value, the orginally occurring spanwise bifurcation cannot be stably retained and eventually to a step-height bifurcation only. Compared to the step-height bifurcation, the spanwise bifurcation is found to be more difficult to obtain, because the symmetric flow present on the spanwise symmetry plane is unstable in two dimensions. For completeness, an extensive analysis of the observed spanwise bifurcation, covering its transient behavior, dependence on flow Reynolds number, channel aspect ratio, and expansion ratio, is included.

Keywords: numerical, symmetric-channel with sudden expansion, spanwise bifurcation, three-dimensional

Mixing Enhancement by Dual Speed Rotating Stirrer

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Stirring is a well-known mean of fluid mixing due to the emergence of complex patterns in the flow, even at low Reynolds number. In this work, we consider a stirrer rotating along a circular trajectory at constant speed. The fluid flow, considered incompressible, inviscid and two dimensional (in a circular container), is modeled by a point vortex model consisting of a vortex rotating in a circular container at constant angular speed. The mixing problem is addressed by considering the Hamiltonian form of the advection equations formulated in the frame of reference moving with the vortex. The dynamics of passive fluid particles is considered using dynamical systems theory. The bifurcation diagram reveals the presence of various degenerated fixed points and homoclonic/heteroclinc orbits whose nature varies for different parameter values.

By considering an initial "blob of ink" in the fluid, we use the various structures of the phase space in the bifurcation diagram to generate a complex dynamics consisting of a dual speed stirrer and capable of better spreading the "ink" in the container. The intensity and speed of mixing are computed numerically in the various cases.

Topological Fluid Dynamics Applied to the Steady Axisymmetric Cylinder with Rotating End-covers

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We demonstrate the application of topological fluid dynamics in guiding the construction of a catalogue or so-called bifurcation diagram of the various streamline topologies of steady axisymmetric vortex breakdown in a cylinder with rotating end-covers. Topological fluid dynamics draws upon the qualitative tools and bifurcation theory developed in the theory of dynamical systems. In the streamfunction-vorticity-circulation formulation of the cylinder problem a low dimensional dynamical system based upon the streamfunction is simplified through a series of nonlinear coordinate transformations hence obtaining a normal form which enables the construction of qualitative bifurcation diagrams. Based upon the qualitative bifurcation diagrams we conduct, in a systematic manner, direct numerical simulations on varying two parameters namely the Reynold number and the aspect ratio thereby obtaining the bifurcation diagram for the problem at hand.

Streamline Patterns in the Flow around a Circular Cylinder

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We consider numerically the topology of instantaneous streamlines in the flow around a circular cylinder. For the range $42 < \mathrm{Re} < 200$, where the flow is 2D and periodic, we identify two topologically distict regimes. In the first regime, $42 < \mathrm{Re} < 45$, the streamline pattern consist of two mildly oscillating Föppl vortices behind the cylinder. For $\mathrm{Re} > 45$, the vortices travel downstream, disappear, and are recreated away from the cylinder. We compare the streamline patterns with vorticity patterns. In the steady regime, we consider the effect of rotation of the cylinder on the streamline patterns. We derive a general theory for bifurcations of patterns under the variation of the rotation

of the cylinder. The theory is confirmed numerically, and it confirms to some extend previous numerical studies.

On the Dynamics of a Transitional Boundary Layer

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A model of the dynamic physical processes that occur in a transitional boundary layer flow is described. The CS-solitons, the closed vortex, the secondary closed vortex and the chain of ring-like vortices are postulated to be the basic flow structures of the transitional boundary layer as well as the turbulent boundary layer. It is argued that the central features of the transitional and developed turbulent boundary layer flows can be explained in terms of how the series vortices interact with each other, and with the CS-solitons. The physical process that leads to the regeneration of the new closed vortex along the border of the CS-soliton is described, as well as the processes of the evolution and the interaction of the vortices to high frequency vortices. The model is supported by recent important developments in the theory of unsteady surface layer separation and a number of 'kernel' experiments which serves to both transitional and developed turbulent boundary layer. An important aspect of the model is that it has been formulated to be consistent with accepted rational mechanics concepts that are known to provide a proper mathematical description of other flows.

A link between the degree of irregularity and the onset of turbulence is given. The chaos dynamic analysis shows that the transitional process is a real deterministic chaotic process.

SESSION W2N
COMPOSITE MATERIALS I

Thermal-Oxidative Aging Effects on the Properties of a CFR Phenylethynyl-terminated Poly(etherimide)

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This paper reports the results of an investigation of thermal-oxidative aging effects on the properties of a carbon fiber-reinforced high-performance phenylethynyl-terminated poly(etherimide). Composite panels and neat resin samples were aged at 204°C in environments of four different oxygen partial pressures: 0 kPa, 2.84 kPa, 20.2 kPa, and 40.4 kPa. Aging times were 1750, 3500, and 5000 hours. Despite the lack of visual evidence of degradation and minimal mass loss from both composite and neat resin specimens following thermal-oxidative aging, transverse flexural strength decreased with increasing oxygen partial pressure and aging time. The retention of transverse flexural strength was described as a function of oxygen partial pressure and aging time; retention was proportional to time^0.29. Profiles of Vickers Hardness across the cross sections of aged neat resin samples demonstrated deeper and more severe degradation with increased oxygen partial pressure. In addition to mechanical properties, the effects of thermal oxidative aging on static and dynamic thermomechanical properties were measured; 5000 hours of aging resulted in a glass transition temperature increase. The size of this increase decreased with increasing oxygen partial pressure. These results, along with additional mechanical and thermomechanical property measurements are reported and discussed.

Composite's Quality Estimation: An Micromechanics and Image Processing Symbiosis

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Many techniques have been proposed to estimate and evaluate the composite's stiffness and strength. Among them, there are the micro-mechanical and macro-mechanical approaches [1]. A correlation coefficient between the two types of analysis, micro- and macromechanics, can be proposed. This coefficient of interdependence, yoke ratio (u), was proposed by Avila et al.[2] as the ratio between the elastic moduli values from the macro- and the micro-analysis, see Eq. (1).

$$u = E(\text{micro})/E(\text{macro}) \qquad (1)$$

The yoke ratio (u) physical meaning is the connection between two types of analysis, numerical and experimental. Furthermore, it represents a correlation between the rate of "imperfections", e.g. voids, generated by the manufacturing process and the numerical modeling, finite element simulation based on image processing. The complex Yoke ratio (z) goes further, as it represents the total percentage

amount of imperfections produced for each manufacturing process. z represents a flaw parameter, and it can be computed by the following equation:

$$z = (1 - u^*)/100 \quad (2)$$

where u^* is the effective Yoke ratio. As the flaw distribution function is highly dependent of the manufacturing process, a statistical study must be performed for each case. The effective yoke ratio for vacuum bagging is 0.921 with standard deviation of 0.058 and relative error is 10.257%. For compression the effective yoke ratio is 0.942 with a standard deviation of 0.039 and relative error is 4.916%. An estimation of flaw volume fraction can be done by multiplying z and the mean value of the specimen total volume. For the ASTM 3039/3039M specimens manufactured by compression, the flaw volume fraction is around 3.01% while for the vacuum bagging the flaw volume fraction is around is obtained 4.09%. The results are encouraging.

Keywords: micromechanics, image processing, finite element method, composite materials

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A Pseudo-Viscoelastic Model for Evaluation of Residual Stresses in Thermoset Composites During Cure

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An important issue in the design of fibre-reinforced thermoset matrix composite structures is the evaluation of the stresses that are produced during the curing process. Numerous studies have been undertaken to develop appropriate constitutive models for this purpose. The most sophisticated models have been based on the hereditary integral form of viscoelasticity [1]. Simpler models have also been implemented. Of interest here is a simplified and numerically efficient constitutive model that accounts for the evolution of elastic properties of the polymer with time and temperature during cure, but ignores the viscoelastic relaxation behaviour. This so-called cure hardening instantaneously elastic (CHILE) constitutive model has been implemented in a finite element (FE) code for process modelling of composite structures [2]. This model has been quite effective in predicting the distortions of many practical, often complex, composite structures employed in the aerospace industry. However, to date the CHILE approach has not been used for predicting local residual stresses and there has been no reconciliation of this approach with the fundamentally more correct viscoelastic approach.

In this study, the CHILE approach is compared with a more computationally intensive viscoelastic approach [1]. Through an appropriately calculated frequency at which the elastic modulus of the polymer is calibrated, the CHILE model is modified such that for the uniaxial loading of a fully constrained block of polymer undergoing a given cure cycle, the predicted residual stresses compare very well with those computed using the full viscoelastic model [1]. This efficient pseudo-viscoelastic model is then incorporated in an FE code and used to model the process-induced deformations of L-shaped composite structures. The results are compared with those predicted by the full viscoelastic model reported in the literature [3].

Keywords: Composites, Cure, Residual Stress, Viscoelasticity

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Synergistic Effects of UV Radiation and Condensation on Degraqdation of Carbon/Epoxy Composites

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The degradation of IM7/997 carbon fiber reinforced epoxy following exposure to ultraviolet radiation and/or

condensation was characterized. Observations of physical and chemical degradation established that these environments operate in a synergistic manner and cause extensive erosion of the epoxy matrix. Transverse tensile strength decreased by 29of cyclic exposure to UV radiation and condensation. Transverse modulus was also reduced, but not as severely. Longitudinal fiber-dominated properties were not affected for the exposure durations investigated. However, it was noted that the synergism between ultraviolet radiation and condensation results in extensive matrix erosion, which will ultimately limit effective load transfer to the reinforcing fibers. Thus, longer periods of environmental exposure can be expected to lead to extensive deterioration of mechanical properties even along the fiber dominated material direction.

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Strongly Nonlinear Temperature Rise in Fibrous Composites

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This work concerns modeling of temperature rise in composites due to dissipation of mechanical energy. An extensive experimental study [1] has revealed that dissipated mechanical energy bothe in thermoset and thermoplastic composites with continuous fibers is approximately proportional to the stress amplitude squared, a result predicted by linear viscoelasticity. However, the corresponding measured temperature rise shows a dramatically different dependence on the stress amplitude squared: it is a cubic function of it, the nonlinear term dominating over the linear one. Linear viscoelasticity is unable to predict such a nonlinear temperature rise. Continuum thermomechanics and molecular mechanics are used to develop a model to predict temperature rise due to internal dissipation of mechanical energy in composites with continuous fibers.

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SESSION W3N
COMPOSITE MATERIALS II

Slip Characteristics during Dynamic Fiber Pullout

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Inertial effects in the mechanism of fiber pullout are examined, with emphasis on how propagation rate of stress waves along the fibre, and thence the pullout dynamics, are governed by friction. With a simple shear lag model, the effect of uniform frictional coupling between the fiber and the matrix is accounted for in a straightforward way. An interesting characteristic is that friction retards the propagation rate of the stress disturbance in the fibre to velocities substantially below the bar wave speed. Furthermore, there are three regimes of behavior, in which the relative motions of the fibre and the matrix differ in a frontal zone just behind the furthest extent of wave propagation depending on values of the normalized fibre wave speed, fibre modulus and the loading rate. For instance, when the fibre wave speed exceeds a critical value for a specified loading rate, the frictional fibre pullout behavior transitions from pure slip to a state where part of the sliding zone slips and the frontal zone sticks. Stability considerations imply that when the fiber wave speed and the loading rate are in a certain regime, a state where the frontal zone has relative slip in a direction opposite to the applied load is attainable. With the aid of a finite element cohesive zone model, the exact elastodynamic problem is also solved and the regime of validity of the shear lag is examined. Finally, some observations are made concerning the effects implied for the propagation of bridged cracks when dynamic effects influence the pullout phenomenon.

Keywords: Dynamic, Pullout, Friction, Inertia

A Micromechanics-Based Nonlocal Model for Isotropic Composites Containing Non-Spherical Inclusions

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A generalization of the Hashin-Shtrikman variational formulation is employed to derive a micromechanics-based, explicit nonlocal constitutive equation relating the ensemble averages of stress and strain for random linear elastic composite materials. The analysis builds on that of Drugan and Willis (1996, *J Mech Phys Solids* **44**, 497-524) and Drugan (2000, *J Mech Phys Solids* **48**, 1359-1387), who derived completely explicit results for the case of an isotropic matrix containing a random distribution of isotropic, non-overlapping identical spheres. Here, it is shown how to derive an explicit nonlocal constitutive equation for a matrix containing a random distribution of non-spherical voids, cracks or inclusions. The model of impenetrable particles considered consists of identical particles with fixed spheroidal shape and random orientation. A convenient statistical description of the microstructure is obtained by placing the particles within security spheres. This restricts the analysis to composites having macroscopically isotropic behavior. A new approach is applied to separate the effects of inclusion shape and spatial distribution. Completely explicit expressions for terms related to inclusion shape are derived for the case of spheres; whereas terms describing effects of spatial distribution are obtained explicitly for both a standard and an improved statistical model. Finally, the new constitutive equation is used to estimate the minimum size of a material volume element over which standard local constitutive equations provide a sensible description of the constitutive response of a matrix reinforced/weakened by spherical particles/voids, when spatially-varying average strain is considered. Results so obtained improve previous remarkably small predictions provided by Drugan and Willis (1996) and mostly confirmed by Drugan (2000).

Keywords: nonlocal constitutive equations, random composites, non-spherical inclusions, micromechanics.

A Model for the Pull-Out of Bone-Shaped Short Fibers

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Recent work has demonstrated that ductile bone shaped short (BSS) fibers, i.e. fibers with enlarged ends, can significantly increase toughness of brittle materials over that of conventional short fibers. In this work, we develop a micromechanical model for the force vs. displacement response of a ductile BSS fiber as it pulls out of a brittle matrix material. The BSS fiber may assume any shape exploiting the compressive strength of the matrix and energy absorption of ductile fibers. Using this model, we investigate the influence of fiber elastic-plastic deformation, fiber-matrix interfacial friction, and fiber shape on the characteristics of the pull-out curves of BSS fibers. Favorable agreement is achieved and insight into the relevant sequence of failure mechanisms is gained.

Alone or with a composite fracture model, this micromechanical BSS fiber pull-out model can be used to design BSS fiber shape and weak fiber-matrix interfacial properties which enhance fiber crack bridging, plastic deformation and pull-out, all of which are important toughening mechanisms. Larger-scale computational fracture models, incorporating the resulting BSS fiber pull-out curves, can predict the strength and fracture toughness of novel structural ceramic composite materials for high temperature applications. Such materials will simultaneously meet the room temperature toughness and high temperature strength requirements for numerous structural applications.

Stress in a Single Fiber Al_2O_3/Al Composite: Analysis of Experiments through Modeling

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We describe the construction of an analytical model of the stress state around a fiber break in an Alumina

fiber/Aluminium matrix single fiber composite. The fiber and matrix strain in the vicinity of the fiber failure have recently been probed extensively in neutron diffraction experiments (Hanan et al, International Conference of Fracture, Dec 2001). Not only do we expect to quantitatively understand the local deformation near the fiber break through this model, but also hope to eventually construct an efficient multi-fiber composite model which incorporates the plastic and fracture phenomena found near the fiber break in the single fiber composite.

The experiments consist of cycling the axial loading between 0 MPa and 100 MPa on a 4.75mm diameter notched Alumina fiber, encased in a 8.25mm diameter quenched Aluminium matrix. After fiber failure, the matrix must carry large tensile and shear stresses. At sufficiently high loads, it yields in residual stresses occur near the fiber break. Interfacial debonding is insignificant in these experiments.

We model the fiber as a tensile element and view the matrix as transferring the load dropped by the fiber at the break over a characteristic length. This load transfer occurs by interfacial shear and the characteristic length depends upon the specimen geometry and material properties. If z is the axial coordinate along the fiber it emerges that the load in the fiber p(z) builds to its far-field value P according to p(z) = P - A sinh(T z) - B cosh(T z) for z ¡ Z and according to p(z) = P(1 - exp(-U z) for Z ¡ z. Z here denotes the extent of the matrix yield in the fiber direction. All the parameters left unspecified above are expressible in terms of the geometric and material properties of the composite.

The residual strains predicted from the above calculation are compared with the experimentally measured ones and found to be in good agreement.

A New Tool for Analyzing Textile Composites

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It has been well appreciated in the composite community that calculating in a tractably efficient scheme the distribution of loads among the constituent fiber tows in a textile composite is extremely challenging. Because of the geometrical complexity of the tow arrangements, the structure is generally nonperiodic; or, if it is periodic, the unit cell (repeating unit) typically contains tens or hundreds of tow segments. It is not feasible to represent each of these tow segments by a large number of finite elements to ensure accuracy of local stresses in all their detail and then solve for the whole system. On the other hand, many of the failure mechanisms in textile composites involve the failure of single tows, so the physics of failure cannot be represented faithfully if stresses are averaged over distances larger than a tow diameter; i.e., the material cannot be homogenized over gauge lengths exceeding the tow diameter.

In this study, a computational code named the Binary Model will be employed to meet these challenges. Two different types of composite, a double interlock textile CMC sheet and a 3D braided T-stiffener, will be analyzed using this code. The numerical predicted deformations will be compared to experimental measurements using speckle interferometry. It will be demonstrated that the Binary Model can capture quantitatively the deformation characteristics of single fiber tow, as well as the global mechanical behavior of the entire composite structure. Further discussions of the benefit of using 3D braided T-stiffeners in replacement of traditional 2D laminate T-stiffener will also be presented.

SESSION R2H
COMPOSITE MATERIALS III

Strain Energy Release Rates for Crack-Induced Delaminations in Fibre-Reinforced Composite Laminates

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Initiation and accumulation of matrix cracks parallel to the fibres in the off-axis plies is the first stage of damage development in multidirectional composite laminates subjected to in-plane tensile loading. Matrix cracking reduces the laminate stiffness and strength and also triggers development of other harmful resin-dominated damage modes such as delaminations.

In this paper, the total strain energy release rate for local delaminations that initiate and grow from the tips of matrix cracks in off- axis plies of symmetric composite laminates is predicted using the Equivalent Constraint Model of the damaged laminate. Contributions of Mode I and Mode II into the total strain energy release rate are identified, and their dependence on the delamination length, crack density and ply orientation angle is examined. Suitability of a mixed mode fracture criterion to predict delamination onset strain in carbon/epoxy laminates is discussed.

Strain energy release rate obtained in this study is compared to a simple closed-form expression for a uniform local delamination derived in earlier work by O'Brien [1].

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Compressible Composites with Interlaminar Microcracks: Exact Stability Solutions for Distinct Roots

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Fracture caused by the instability is considered for layered composites compressed along the interface, which contains an arbitrary number of microcracks. The layers have different properties and are modeled by elastic or elastic-plastic, isotropic or orthotropic, compressible bodies. For elastic-plastic layers the concept of continuing (sustained) loading is applied, which allows us to neglect the changes of loading/off-loading zones during the stability loss. For the case of distinct roots of characteristic equations, an exact analytical solution of the problem is found in the common form for finite (large) and small deformations. The solution is derived using the complex potential method within the scope of the exact approach based on equations of the 3-D linearised stability theory [1]. If there are no initial stresses, the developed representation of solutions is converted into the classical Lekhnitskii's representation [2] of linear elasticity theory of an orthotropic body. In so doing, the linear relationship problem (Riemann-Hilbert problem) is formulated for the case of distinct roots of characteristic equations. The problem is a homogeneous one, since the right-hand sides in the equations are equal to zero. It is rigorously proved that critical loads are independent of the number and disposition of interfacial microcracks and coincide with the critical load for one microcrack on the interface. The exact solution of the considered problem is determined by the roots of equation, which correspond to the problem of the near-the-surface instability of a half-plane with a free surface. Therefore, the critical load coincides with the smallest value of critical loads for near-the-surface instability in the materials of layers.

Keywords: stability, composites, exact solution, interfacial microcracks.

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The Effect of a Crack on a Circularly-Layered Fiber Reinforced Composite

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The interaction of a crack with coated fibers plays a crucial role in studying the material properties, assessing the strength and investigating the damage evolution of a reinforced composite material.

The object of this paper is to present a general methodology that allows us to investigate the interaction of a crack with two circularly layered fibers perfectly bonded to a matrix of infinite extent. The fibers may be formed of many layers with different elastic properties and may be placed randomly in the matrix. The crack could be completely inside or outside or partially cutting the fibers. The matrix is subjected to loading, which induces anti-plane deformation, but is otherwise arbitrary.

The methodology to study this problem involves several steps. First, the solution of the interaction of a screw dislocation with two circularly layered fibers is presented where the matrix may be subjected to remote loading and/or arbitrary singularities inducing anti-plane deformation. The solution for the dislocation problem is obtained as a transformation applied to the solution of the corresponding homogeneous problem. This formulation casts the problem in terms of functional equations relating the values of the stress functions at various points. A group transformation allows us to express the solution of a single circularly layered fiber as an infinite rapidly convergent series involving modified coefficients of the series representing the solution of the homogeneous problem. Then the solution of the two fibers is obtained by using the procedure of iteration.

Second the crack is modeled as a pile-up of screw dislocations and the solution for a single dislocation is integrated along the crack length to yield a singular integral equation subjected to a closure condition. Standard numerical techniques are then applied to effect the solution to the integral equation and the stress intensity factors are obtained at both crack tips.

Mode-I Fracture in Pultruded Composites

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An experimental and analytical study is carried out to characterize the fracture behavior of fiber reinforced plastic (FRP) pultruded composites. The composite material system used in this study consists of roving and continuous filament mat (CFM) layers with E-glass fiber and polyester matrix materials. Eccentrically loaded single-edge-notch ESE(T) fracture toughness specimens were cut from a monolithic pultruded plate with $0.5''$ thickness. The fracture toughness of this material is characterized for notches parallel and transverse to the roving direction. A three-dimensional (3D) micromechanical constitutive model is developed and calibrated for this composite material system. This non-linear constitutive model is a combination of nested micromechanical models for the roving and CFM layers. A 3D non-linear lamination theory is used to define a nonlinear-homogenized response of an alternating sublaminate made of the roving and CFM layers. The ability of the proposed micromodel to predict the effective elastic properties as well as the nonlinear response under multi-axial stress states is verified and compared to the stress-strain response from off-axis tests. The 3D constitutive model is used with a cohesive layer in a finite element (FE) to study the fracture response. The properties for the cohesive layer were calibrated from ESE(T) specimen with $a/w = 0.5$. Good prediction from the proposed model is reported for a range of different ESE(T) and SEN(T) crack geometries.

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Effective Mechanical Modeling of Composite Conductor

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Compact and lightweight electromagnetic machinery (EM) has been envisioned as a critical component in future combat vehicles and weaponries. One of the integral elements in the system is the electromagnetic composite conductor. This paper introduces an analytical modeling and numerical approach to predict the effective mechanical constants of composite conductor in electromagnetic machinery system. The analytical model was developed based on a two-step homogenization algorithms and mechanics analysis for composite unit cell consisting of outwrapped composite insulation layers and the inner metallic conductor core. The procedures of using numerical approach and finite element method to determine the unit cell effective constants were also described and the results were presented and compared with the analytical solutions.

Acknowledgment: This work was supported in part by an appointment for W. Sun to the Research Participation Program at the U.S. Army Research Laboratory, administrated by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and ARL.

SESSION F2N
COMPOSITE MATERIALS IV

Fracture-toughness Improvement Using Optimally Shaped Short Ductile Fibers

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Short fiber reinforced composites have a number of advantages over continuous fiber composites, including low-cost manufacturing methods and flexibility of properties based on controlling the flow of materials. The fibers offer stiffness and strength to the matrix through complimentary, but in some regimes competing, mechanisms. In general, the better the bond between fiber and matrix, the more efficient the load transfer to the fiber and the stiffer the composite. The mechanism of strength and toughness increase from the fiber-reinforcement is more complicated. Fibers can bridge the fracture surface, providing a decrease in the net stress intensity factor and increase in energy dissipation through bridging, often with fiber pullout, fiber fracture or plasticity, etc. The role of fiber strength is direct: the higher the strength, the better. An interesting way to manipulate this trade-off is to use shaped ductile fibers that provide a degree of mechanical locking absent in straight fibers. This locking enables us to fully utilize the plastic potential of the fiber in increasing fracture toughness.

The purpose of this work is to discover the optimal shape of the fiber end for composites with weaker interfacial bounding. Therefore, fibers can anchor inside the matrix and resist pullout to increase fracture toughness while

maintaining a high stiffness for the composite. The copper fiber and epoxy have been used to form our representative volume element (RVE). We have simulated single fiber pullouts using the finite element method and compared these results with our experimental data.

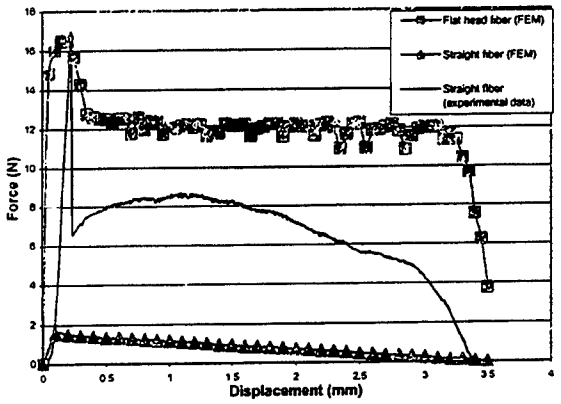


Figure 1-a: Comparison of the simulated results with experimental data, where use ANSYS v5.6 for the single fiber pullout test with flat head fiber and the straight fiber. All simulations use the 0.319mm diameter copper fiber with 3.5mm embedment in epoxy matrix and 3 mm free length.



Figure 1-b: Flat head short fiber



Figure 1-c: Plastic strain distribution of the flat head fiber during the pullout

Keywords: fiber pullout, fracture-toughness, FEM

The support of the Army Research Office under contract DAAD19 01 1 0529 is acknowledged.

Vibration of Rotating Turbine Blades Made of Functionally Graded Materials

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Functionally graded materials (FGMs) for high-temperature structural applications are special composites, microscopically inhomogeneous whose thermomechanical properties vary smoothly and continuously in pre-determined directions throughout the body of the structure. This feature is achieved by gradually varying the volume fraction of constituent materials that usually are from ceramics and metals.

The ceramic in a FGM offers thermal barrier effects and protects the metal from corrosion and oxidation, while the FGM is toughened and strengthened by the metallic composition.

It should be remarked that the research work involving thin-walled structures made of FGMs was mainly devoted to plates and shells. To the best of the authors' knowledge, in spite of its evident practical importance, no research work related to the modeling and behavior of rotating blades operating in a high temperature environment and made of functionally graded materials has been yet accomplished. This paper is devoted to this topic.

Herein, the case of straight, pretwisted tapered thin-walled beams rotating with a constant angular velocity and exposed to a steady temperature field experiencing a linear variation through the blade thickness is considered. It is assumed that the blade is made of functionally graded materials whose properties vary continuously across the blade thickness and that the material properties are temperature dependent.

In this context, the vibrational behavior of rotating blades is investigated and pertinent conclusions are outlined.

This paper represents an extension for this case of a number of results previously obtained by the same authors.

The preliminary results that are obtained highlight the great performances obtained when the FGM concept is applied in this context. The next plot supplies the variation of the fundamental natural frequency as a function of the temperature gradient for a pretwisted and nonrotating beam of uniform cross-section.

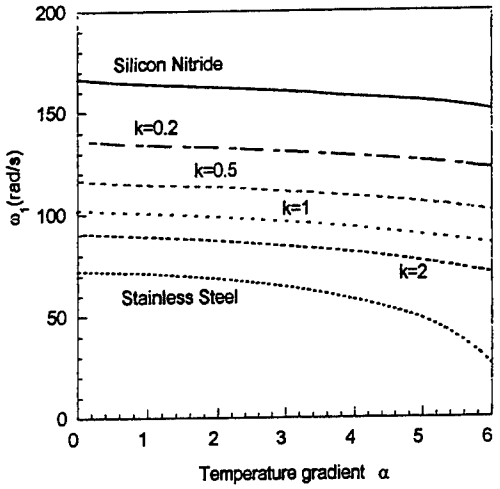


Fig. 1 First flapping-lagging natural frequencies vs. temperature gradient for various volume fracture exponents ($\Omega = 0, \beta = 90, \sigma = 1$)

Keywords: Functionally Graded Materials, Rotating Blades, Thin-Walled Beams, Composite Structures

A Nonlinear Solid Shell Element Formulation for Analysis of Composite Panels under Blast Wave Pressure Loading

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A geometrically nonlinear shell element formulation is used to determine dynamic response of composite structures under blast wave loading. The key ingredients of the analysis are a geometrically nonlinear solid shell element based on the assumed strain formulation to model composite panels and the incorporation of the effect of progressive damage and strain-rate on the stiffness and the strength. The assumed strain formulation is used to alleviate element locking. As for the progressive damage, the effect of fiber failure, matrix cracking and fiber-matrix shearing failure on the stiffness and the strength has been considered. A three-parameter viscoplasticity model has been used to represent strain-rate dependent behavior. Several example problems have been solved to investigate the behavior of composite panels undergoing large deflection. One of such examples is a square composite panel exposed to a blast shock wave normal to the plate. The blast wave loading is assumed to be uniform over the plate surface and the time variation of the blast pressure is expresses by the Friedlander decay function. Figure 1 shows the strain-rate effect on displacement at the plate center with the elapse of time.

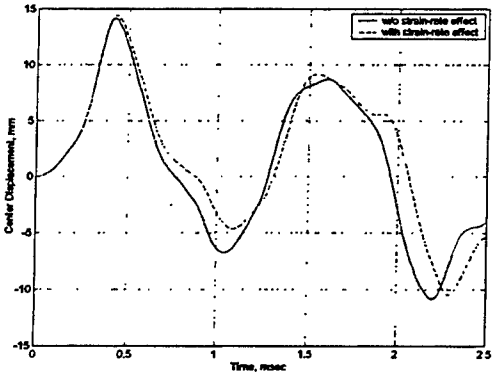


Fig. 1 Strain-Rate Effect on Dynamic Response of Composite Structure

The results from this and other numerical tests demonstrate that the assumed strain solid shell element formulation is effective for dynamic analysis of composite structures that exhibit high-strain rate effect under blast wave pressure loading conditions.

Keywords: Composite Structures, Strain-Rate Dependent Characteristics , Blast Wave Loading, Assumed Strain Formulation

Thermal Fatigue of Particle Reinforced Metal Matrix Composites Induced by Laser Heating and Mechanical Load

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Particle reinforced metal matrix composites (MMC) are significant improvement in modulus-to-density and strength-to-density while the behavior is nearly isotropic. For the excellent performances, MMC have been used for structural components in the aerospace and automotive industries, where they are often subjected to the coupled loads of thermal load and mechanical load. In the present paper, the thermal fatigue of particle reinforced metal matrix composites induced by laser heating and mechanical load is numerically and experimentally studied.

In the experiment, SiC particulate/6061 Al composite is chosen as a model PMMC system for this study. The composites with 15 wt pct SiC were fabricated by melt casting route, and as-cast ingots of the composite were subsequently extruded. A multi-pulse laser beam was used to produce the heating cycles. The mechanical load was static tensile stress. The thermal stress fields including the macro-stress and micro-stress fields for the particle reinforced metal matrix composites induced by laser heating and mechanical load were numerically investigated by a ANSYS code. In the study, the reinforced particle is assumed to be elastic and the metal matrix elastic-plastic. For different microstructure of particle size, particle shape and particle distribution, the stress and strain fields are also stimulated. The thermal fatigue life was predicted by the numerical study. It was found that the stress was deeply dependent on the shape of reinforced particle and the stress in particle was much higher than that in the matrix. The high stress in particle can result in the particle broken. However in the cluster particles region the stress in particle is higher than that in the uniform region. The stress in the matrix is lower in cluster region than that in the uniform region. The numerical results can explain the experimental results such the mechanism for micro-crack initiation and macro-crack propagation. The thermal fatigue life for experimental and numerical study was good consistent.

Keywords: Particle reinforced metal matrix composites,

laser heating, thermal fatigue, experimental and numerical investigation

Energy Limit Method for Strength Design of Reinforced Concrete Beams

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This paper deals with new and improved strength design methods of reinforced concrete beam structural elements and it is based on the energy limit concept. Proposed theory introduces two center of rotation in the cross section of a beam element. These two centers are located at the upper and lower edges of the beam element and account for tension and compression in concrete beam cross-section, thus totally eliminating the need of the determination of the true location of neutral axis. Proposed method of analysis is very simple to use, yet powerful enough to accurately account for highly complex cross sections and reinforcement arrangements. Proposed theory is illustrated by numerous examples and its validity is demonstrated by comparison with ACI-318 equations and experimental data. All data presented in this paper along with computerized tools can be obtained from www.openseismic.com

Keywords: Reinforced concrete beam, reinforced concrete design; energy limit method, bending

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SESSION F3N
COMPOSITE MATERIALS V

Modeling of Interface Mechanical Behavior of Bimaterial Systems By Cohesive Zone Models

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We seek to understand the mechanics of heterophase interfaces commonly encountered in composite material systems used in elevated temperature applications. Interfaces are regions that separate domains of distinctly different thermal, chemical and mechanical properties, ranging from a simple twin boundary of atomic thickness in metals to complex interfaces with finite width in metal-ceramic systems. The interface between matrix and reinforcement is important in all types of composite materials. The nature of the interface can influence various aspects of the performance of the composite. To evaluate the interfacial mechanical properties, thin slice push-out test has emerged as the *de-facto* experimental tool. In this work push-out test results are used as the basis to determine the constitutive behavior of a specific MMC interface; however, our overall objective is to develop a generic methodology to characterize interfaces within the framework of the mechanics of *continuous* media.

In this paper, two different forms of CZMs (exponential and bilinear) are used to evaluate the response of interfaces in various composite systems and examine if the shape has any effect on the simulation. It is shown clearly that among various CZMs, only bilinear CZM has the ability to represent the entire load-displacement response observed in experiments. It is also clearly shown that in addition to the two independent parameters, the form of the traction-separation equations for CZMs plays a very critical role in determining the macroscopic mechanical response of the composite system. Meanwhile, the sensitivity of the various cohesive zone parameters in predicting the overall interfacial mechanical response (as observed in the thin-slice push out test) is carefully examined. Many researchers [1-3] have suggested that two independent parameters (the cohesive energy, and either of the cohesive strength or the separation displacement) are sufficient to model cohesive zones implying that the *form (shape)* of the traction-separation equations is unimportant. However, it is shown in this work that in addition to the two independent parameters, the form of the traction-separation equations for CZMs plays a very critical role in determining the macroscopic mechanical response of the composite system. It is our view that the CZM represents the physics of the interface separation process and hence the shape of the CZM should in some sense depend on the inelastic processes occurring at the micromechanical level. Hence when using CZMs to model separation in a given material system, an appropriate shape (form), depending on the type of material system and the inelastic micromechanical processes, should be used. Otherwise, the CZM based modeling and simulation will not yield meaningful results.

Keywords: Cohesive zone models, Metal-ceramic interface, Push-out test, Finite element analysis, Thermal residual stress

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Mesomechanics of Fabric Reinforced Composites

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Prediction of thermal and mechanical properties of fabric reinforced composites is available in the literature using finite element analysis and several micromechanical approximations, including iso-strain, iso-stress, classical lamination theory, and combinations of micromechanics and finite element analysis where the FEA is used to perform the integrals in the micromechanics. Generation of FEA meshes can be cumbersome and restricting approximations of the geometry must be made in order to construct the mesh. Existing micromechanical approximations are limited to prediction of a few of the mechanical properties needed, namely the two axial moduli.

The present work attempts to predict all the engineering properties including the three shear moduli, three axial moduli, three Poisson's ratio, and three CTE. The geometry of the fabric is measured by optical microscopy and modeled with great accuracy and simplicity. The microscopic dimensions of the fabric representative volume element are geometrically mapped into surfaces using Mathcad. The procedures for mapping the surfaces of the RVE are detailed in the paper. Micromechanics theory is used at the microscale to find the tow-composite properties and at the mesoscale to find the fabric-composite properties. The theory used is that of micromechanics with periodic microstructure [1], where the solution is sought in terms of a triple Fourier expansion. Since the fabric is inherently periodic, the theory is ideal to model the mesoscale geometry. Although any micromechanical model could be implemented at the micro-scale, periodic microstructure is used because a single theory yields all the tow mechanical properties and is consistent with the modeling at the mesoscale. The fact that the tow is transversely isotropic is accounted by averaging, as describe in the literature [2].

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Mixed Mode Delamination and Bridging, Modelling in Laminated Plates

D. Bruno, F, Greco and P. Lonetti

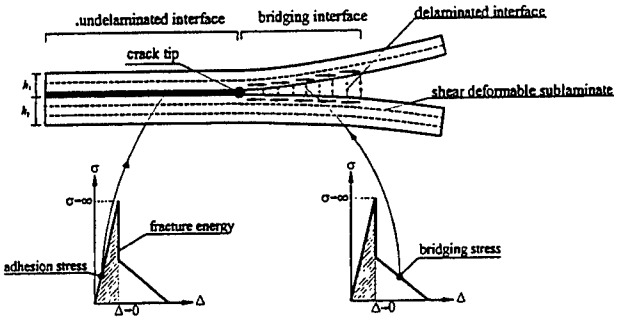
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Plate-based models, which are frequently used in the literature, are unable to accurately predict the energy release rates at the delamination tip, especially when mixed mode cracking is involved. As matter of fact, in these models the laminate is considered as an assembly of two sub-laminates in the cracked zone and of a unique laminate in the undelaminated one, and this leads to a notable underestimation of the actual resistance of a delaminated laminate since shear effects and the local crack tip strain state are not accurately estimated. Consequently, a continuum formulation is often required to obtain realistic results. Unfortunately continuum approaches turn out to be computationally expensive. Unlike classical delamination models, the proposed approach, in spite of its simplicity, is able to capture appropriately delamination behavior avoiding the complex continuum approach.

A refined laminate model based on sub-laminates and interface elements is proposed to analyze mixed mode delamination and bridging phenomena. Interface damaging is described by combining a penalized interface law, representing perfect bonding along the undamaged interface, and a damageable interface law which simulate the bridging mechanisms. The proposed model includes mixed mode delamination with a coupled bridging law for mode I and II advancing and no limitation for crack location across the plate thickness. The laminate is modeled as an assembly of sub-laminates for which the first-order shear deformable layer-wise kinematics is adopted, and the governing equations are formulated in the form of a non-linear differential system with moving intermediate boundary conditions related to opportune delamination and bridging growth conditions. Results show that when the delamination is simmetrically located across the thickness, one sub-laminate is needed for an accurate solution as confirmed via finite element comparisons. On the other hand, for a general delamination geometry more than one sub-laminate element is necessary to obtain a proper simulation of delamination and bridging behavior. The proposed interface-based approach turns out to be efficient in delamination problems producing a direct and

self-consistent energy release rates evaluation since mode partition is obtained directly without a post-processing. Moreover, it provides useful results evidencing the main quantities controlling delamination and bridging behavior.

Keywords: Laminates, Delamination, Bridging, Interface elements



Laminate modelling around the delamination tip.

Laminate modelling around the delamination tip.

Nonlinear Oscillations Pliable to Shear Transversal Deformations and Compression of Composite Plates

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The majority of researches in nonlinear dynamics of structure thin-walled elements (shells and plates), carried out till now, were based on the Karman quadratic theory, being the generalization of the Kirchhoff-Lave classical linear theory on the case of geometric nonlinearity. Some papers used the relations of nonlinear technical theory, the basis of which makes the S.P.Timoshenko shear model. However, the theories, that base on the hypotheses of the above authors, do not allow one to consider the peculiarities of composite materials behavior in full measure. Therefore it was necessary to develop a mathematical model of nonlinear dynamic strain of shells and plates so that it would take into account such specific peculiarities of composites as pliability to transversal shear strains and transversal compression. As a result we have obtained a system of six differential equations in partial derivatives according to two spatial coordinates and time. Each of these equations is of the second order relative to the generalized displasements. Besides, the corresponding consistent initial and boundary conditions have been obtained. As an example of application of the model proposed the nonlinear transversal oscillations of composite strip-plate are considered. The correlation of the basic frequency of transversal oscillations from the amplitude are obtained in the close form. The frame curves, characterizing the nonlinearity of the process in question, depending on the parameters of transversal shear rigidity and pliability to transversal compression are constructed. The correlation between the amplitudes of longitudinal and transversal wave processes and bending oscillations is determined.

Application of the Theory of Doubly Periodic Riemann Boundary Value Problems to Composites

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Macroscopic behavior of heterogeneous materials depends on their microstructure pattern to a great extent. Many natural, especially man-made materials possess periodic or approximately periodic microstructures. With the continuing replacement of traditional materials by various composites, micromechanics for materials with periodic macrostructures has attracted the attention of many scholars. The concept of eigenstrain and the Fourier series expansion technique have been extensively used to solve the problems of heterogeneous materials. For an infinite linear elastic solid containing an ellipsoidal inclusion, the important result was given by Eshelby (1957), and the corresponding exact eigenstrain was obtained. However, in general, it is still a difficult task to determinate the exact Fourier coefficients for solids with periodic inclusions.

The complex variable method as well as the theory of boundary value problems for analytical functions are powerful tools for 2-dimensional heterogeneous material problems. Recently an efficient method for doubly periodic Riemann boundary value problems was developed and it was used to solve doubly periodic problems for homogeneous materials.

This paper constitutes a continuing study in seeking for rigorous and efficient analytical methods for heterogeneous materials with periodic microstructures and in understanding behaviors of such materials. An infinite elastic solid containing a doubly periodic parallelogramic array of cylinder inclusions under longitudinal shear is dealt with. A rigorous and efficient analytical method is developed by using Eshelby's equivalent inclusion concept integrated with the new results for doubly periodic Riemann boundary problems, and an exact solution is obtained. Numerical results show that the stress fluctuations in such heterogeneous materials as well as their dependence on periodic microstructure parameters. Also, the overall longitudinal shear modulus of composites with periodic distributed fibers is studied. Several problems of practical importance, such as the ones of doubly periodic holes or

rigid inclusions, singly periodic inclusions and single inclusion, are solved or resolved as the special cases.

Keywords: Micromechanics; doubly periodic inclusions; Riemann boundary problems; mechanics of coposites

Calculation of Anisotropically Rectangular Plates on the Elastic Foundation Dependent on Normal Reactive and Tangential Stress-strain Effects

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This paper is considered the rectangular plate on the elastic foundation with registration of reactive normal and tangential stress-strain effects. The generalized differential equations describing a bend of plates on elastic compressed two-dimensional and shift foundation are received. The rectangular plate on the elastic basis with registration of reactive normal and tangents stress-strain effects is considered. For the resolving of the abovementioned task on distortions/deformational stress-strain state of the plate interacting with the pliable/compliant basis the differential equations are made in view of exterior action. As a model of the elastic basis is accepted the Pastemak-Vlasov's (V.Z. Vlasov & N.N. Leont'ev. 1960) two-dimensional model. Thus is taken into account both vertical, and tangents reactive pressures. The task is solved within framework of the technical theory of slices at small elastic deformations. The double interaction effect in the ration of contact between slices with the elastic basis is accepted. The task in such statement for an izotropic plate at temperature action was worked out by E.A. Palatnikov (E.A.Palatnikov 1978). The equations of curving anizotropic of composite slices are given in the literature (T.Sh.Shirinkulov 1992). Thus, are obtained the set of equations in moving, the solving of which represent the difficult mathematical task. Un like these investigations the method of conclusions of solving equations directly in pressure and vertical moving is offered that decisions are easy to receive by using methods of mathematical physics.

Keywords: anizotropically, rectangular, plates, elastic, foundation.

SESSION T3D
COMPUTATION FLUID DYNAMICS

Atomistic Simulation of a Liquid Drop Sliding on a Solid Surface

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Models for overcoming the singular behavior of the no-slip continuum formulation for flow in the neighborhood of a moving contact line are typically incorporate physics or chemistry beyond standard flow formulations. A diffuse rather than mathematically discontinuous interface is known to regularize formulations, as is a local relaxation of the no-slip condition. A commonality of these popular approaches is that they introduce small length scales into the continuum formulation: the density changes on a nanometer scale across a diffuse liquid-vapor interface and slip lengths are typically inferred to have a similar scale. However, since this is also the molecular scale, it is well understood the continuum description itself might fail.

In this study, atomistic simulations provide details of the flow in and around an $\approx$ 10nm diameter drop on an atomic solid (FCC) substrate pulled by a body force through its own vapor. Standard truncated and shifted Lennard-Jones two-body potentials govern all atomic interactions. Atomic interaction energies set the liquid-vapor contact angle and are chosen to give a rigid, atomically smooth solid wall.

It is found that there is a small region of slip near the leading edge moving contact line. In the frame of the drop, a streamline extends from the "bulk" liquid in the drop to what appears to be a critical point at the leading contact line. Streamlines below this dividing streamline show the expected recirculation within the droplet, those above exit the liquid through the advancing fluid-vapor interface, which indicates evaporation out the leading edge. Leading edge evaporation is another commonly discussed mechanism for regularizing the flow. The degree slip and evaporation are examined at different wetting angles and in the context of continuum models.

Unsteady Fluid Flow in a Lid-Driven Cavity Due to a Moving Thin Partition

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A finite-volume-based computational study of unsteady laminar fluid flow within 1×2 and 2×1 lid-driven cavities due to the movement of a thin partition that leads to two non-communicating square cavities is presented. Within the bottom half in the 1×2 cavity, the clockwise-rotating vortex which is generated by the motion of the horizontal partition merges with two existing vortices spinning in the same direction. Within the top half of the 1×2 cavity, the emerging counter-clockwise-rotating vortex is strengthened, thus weakening the clockwise-rotating vortex below the moving lid. Once the cavity is divided into two square cavities, the flow in the bottom half undergoes a rather complicated decay involving the birth, growth and decay of intermediate vortices of opposing senses. Within the top half, a steady lid-driven flow in a square cavity is eventually reached. Within the 2×1 cavity's right half, since the movement of the thin vertical partition is favorable to the rotation of the clockwise-rotating primary vortex, little change in the flow structure is observed. Within the left half, a counter-clockwise-rotating vortex continues to grow. Upon division of the flow domain into two square cavities, flow structures within both halves are modified leading to two identical steady flow fields.

Computation of Vortex-Dominated Flows Using Compressible Vorticity Confinement Methods

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Vorticity confinement methods have been shown to be very effective in the computation of flows involving the convection of thin vortical layers. Indeed, these are the only Eulerian methods whereby simulations of these layers remain very thin and persist long distances without significant dissipation. Initially developed by Steinhoff and coworkers for incompressible flow, these methods have been used successfully to predict complex flows, particularly involving helicopter rotors. Recently, the method has been extended to a compressible finite-volume form, which will enable the methods to be used for a much broader class of problems. In this paper, we examine the ability of the compressible vortex confinement methodology to handle two important classes of vortex-dominated flows. Specifically we consider cases of massively separated flows and flows involving the interaction of a shock wave and a density inhomogeneity. We evaluate the effectiveness of the method by comparisons with experimental data and available state-of-the-art computations. An important conclusion of the present work is that vortex confinement for cases of massively separated flows, without modeling the viscous terms and on an essentially inviscid grid, can result in a reasonable approximation to turbulent separated flows. The computed flow structures and velocity profiles were in good agreement with time-averaged values of the data and with LES simulations even though the confinement approach utilized more than a factor of 50 fewer cells in the computation (20,000 compare to more than 1 million). Similarly, outstanding results for shown for the shock interaction problems where excellent detailed agreement for complicated vortical structures were found compared to data and adaptive grid computations.

Reactive Flows and Slow Manifolds

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A wide variety of combustion processes involve a great number of elementary reactions occurring simultaneously within a complex flow field. These processes are modelled by a large number of partial differential equations representing the evolution of numerous reactive chemical species, coupled with the full Navier-Stokes equations. A fully resolved solution of these model equations, which incorporates detailed finite rate chemical kinetics, often requires a prohibitive amount of computational resources. Hence, there is a need to develop methods which rationally reduce the model equations such that numerical simulations can be accomplished in a reasonable amount of computational time. Elementary chemical reactions occur over a wide range of time scales which is manifested as stiffness in the model equations, and subsequently high computational costs. For stable systems, this stiffness can be reduced by systematically equilibrating the fast time scale chemical processes and resolving only the relevant slow time scale chemical processes, as done in the method of Intrinsic Low Dimensional Manifolds (ILDM) by Mass and Pope (*Combustion and Flame*, pp. 239-264, vol. 88, 1992). The reduced model equations describe the slow dynamics under the assumption that the fast dynamics can

be neglected. Most chemical times scales are faster than time scales associated with fluid mechanical phenomenon such as convection and diffusion. Nevertheless, it is important that the reduced model equations maintain the coupling of the flow processes with those chemical processes which occur at similar time scales.

In this work we illustrate how this coupling of fluid and chemical processes is maintained such that the approximate and cheaper numerical solution of the reduced model equations is consistent with the more accurate and expensive numerical solution of the full model equations. We give an improved extension of the method of intrinsic low dimensional manifold (ILDM) to systems where reaction couples with convection and diffusion. The ILDM method is well suited for spatially homogeneous problems and provides a systematic way to overcome the severe stiffness which is associated with full models of detailed kinetics, and thus significantly improves computational efficiency. However, significant errors can arise when the ILDM is used in reactive flow systems. Motivated by techniques from center manifold theory, reduced model equations are obtained by equilibrating the fast dynamics of a closely coupled reaction/convection/diffusion system and resolving only the slow dynamics of the same system in order to reduce computational costs, while maintaining a desired level of accuracy. The improvement is realized through formulation of an elliptic system of equations. It is demonstrated, with the help of a simple reaction diffusion system, that the error incurred by the new method is less than that incurred by use of the simpler Mass-Pope Projection (MPP) of the convection diffusion effects onto the ILDM. The method is subsequently applied to premixed laminar flames of ozone decomposition and methane combustion (S. Singh, S. Paolucci and J. M. Powers, *J. Chem. Phys.* to appear, 1992).

Keywords: ILDM, slow manifold, reactive flow, chemical kinetics.

Reynolds Stress Turbulence Model for Prediction of Shear Stress Terms in Film Cooling Cross Flow

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Reynolds stress models are computationally more complex and time consuming but have the potential of greater accuracy and wider applicability. Turbulent cross flows and film cooling has highly complex characteristics of fluid dynamics. In this work, we computationally simulated a three-dimensional, separated hole film cooling problem of flow over a flat plate, using Reynolds stress model (RSM). The Reynolds number of the jet was 4700 . our computational domain included the space above plate plus the film cooling jet channel. in our numerical simulation, the SIMPLE finite volume method with a non-uniform staggered grid was implemented. Our result were compared with Ajersch et.al experimental and numerical (k-e turbulence model). Also were compared with Taeibi-Rahani and keimasi numerical simulation work's (SST turbulence model). Comparison between the measured and computed shear stress terms , show that RSM turbulence model in our work has better agreement with experimental data.

Keywords: RSM-film cooling-finite volume-turbulence

SESSION M2J
DYNAMICS I

The Role of Internal Variables on the Control of Viscoelastic Structures

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The internal variables (IV) cannot be measured by any kind of experiment, i.e., they are not phenomenologically or directly observable by any type of sensor. Since these coordinates account for the time dependence of material damping to the system, the questions arises as to their importance in the design and implementation of a control system. Thus, a main goal of this paper is to check the viability of reconstructing the internal variables for use in control system design. One of the drawbacks of IV methods is that the inclusion of these coordinates increases the order of the system, sometimes significantly. So, it is important to know whether the performance of the closed-loop system is improved when the IV are fed back in the control scheme. This work is an extension of an earlier work [1] done by the authors where the utility of reconstructing the internal variables for use in the control design. While the previous work was a comparison between full-state feedback (FS) and output feedback (OF)

for lumped-parameter systems, this paper explores similar issues for a simple continuous system. First, it is shown how the equations of motions are derived from principles of irreversible thermodynamics and how the finite element matrices are obtained from them. With this model, a more detailed study can be made in terms of control performance regarding the internal variables. Two control approaches are again analyzed: FS and OF feedback . A linear quadratic regulator (LQR) is used, which is suitable to the problem addressed here for allowing the investigation of the influence of the internal variables through the manipulation of state weighting matrix. In the FS case a Kalman filter is used to estimate the states that are not measured, including the IV, and the optimal gains for the controller are found via solution of the Riccatti equation for the LQR. The gains used for OF are found via the optimization of a Lyapunov criteria.

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Capture into Resonace: A Novel Method of Efficient Control

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We discuss a possibility of using a resonance phenomena (namely the capture into a resonance) as a very efficient method to control the behaviour of a dynamical system. In a typical dynamical system the interaction between an unperturbed system and a weak superimposed wave can be reduced to a purely resonant interaction occurring on a certain surface in the phase space. We let the internal dynamics bring the system close to that surface and apply a very short control pulse to ensure the capture of a phase point into the resonance with a wave. A captured point is then transported by the wave and finally we apply a second control pulse to release a phase point from the resonance. As a model problem we consider a dynamics of a charged particle in a electromagnetic field. We compare the cost of the proposed control with other methods and discuss possible applications of this technique.

Wavelet-Galerkin Method for the Free Vibrations of an Elastic Cable Carrying an Attached Mass

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A multilevel representation of Daubechies compactly supported wavelet has been used to study the free vibrations of elastic catenary cables carrying an attached mass. Anti-derivatives of wavelets are used to guarantee satisfaction of boundary conditions. Natural frequencies, mode shapes and dynamic tensions are obtained and compared with the classical Fourier series representation. The localization feature of wavelets has been implemented to enter the singularity region that is produced by the attached mass. More wavelets are used near the mass location and the spurious oscillations in the solution are minimized with few number of terms in the series. However, the Fourier solution shows many oscillations along the cable length and Gibbs phenomenon at the mass location. In both methods, reverting and swapping modes are discovered in which higher modes revert to lower modes and that the longitudinal displacement components become greater than the transverse ones even for cables with small sag to span ratios.

K-L or POD Analysis of Large Amplitude Vibrations of Forced Geometrically Exact Arches

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During large amplitude motions of thin arches there exists strong nonlinear coupling among the dynamics of extensional, bending, and shearing vibrations. Regardless of the strong nonlinear coupling, experimental dynamics[3] and simulations [2] indicate that the arch motion is dominated by a few degrees-of-freedom. Identification of these active degrees-of-freedom would result in the construction of low order reduced models (coupled nonlinear oscillators).

In this work, we compute the active degrees-of-freedom of forced planar arches with exact geometric nonlinearity. The dynamics are appoximated as accurately as desired by the finite element discretization of the equations

of motion of gemetrically exact rods. The computational dynamics of the coupled extension-bending-shearing vibrations are processed by the method of Proper Orthogonal Decompositions(POD or K-L). Originally derived for one-dimensional dynamical fields[1], we extended the POD method to process the coupled fields of extension-bending-shearing [2]. By means of this powerful method we identify and compute the shapes of PO (proper orthogonal) modes that dominate a motion of the arch. For the case of planar arch excited by a harmonically varying force applied at its middle point, we identify all active degrees-of-freedom for large amplitude vibrations, regular and chaotic. We find that all vibrations are dominated by a few degrees-of-freedom.

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Coupled Triggers of Coupled Singularities and Transformation of Homoclinic Orbits in the Special Rheonomic Systems

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Tthe theorem of existence of coupled triggers of the coupled singularities is presented in this paper. Theorem of the existence of sets of homoclinic orbits with copupled triggers of coupled singularities is defined. By using examples of the simple engineering systems: coupled gears pair, Watt's regulator, and gyro-pendulum in the gravitation field these theorems are applied for investigatng the character of homoclinic orbits and structure of the phase portrait of nonlinear dynamics of these dynamical systems. For special rheonomic systems with one or more deegrees of freedom, which have equivalent holonomic stationary conservative systems, phase portraits of relative motions and existance of possible homoclinic orbits are investigated by applying the theorems mentiones above. By using MathCad the phase portraits and corresponding family of midifying kinetic potencial curves are composed and presented.

SESSION T2K
DYNAMICS II

Exploiting Discontinuities for Stabilization of Recurrent Motion

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A rigorous mathematical technique is presented for exploiting the presence of discontinuities in nonsmooth dynamical systems in order to control the local stability of periodic or other recurrent motions. The methodology is illustrated with examples from impacting systems, namely a model hopping robot, a Braille printer head, and a class of passive bipedal walkers. It is shown how initially strongly unstable motions can be successfully stabilized at negligible cost and without active energy injection.

On the Dynamics of a Railroad Freight Wagon Wheelset with Dry Friction Damping

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We investigate the dynamics of a simple model of a wheelset that supports one end of a railroad freight wagon by springs with linear characteristics and dry friction dampers. The wagon runs on an ideal, straight and level track with constant speed. The lateral dynamics in dependence on the speed is examined. We have included stick-slip and hysteresis in our model of the dry friction and assume that Coulomb's law holds during the slip phase. It is found that the action of dry friction completely changes the bifurcation diagram, and that the longitudinal component of the dry friction damping forces destabilizes the wagon. A speed range exists in which an erosion of the domain of attraction takes place and its dimension becomes fractal. This may lead to existence of transient chaos with dramatic consequences for the safety. The model was investigated earlier [1], and Pascal [2] has described a derailment due to chaotic behavior.

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Lumped Mass Track Model with Rubber Bushings

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Accurate modeling and simulation of the dynamic behavior of a tracked vehicle is sought by accounting for the longitudinal as well as for the lateral elasticity of the track. The primary objective tobe achived by using this approach is that the model allows for steering and turning maneuvers, for which the lateral shear and friction forces play an important role. Also, the pressure distribution under the track can be evaluated with more accuracy than using the rubber-band type track models, mainly because now it is possible to compute the pressure under those portions of track between two road wheels. Each track shoe is modeled as a lumped mass, whose kinematics and dynamics are known at each moment of time. The assumption that the three bushing elements between any two neighboring track shoes can be modeled as one rubber bushing is made. To decrease the computation time, only the portion of track ofinterest (the one in contact with the ground, the road wheels and the sprocket) needs to be modeled as lumped masses, while the upper portion of the track canbe modeled as a continuous belt. Boundary conditions are set at the connecting points between the two types of track models. Comparisons with the extended rubber-band track model are made.

Keywords: track model,multibody dynamics

Bifurcations of Periodic Orbits in a Class of Autonomous Non-conservative Perfect Systems

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The present work examines in detail the structure of periodic orbits and their bifurcations for perfect discrete systems under partially follower forces, with or without viscous damping. The motion of such a class of autonomous non-potential dissipative systems is governed by a set of highly non-linear ordinary differential (field) equations that can be integrated only numerically. The main objective of this paper is to study the (global) bifurcations associated with different types of periodic motions of the system, and establish a relationship between periodic orbit bifurcations and chaotic-like orbits at certain parameter ranges. This is achieved by employing a non-smooth temporal transformation of the time variable, that transforms the strongly non-linear initial value problem to an equivalent boundary-value one, to be dealt by employing already established numerical schemes. The theoretical findings are subsequently applied to the classical 2-degree-of-freedom model of Ziegler, for which a variety of numerical results exist, based mainly on fully non-linear straightforward dynamic analyses. Complicated series of periodic orbit bifurcations are computed, of relatively large periods, and numerical simulations indicate that chaotic-like transient motions of the system may appear when a forcing parameter increases above the divergence state. At these parameter values there co-exist numerous branches of bifurcating periodic orbits and it is conjectured that sensitive dependence on initial conditions due to the large number of co-existing periodic orbits causes the chaotic-like transients observed in the numerical simulations.

Keywords: partial follower loading, periodic orbits, global bifurcations, chaotic-like transients

Hamiltonian Mechanics for Functionals Involving Second Order Derivatives

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Hamilton's principle and his celebrated canonical equations are equivalent forms for Newton's second order differential equations of motion and the same is true for the further development of this analytical approach to mechanics culminating in the celebrated Hamilton-Jacobi equation. Classical variational mechanics invokes kinetic energy functions, which are expressed in terms of momenta or velocities and this is then developed where the first derivative is the highest temporal derivative. It is of interest to examine the extension of this theory to cases when the Lagrangian involves second order derivatives; such circumstances arise in spatial mechanics, and for

such functionals the Euler-Lagrange equations are fourth order. Accordingly, the generalization of Hamiltonian theory for such systems is ideally suited to problems of beam flexure. The mathematical structure of the Hamiltonian theory remains essentially intact; the change in the independent variable from time to space implies a change in the physics of the problem from determining trajectories of particles in time to finding deflected configurations of beams in space.

In this paper, a theory for the Hamiltonian mechanics of systems described by fourth order differential equations is developed and is illustrated by an example invoking the flexural analysis of beams. The variational formulations associated with Newton's second order equations of motion have been generalised to encompass problems governed by fourth order ordinary differential equations. This new formulation is applied, as an example in the analysis of Euler-Bernoulli beams. The mathematical structure of the Hamiltonian theory remains in tact and its further extension to functionals depending on, say, third order derivatives, becomes largely self evident.

The canonical equations associated with functionals with second order derivatives emerge as four first order equations in each variable. The transformations of these equations to a new system wherein the generalised variables and momenta appear as constants, can be obtained through several different forms of generating functions. The generating functions are obtained as solutions of the Hamilton-Jacobi equation. This theory is illustrated by application to an example from beam theory the solution recovered using a technique for solving nonseparable forms of the Hamilton-Jacobi equation.

Finally it is considered important to emphasize that whereas classical variational mechanics that uses time as the primary independent variable, here the theory is extended to include static mechanics problems in which the primary independent variable is spatial.

Control of Hopping Apparatus

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Creation of WM is a complex problem [1, 4] because they are systems with variable constraints [1]. The simplest device, which realizes statically unstable gait, is a hopping (or running) apparatus. The models of such machines are traditionally used [1, 5] for improvement of control algorithms since they demand rather simple control systems and design of actuators. M. Raibert constructed the working sample of the hopping device in Leg Laboratory (MIT) and the further researches of the laboratory continue to develop this scientific direction [3].

Note that at synthesis of control algorithms in [5] the traditional approaches were used. However, the algorithms, which are taking into account variable constraints of controlled system, have the certain advantages [1].

For the solving of the problems of WM control (as systems with variable constraints) was developed and used a number of control algorithms [1, 2] which are based on the methods of periodic optimization.

In the present work the statically unstable one-legged (hopping) machine which is constructed with using of simple elements is examined. This model is close to [5], but the control system is based on the algorithms, which are taking into account the variable constraints [2].

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Keywords: walking machine; control algorithm; variable constraints; periodic optimization

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SESSION W2M
DYNAMICS III

Kinematical Investigations of the Five-Link Lever Mechanism

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The mechanisms with two degree of freedom are applied in various areas of engineering ever more. The general description of movement on an example of five

link co-axial hinge mechanism with two degree of freedom was considered by Bessonov and also of kinematical dependence between two generalized coordinates in implicit form are determined. For definition of position functions of any points of links we investigate a kinematics of five link co-axial hinge mechanism. Here the location of each of two entrance links, which related by hinge with unyielding prop, determined by one different from each other generalized coordinate - angle of its rotation. The location of intermediate links are defined by two independent generalized coordinates - angles of rotations of entrance links. Unknown intermediate parameters, which defined by angle of rotation of intermediate links rather entrance ones, are excluded from equations by vector algebra methods. As the result we have two independent equation are determined by generalized coordinates i.e. by angles of rotations of entrance links. Further, we offer the interconnection method of these two generalized coordinates by transfer mechanism. Finally, we have mechanism with single degree of freedom for the fixed rule of one of entrance links or beforehand setting the functional relation between entrance links. The law of movement we shall express through angle of rotation one of link. Thus, in general view the final analytical formulas of the points positions functions which carrying to any links of mechanisms are found. In particular from those formulas can be obtained the appropriate formulas for structural schemes of specific mechanisms. The obtained results allow to perform further calculations for definition of dynamics of the mechanism.

Semi-active Fluid Mount Design

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Passive fluid mounts are used in automotive and aerospace applications to isolate the cabin from the engine noise and vibration. But due to manufacturing and material variabilities, no two fluid mounts act the same. So, fluid mounts are tuned one by one before it is shipped out. Since none of the passive fluid mount parameters are controllable, the only way to tune the mount is to either change fluid, or change inertia track length and diameter, or change rubber stiffness. This trial and error manufacturing process is very costly. To reduce the fluid mount notch frequency tuning cycle time, a new fluid mount design is proposed. In this new fluid mount design, the notch frequency can be easily modified using passive or semi-active control approach. In this presentation, the new design concept, and its simulation results will be presented.

On a Receptance Coupling Method for Tool-Point Frequency Response Prediction in High-Speed Machining

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While interest in high-speed machining applications continues to grow worldwide, the achievable material removal rate continues to be limited by chatter, or self-excited vibrations that lead to unstable machining conditions, in many instances. Previous research has shown that the limiting depth of cut at a given spindle speed for a high-speed machining operation to remain stable is determined by the frequency response at the tool tip of the spindle/holder/tool assembly. We present and discuss the accuracy of a method that combines receptance coupling substructure analysis (RCSA) with theory and experiment for the rapid prediction of tool-point frequency response. The basic idea of the method is to combine the measured direct displacement vs. force receptance at the free end of the spindle/holder system with analytical expressions for the tool receptances. These analytical expressions were derived and used to study vibrating systems by means of receptance coupling more than fifty years ago by British researchers, notably Duncan, Johnson, and Bishop. The main difficulty with the method we present lies in our inability to measure experimentally all four of the direct receptances (relating displacement and rotation to applied force and moment) of the spindle/holder system.

Keywords: receptance coupling, high-speed machining, chatter, frequency response

Deformation Mechanism and Defect Sensitivity of Notched Free-free Beam and Cantilever Beam Under Impact

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This paper first studies the Dynamic behavior of pre-notched free-free beam and cantilever beam subjected to step loading at its free end, as typical structures with imperfection. Special attention is paid to the deformation mechanism and the defect sensitivity in the plastic energy dissipation. By employing rigid, perfectly plastic material idealization, complete solutions are obtained for all combinations of the notch size, notch position and the magnitude of load. Other than a one-hinge mode, 2- and 3-hinge

modes are observed and analyzed. It is revealed that the first hinge, which is the one closest to the loading point, dissipates most of the input energy. If the first hinge forms at the notched section, the energy dissipation is highly sensitive to the notch; otherwise, it is insensitive. It is also noted that when the load increases, the defect sensitive region shrinks to a narrower region close to the loading point, indicating that under large load, a remarkable effect of the notch on the energy dissipation may appear, only if the notch is very close to the loading point.

To analyze the interaction of the traveling hinges and the notched section, a pre-notched cantilever beam subjected to a rigid striker on its free end is analyzed. It is found that for a heavy striker, the stationary hinge either on the root or on the notched section dissipates most of energy and only when the notched section is sufficiently close to the impact point, the plastic hinge can move across the notch, indicating that the energy dissipation is insensitive to the notch. However, for a very light striker, the energy dissipation is the most sensitive to the notch when the latter is close to the impact point, while the deformation mode in the late stage also greatly affects the defect sensitivity.

Low-Cost Health Monitoring Using the Impedance Method

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Current research on impedance-based structural health monitoring technique at Center for Intelligent Material Systems and Structures will be presented. The basic principle behind this technique is to apply high frequency structural excitations (typically higher than 30 kHz) through the surface-bonded piezoelectric transducers, and measure the impedance of structures by monitoring the current and voltage applied to the piezoelectric transducers. Changes in impedance indicate changes in the structure, which in turn can indicate that damage has occurred. Two examples, including gas pipelines and composite structures, are presented to illustrate the effectiveness of this health monitoring technique to the wide variety of practical field applications. Although many proof-of-concept experiments have been performed using the impedance methods, the impedance-measuring device (HP4194A) is still bulky and expensive. Therefore, an operational amplifier-based turnkey device has been developed that can measure and record the electric impedance of a PZT. The performance of this miniaturized and portable device has been compared to our previous results and its effectiveness has been demonstrated.

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Solid Rotor Dynamics

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A traditional practice in Rotor Dynamics Analysis is to use beam models for both lateral and torsion analysis. Such an analysis limits the capabilities for the modern day design of high-speed machinery. An analysis using solid models of rotating machinery is demonstrated in this paper. To demonstrate solid rotor dynamic analysis an example of a twin spool rotor is considered from the literature. The current practice is to make use of a beam model.

Five different case studies are made to illustrate the solid rotor dynamics of the system. ANSYS was adopted to solve this problem.

Case 1: Beam Model in ANSYS is made to show the equivalence of the results. The results agree with the literature for both forward and backward whirl modes.

Case 2: Beam Model with Spin Softening effects is considered. A special subroutine "useracel" is adopted. It is shown that for backward whirl, natural frequency decreases with spin speed and the effective stiffness becomes zero when the spin speed becomes the natural frequency of the stationary shaft. Conventional beam models do not predict this aspect of backward whirl frequency.

Case 3: Solid Rotor Model with Lumped Masses and Inertias using SOLID-45 elements with 8 nodes each having three degrees of freedom of translation. Stress stiffening effect is not included as the disks are still left as masses. The results are presented.

Case 4: Solid Rotor Model with Disks and no stress stiffening is considered. Typical mode shapes are shown which agree with the literature beam mode shapes. In this case, the forward whirl frequency becomes zero at a spin speed slightly more than 2 1/2 times that of the stationary shaft natural frequency. However, such is not a real case as the stress stiffening will counter this effect and hence its importance.

Case 5: Solid Rotor Model with Disks with Stress Stiffening is considered. The Campbell diagram shows that forward whirl frequencies do not vanish as in the previous

case at higher spin speeds due to stress stiffening effect. Thus the solid rotor models become more practical in applications.

SESSION M2L
ELASTICITY I

Boussinesq Problem in Three-Dimensional Anisotropic Elasticity

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The Boussinesq problem in which a unit point load applied at the boundary of an elastic half space is investigated in this paper. The well-known two-dimensional Stroh formalism is extended here to analysis the Boussinesq problem for a generally three-dimensional anisotropic half space. Based on the Fourier transform method, the framework of the Stroh formalism is established in three-dimensional anisotropic elasticity. The generalized Stroh eigenrelation is formulated on an oblique plane with the normal to the oblique plane lies on the $x-y$ plane. The main objective of the present work is to develop the three-dimensional Stroh scheme, which can be applied to solve various mixed boundary value problems. The displacement field produced by a concentrated point load at free surface is expressed in Fourier integral representation with integrand in terms of multiplication of complex eigenvectors. Finally, the explicit Green's function solutions are presented for a transversely isotropic half space.

Keywords: Boussinesq Problem, Stroh Formalism, Anisotropic Half Space, Fourier Transform Method.

The Present State and Needed Development of the Strain-Gradient Stress Analysis

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Strain-gradient stress analysis is based on utilization of a well-known dependence between the path of flowing energy and the inhomogeneity and anisotropy of the body – the path of the flowing energy is not rectilinear. It is bent and twisted, depending on the degree of inhomogeneity. When the flowing energy can be modeled as a transversal wave radiation, the energy beam impinging upon a body is resolved into two conjugated beams, depending on the form and patterns of the material anisotropy. Two forms of energy exhibit this feature; phonon energy representing energy of mechanical waves, and photon energy representing energy of electromagnetic radiation. Obviously, the magnitude of this effect depends not only on the magnitude of inhomogeneity but also on the spectral frequency of the phonon and photon radiation, as velocities of elastic and electromagnetic waves in physical bodies are wavelength dependent. The term inhomogeneity denotes in this case alteration of density that is directly related to alteration of the otpical density. Basis relations between the patterns of radiant energy propagation in physical bodies and the form of energy are well described in case of photon energy [1]. Those relations were taken as the basis for relations between the stress and strain gradients and the curvatures of two conjugated light beams that propagate in transparent stressed bodies.

In the case of a plate subjected to a two-dimensional stress state (stress components do not depend on the thickness coordinate) where a light beam impinges upon a surface point (x,y) of the plate of thickness b in the z-direction, the basic relation of the strain-gradient stress analysis can be presented as relations between the slopes of the emerging light beams and the gradients of principal stresses, in the form [2]:

$$\begin{pmatrix} \alpha_i \\ \beta_i \end{pmatrix} = \frac{b}{n_0} \begin{pmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \end{pmatrix} n_i, \; i = 1,2, \text{ and} \qquad (1)$$

$$n_1 = C_1\sigma_1 + C_2\sigma_2, \; n_2 = C_1\sigma_2 + C_2\sigma_2.$$

When the stress state is symmetrical, both conjugated rays deflect coplanarly in the plane of symmetry.

Experimentally determined strain-gradient functions for different plates have been evaluated using the derived relations and compared with the analytically obtained predictions of plane stress solutions. Comparison is satisfactory in regions where the stress state is close to two-dimensional. Rapid changes of the slopes of emerging light indicate presence of three-dimensional stress state. To determine values of stress components it is needed to incorporate three pieces of information into the analytical procedure of evaluation of experimental results: on the size of the local three-dimensional effect; on the distribution of in-plane stresses across the plate thickness; and on the distribution of thickness stresses across the plate thickness. Corresponding funcitons being investigated are: a section of parabola; a section of parabola; a section of cosine function.

Keywords: Stress analysis, optical methods, strain-gradient light bending, three-dimensional stress state

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A Novel Sinc Solution of Boundary Integral Form for Two- and Three-Dimensional Bi-material Elasticity Problems

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A heretofore unavailable procedure for Sinc solution of boundary integral form to a class of two and three-dimensional bi-material elasticity problems is presented. The procedure is based on boundary collocation via the use of Sinc approximation. The Sinc approach automatically concentrates points near a point (or line) of singularity, and consequently has the advantage of exponential convergence in spite of unknown-type singularities in a neighborhood of a re-entrant corner, a crack, or at an interface of two layers at a free edge. The system of boundary integral equations for a three- or two-dimensional bi-material elastic body is reduced to a system of algebraic equations via Sinc collocation. Explicit Sinc formulas are derived for transformations, their derivatives, Sinc interpolation, quadrature, and approximation of Hilbert transform.

The solution of the system of resulting algebraic equations is carried out by the method of block Gaussian elimination, involving simultaneous matrix operation on each of the block. A model two-layer bi-material elasticity problem is numerically investigated as an illustration of this novel approach. Extension of this investigation to Sinc convolution is currently under way, and will be reported in the near future.

Keywords: Sinc, Boundary Integral, Collocation, Bi-Material.

Asymptotic Method in Static and Dynamic Problems of Thin Plate on Asymmetric Theory of Elasticity

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The main aims and problems of asymmetric (momental, micropole) theory of elasticity (ATE) consist in setting the structural properties, the definition of true stress state, the full spectrum of frequency of natural vibrations of polycrystalline, grained and composite technical materials. The researches devoted to the theory of thin plates and shells are of special importance in ATE. In this work boundary problems of static and initial-boundary problems of dynamic of thin plate on ATE are researched with the help of singular disturbed asymptotic method.

Static theory of thin plate on ATE is set forth on the basis of unique approach, i.e. asymptotic method of integration of equations of three-dimensional problem of ATE. The applied two-dimensional theories of thin plate on ATE are worked out. Boundary layer on ATE is studied in detail, the existence both of force and momental boundary layers is proved. The speeds of attenuation of quantities of boundary layer are stated. The interaction of interior stress state with boundary layer in the case of various types of three-dimensional boundary conditions on ATE is analyzed.

The problem of reducing of three-dimensional dynamic problem on ATE for thin plate to two-dimensional is studied including the problem of satisfaction to boundary and initial conditions. The problem of construction of interior stress state of thin plate on asymmetric theory of elasticity in dynamic conditions is considered. The definition of interior stress state is reduced to some iterational process in each stage of which it's necessary to solve some two-dimensional equations. The applied two-dimensional theory of thin plates on asymmetric theory of elasticity is constructed on the basis of initial approach of interior problem. The defined equations, boundary-initial conditions and functional of general variational principle of applied two-dimensional dynamic theory of thin plate on ATE are derived. In close proximity to lateral surface of plate stress state of boundary layer on asymmetric theory of elasticity originates, which attenuates abruptly when it goes far from the edge. The introduction of this stress state gives opportunity both to satisfy to boundary conditions on lateral surface of plate which are formulated in the terms of three-dimensional asymmetric theory of elasticity, and to set boundary conditions of interior problem, and to define stress state in close proximity to edge, which has quasi-static behaviour. Despite the fact that two-dimensional dynamic equations of interior problem

(in contrast to similar problem on classic theory of elasticity) are of hyperbolic character, the problem of boundary layer within time is also researched.

Longitudinally - Transversal Curving of the Tape Bases with Allowance for Influences of Tangents of Jet Pressure

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The tape bases interacting with the elastic basis for want of account of jet tangents of pressure of the basis on contact is considered. The flexural rigidity of the base is characterized by function of coordinates, which can be both continuous on all length of the base, and sectionally continuous, saving constant significance within the limits of the certain plots(sites) of a construction. The variable transversal load, point force and force couple with appropriate moment acts on the base. The base except for transversal loads on extremities is contracted to an ottoman is central by the enclosed forces.

The solution of an analytical character, system of the differential equations of the fourth order with variable factors circumscribing longitudinal - transversal curving of the label bases is obtained.

For determination of vertical and horizontal transitions of points of a surface of the basis as in theory elasticities, is accepted, singular integral equations, the nucleus of which integral expresss as a number on special functions.

Because of correlations of the base and basis, the solution of a considered problem is reduced to a research an infinite system of the algebraic equations with infinite unknowns. The resolvability of a system and existence of its solution mathematical will be strictly justified also system is decided by a method of a reduction. With the help of solutions of the algebraic equations the formula for calculation jet pressure of the basis, internal gains of the base appropriate to concrete external loads with concrete mechanical properties of a material of the base is resulted which will be easily realized for engineering accounts.

Regularization of a Solution of the Cauchy Problem for the System of Equations of Elasticity in Displacements

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In the present article, we consider the questions of regularization of a solution to the Cauchy problem for the systems of differential questions of elasticity, the questions of static's of an isotropic elastic medium. Given the displacement and tension vectors on a part of the piecewise smooth boundary of a domain, we reconstruct the field of displacements inside the domain occupied by the elastic body.

The system of equations for the static's isotropic elastic medium is an elliptic system of second-order differential equations with constant coefficients in the components of the displacement vector. The Cauchy problem for elliptic equations is well known to be ill-posed; a solution is unique but unstable (Hadamard's example). To make the statement well-posed, we have to restrict the class of solutions. During the last decades the classical ill-posed problems of mathematical physics have been of constant interest. This direction in studying the properties of solutions to the Cauchy problem for the Laplace equation was originated in the fifties in the articles by M.M.Lavrent'ev and S.N.Mergelyan and was further developed by V.K.Ivanov, Sh. Ya. Yarmukhamedov, et al. [1-6].

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SESSION T2M
ELASTICITY II

Theory of Elastic Materials with Voids in NDT of Bond Quality

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Microcontinuum theories extend the classical framework to reflect observed material behaviour infered as due to the influence of structural features of the medium at the microlevel. Attribution of a class of observed phenomena to a particular feature led to a feature specific direction of extension. Experience with granular materials for instance, provided the impetus for the formulation of the theories of elastic materials with voids, nonlinear and then the linear. The viods are microlevel vacous pores - devoid of any material - distibuted throughout the medium.

Minute pores a large number of them spread over a solid region become detrimentally effective, when the region happens to be the thin interface layer of adhesive in a composite structural element like an aircraft wing. A void in the context of adhesive bonding being a region which ought to but doesn't contain the adhesive, it is suggested that the linear theory of elastic materials with voids (LEMV) could be profitably employed in NDT of adhesively bonded interfaces for presence of porosity. In particular, to facilitate NDT of composite plates in the Lamb and Leaky Lamb wave (LW/LLW) technique the mode dispersion and attenuation are shown to be influenced by the presence of porosity in the interface. It is also shown that the stresses carried by the early Lamb modes can be used as possible means to identify the specific modes to be generated in LW/LLW NDT.

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Local Stresses in Composite Plates with Pin-loaded Holes

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A new analytical method for solving mixed boundary value problems along holes in composite plates is developed. It addresses problems where part of the hole boundary is stress-free, and the other part subjected to displacement or/and load boundary conditions. The method is based on the complex variable theory. The special stress functions are derived which automatically give normal and tangential stresses equal to zero over the unloaded part of the hole boundary.

By using these special complex stress functions that automatically satisfy the stress-free boundary condition, the present approach also simplifies and speeds up the numerical calculations for the implementation of the boundary conditions in the collocation method. Henceforth, only the boundary conditions on the loaded part of the hole need to be enforced.

The present approach is quite general and could be applied to a range of engineering problems. As an example, it is applied to orthotropic composites plates with a pin-loaded hole. In this case the contact of the pin and the plate is only partial and depends upon the load. This feature leads to moving boundary conditions and consequent non-linearity of the problem. Mathematically, this problem falls within the scope of a mixed boundary value problem with moving boundaries. An inverse formulation in conjunction with the equidistant collocation method is used to solve the problem. Both clearance and friction at the pin-hole interface are taken into account. The particular results are obtained for T800/924C carbon fibre-epoxy laminates. The influence of different lay-ups, initial pin displacement and clearance on the local stress field and the contact angle is determined. The analysis can be useful in the preliminary design of bolted joints.

Keywords: composite, stress, pin-loaded hole, collocation method.

Some New Results in 3D Thermoelasticity

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Generalization of Green's functions onto a case the problems in theory of statical and dynamical thermal

stresses is given here. The considered functions are a convolution over the body volume , of two influence functions. The first function is the Green's function (in statical thermoelasticity) or (in dynamical thermoelasticity) for the problem in heat conduction. These functions are the functions of influence of a unit heat source onto the temperature. The second function is the function of the influence of unit concentrated body forces onto the bulk dilatation or in statical or dynamical thermoelasticity, respectively . Thus, the introduced functions of the influence of a unitary heat source onto the displacements are determined by the formulae:

(1) in thermoelastostatics, and
(2) in thermoelastodynamics. In Eqs. (1) , (2): ; the coefficient of the linear thermal dilatation; Lame's elastic constants. On the base of functions in Eqs. (1),(2) the author suggested the following new integral formulae for displacements:
(3) in thermoelastostatics, and
(4) in thermoelastodynamics. Eqs (1) - (4) present the generalization of the Green's integral formulae for the heat conduction and elasticity onto statical and dynamical uncoupled thermoelastisity .

The investigations have shown that the possibilities of realizing of Eqs. (1) - (2) are so vast that they could be a subject for a handbook on influence functions in the theory of thermal stresses. They are, for example, the solutions for locally mixed problems for canonic bodies for Cartesian, , cylindrical, spherical and other systems of orthogonal coordinate. As examples, some new solutions of 3D problems are presented.

Keywords: influence function, bulk dilatation, thermal stresses

Correctness of the Plane Elasticity Problem in a Semi-plane

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As is well known, any homogeneous deformable solid occupies a bounded region, and when continuously changing the tractions imposed on its smooth boundary, the continuous and bounded stresses (strains) and displacements arise. Therefore, while modeling the stressed state by means of the plane elasticity problem in a semi-plane, one should demand that stresses and displacements be continuous and bounded. Besides, to integrate differential equations of plane elasticity, the method of the integral Fourier transform is sure to be the most efficient one; this transform requires that stresses should be absolutely integrable.

The plane elasticity problem in terms of stresses with the tractions prescribed on the boundary of a semi-plane consists in solving the two differential equilibrium equations and the compatibility equation for the first invariant of stress. By direct integration of equilibrium equations, stresses being absolutely integrable, it is proved that such a restriction requires that the resultant vector and moment of external tractions and body forces be equal to zero. If this is the case, the expressions of displacements on the boundary through the tractions and vice versa are set up by integrating the Cauchy relations. As the tractions should satisfy the above-mentioned equilibrium conditions, these relations yield that displacements on the boundary can't be given in an arbitrary way - one component is forced to satisfy an integral compatibility condition.

The relations between the tractions and displacements on the boundary of a semi-plane derived prove that there exists only one correct plane elasticity problem in a semi-plane subject to equilibrated tractions. In the case of essentially mixed boundary conditions they make it possible to mathematically rigorously deduce the set of integral equations of the second kind for determining the unknown tractions through the imposed displacements, and thus solve the mixed BVP.

Keywords: correctness, plane elasticity problem in a semi-plane, relations between tractions and displacements, integral equations

Method of Direct Integration of Equations for Two- and Three-dimensional Thermoelasticity Problems

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A method of direct integration of the differential equations for quasi-static two- and three-dimensional thermoelasticity problems in terms of stresses which uses no auxiliary harmonic or biharmonic functions is proposed. The

solutions of some problems in infinite regions without corner points as well as of the two-dimensional problems in a rectangle are constructed. The method is based on the following: (i) integration of thermoelasticity equations; (ii) determination of the relations between the stresses; and (iii) selection in each case of the so called governing stresses. Consequently, the key compatibility equations in terms of stresses are written down for the governing stresses. To solve them in the case of the plane problem in a rectangle, a method for separation of variables and constructing the complete by the appropriate coordinates sets of functions, which correspond to Saint-Venant's principle and consist of the eigen- and associated ones, is proposed. The solutions of the key equations are presented by using these complete sets. The displacements are found by integrating the Cauchy relations.

It is proved for three-dimensional problems of MDS that there exist only three original integro-differential compatibility equations in terms of strains. If the so called co-ordination conditions are satisfied, they can be naturally reduced to the corresponding three Saint-Venant's differential compatibility equations depending on which three of the six Cauchy relations have been selected as the governing ones for finding displacements. Consequently, three corresponding compatibility equations in terms of stresses are written down. Together with equilibrium equations they constitute a complete set of equations in terms of stresses for three-dimensional problems.

Integral equilibrium conditions for stresses and integral compatibility conditions for strains and displacements, which are independentl of the physical models of deformation, are deduced.

SESSION M2R
FLOW CONTROL

Effect of the Cavity on Reduction of Skin-Friction Drag

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Contrary to our physical intuition, some experimental results showed that skin-friction drag may be reduced by using D-type roughness or a chain of small-size cavities, which provides a possibility of using a cavity as a passive device for drag reduction. The objectives of the present study are to identify the effect of the cavity length and depth on the flow and drag characteristics in a turbulent boundary layer flow using large eddy simulation. The Reynolds number based on the free-stream velocity and momentum thickness at the cavity is 1520. Six different sizes of the cavity are examined for turbulent flow. Furthermore, an intensive parametric study over a broad range of the depth and length of the cavity is performed for laminar boundary layer flow over a cavity at Re = 75 and 300. In case of turbulent flow, the flow inside and over the cavity remains relatively quiescent when drag reduction occurs, whereas the shear layer over the cavity and the recirculating bubble inside the cavity actively interact with each other when drag is increased. In the latter case, shear layer instability is generated and it increases the turbulence intensities and the pressure drag. Since the generation of the shear layer instability mainly depends on the depth of the cavity, it is believed that there ex ists an upper limit of the cavity depth for skin-friction reduction. Also in laminar flow, the flow shows an oscillatory nature due to the shear layer instability when the cavity depth is sufficiently large. In this case, the total drag substantially increases due to the significant increase of the pressure drag. On the other hand, when the cavity depth is small, the flow ultimately reaches a steady state and total drag is decreased. Total drag is also decreased even when the cavity length is large enough for the separated flow to reattach to the cavity bottom. It is interesting to note that, contrary to the riblet, the cavity can reduce drag even in laminar flow.

Optimal Shape Design of a Plane Diffuser in Turbulent Flow

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Diffusers are widely used as an important component of turbomachines that can produce a high pressure by broadening their width to decelerate the velocity. Many researches have been preformed to design an efficient diffuser shape. Among them, Stratford (JFM, 1959) experimentally designed an optimal shape of a diffuser by adjusting the diffuser walls such that the shear stresses are zero all over the diffuser wall. On the other hand, optimal shape design methods using the optimal control theory have been applied to the design of the optimal diffuser shape in laminar flow (Cabuk & Modi, JFM ,1992) and in turbulent flow with a Baldwin-Lomax model (Zhang et al., Inverse Problems in Engng, 1995). In the present study, we design an optimal shape of a diffuser in turbulent flow using the optimal control theory and show that maintaining zero skin friction in the pressure-rise region is an optimal condition for maximum pressure recovery

at the diffuser exit. We use a $k-\epsilon-v^2-f$ turbulence model by Durbin (AIAA J, 1995) that is known to predict separated flows very well. From an initial shape, an optimal diffuser shape for maximum pressure recovery is obtained through an iterative procedure. The diffuser length is fixed, and the lower wall shape is changed freely with the upper wall fixed. The shear stress distributions along the wall for the optimal shape is indeed zero along the lower wall throughout the pressure-rise region, and thus there is no separation in the flow. The pressure distribution along the wall clearly shows that the optimal shape has a higher pressure rise than the initial shape. For the optimal diffuser shape obtained, a large eddy simulation is also carried out to investigate the turbulence characteristics near the zero skin-friction wall and its result will be also shown in the presentation.

Keywords: Optimal shape design, Diffuser, Separation, Pressure rise

On Control of a Pair of Vortex Paches

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In the present work we discuss two methods of controlling the motion of two elliptical vortex patches, including forcing or preventing the merging, by putting a point vortex of a time-varying strength in the center of the vorticity. One way is to use the method of flat coordinates (a brute force method), the other is to use the adiabatic control (using control as a small perturbation). We show that one can make a control much more efficient by using the internal dynamics of the system. We perform a set of numerical simulations that confirms the analytical results. Using this problem as an example we compare these approaches and discuss there relative advantages and disadvantages. We compare the theoretical results with numerical solutions of Navier-Stokes equations.

Adjoint-Based Control and Analysis of Free-Shear Flow Noise

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It is difficult to predict free-shear flow noise because its source is complex (typically turbulent) and only a tiny fraction of the flow's energy (10^{-3} to 10^{-5}) "leaks" out as noise. Even simple phenomenological models are lacking. Recently, direct numerical simulation (DNS) has provided detailed data for two-dimensional mixing layers [1], axisymmetric jets [2], and three-dimensional turbulent jets [3], but the noise mechanisms remain veiled due to the complexity of the data and there may be, in fact, no significant simplification possible that points the way for noise reduction. Currently, trial-and-error iterations are the standard practice, but there is no generalization or even understanding of these results. In light of this, we use DNS of the flow equations and their adjoint to optimize controls, thus overcoming the flow's complexity. Comparing the original and the flow quieted by this automatic procedure shows the changes that must be affected to reduce noise.

In present study, we reduce the noise of a two-dimensional mixing layer, a model of a jet's near-nozzle region. The control is a body force ϕ which has support only in a small region near the "splitter plate". The forcing ϕ is optimized using gradient information provided by solution of the adjoint system forced by an appropriate measure of the noise in the far-field. After 7 conjugate gradient iterations, noise is reduced by 6.3dB. The forcing identified is weak and has an unintuitive form. Comparison of the near-field pressure evolution with and without control shows that there is a nearly imperceptible effect on the large-scale structural dynamics. The turbulence kinetic energy is also almost unchanged, so the noise reduction is not due to turbulence suppression.

Keywords: flow control, aerodynamic noise, free-shear flow, turbulence

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Capturing of the Horseshoe Vortices by Vortex Fusion

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Junction flows occur when a boundary layer encounters a surface-mounting obstacle, producing horseshoe vortices that wrap around the obstacle. The essential ingredients of forming large-scale horseshoe vortices include

upstream vortical influx, stagnation zone of finite extent, longitudinal stretches of vortex filament, and vortex fusion by viscosity. As a vorticity-ladden boundary layer flow approaching the forward stagnation zone created by a three-dimensional obstacle, the vortex lines wrap around the obstacle. The vorticity is strengthened by longitudinal stretching of the vortex lines, which are then accumulated and co-rotated among themselves in front of the obstacle and fused into a large-scale horseshoe vortex around the obstacle.

With the objective of seeking junction flow control, the hydrogen bubble flow visualization technique was used and pressure measurements were carried out in a water channel with a test section of 0.6 m wide, 0.4 m deep and 8 m long, and an adjustable mean flow speed of up to 0.5 m/s. The structure was mounted from the top of the test section in an inverted position. Vortices were generated by a small control rod placed upstream, whose submergence depth was the determining factor of the vortical influx. A thin square plate of 10-cm × 10-cm was used as an obstacle to produce the horseshoe vortex. A long airfoil of 1-cm chord was placed horizontally near the water surface upstream of the thin square plate. It was found that the original horseshoe vortex moved toward and circulated around the airfoil. The junction flow immediately upstream of the obstacle was noticeably steady and free of disturbance. Measurement also showed an 80% reduction in pressure fluctuation. The process was insensitive to the streamwise location of the airfoil (large capture zone), the horseshoe vortical structure, stream speed and acceleration, upstream vortical influx, and magnitude/sign of airfoil's angle of attack.

It is observed that capturing of the horseshoe vortices is based on vortex fusion. The starting vortices at the trailing edge of the airfoil co-rotate and fuse with the horseshoe vortex, bring the horseshoe vortices forward, and circulate around the foil. When starting vortices from the trailing edge of the foil and the horseshoe vortices are of the same sign, a stronger circulation around the airfoil is generated and a tighter capture occurs. In the case in which the foil's angle of attack produces starting vortices, which are of the opposite sign of the horseshoe vortices, cancellation of vorticity takes place during the process of vortex fusion. The circulation around the foil is, therefore, weaker. In fact, any cylinder generating a standing vortex can bring the horseshoe vortices closer through co-rotation of vortices. Capture of horseshoe vortex by a 6-mm circular rod has also been noted. However, the capture range is limited, and its holding power is weak. The vortex can occasionally run away. Experimental results with an obliquely mounted square cylinder were similar, demonstrating that the captures and controls were effective for all angles of attack.

SESSION T3E
FLOW INSTABILITIES

Intermittent Instability Induced by Long-Wavelength Klebanoff Modes

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This paper presents theoretical results on the stability properties of a Blasius boundary layer perturbed by Klebanoff modes. The latter are taken to be the signature of a low-frequency three-dimensional convected gust, which may be either isolated or periodic along the spanwise direction. They can be treated as a distortion to the basic state because of their extremely low frequency and long streamwise wavelength. It is found that even relatively weak Klebanoff modes may alter the curvature of the underlying mean flow by $O(1)$ in a near-wall region. The resulting perturbed flow may support linear instability modes with a streamwise wavelength much shorter than the spanwise length scale of the distortion.

When the amplitude of the Klebanoff modes exceeds a threshold range, the instability modes become predominantly inviscid, and their growth rates and characteristic frequencies are much higher than those of the Tollmien-Schlichting waves in an unperturbed Blasius flow. A localised distortion supports both sinuous and varicose modes of instability, with the sinuous modes being more unstable than the varicose modes. The instability is intermittent in time and localised in space, occurring only in certain phases of the modulation cycle and within a specific window(s) along the streamwise direction. In particular, the dominant sinuous modes appear only during the phase in which a low-speed streak exists. A periodic distortion supports spatially quasi-periodic modes through a parametric resonance mechanism.

The nonlinear development of a localised sinuous mode is studied. The nonlinear solution indicates the onset of fully nonlinear yet inviscid dynamics. We suggest that the temporally intermittent and spatially localised instability and its subsequent nonlinear development lead to patches of streak oscillations. The apparent convection velocity of such patches is estimated to be about 0.81 times the free-stream velocity.

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Characteristics of the Shear Layer Separating from a Circular Cylinder

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The instability of a separated shear layer in a cylinder wake is investigated using large eddy simulation of turbulent flow over a circular cylinder at Re= 1600 and 3900 based on the free-stream velocity and cylinder diameter. The time integration method is based on a fully implicit, fractional step method and all terms are advanced with the Crank-Nicolson method in time and are resolved with the second-order central-difference scheme in space. A non-uniform C-type mesh of 673 × 160 × 64 grid points is used for both Reynolds numbers. The computational cost required is about 8 hours per one shedding cycle using 42 processor elements in CRAY T3E. Many trace points are located near the separating shear layer in order to investigate the shear layer characteristics. The existence of the shear layer fluctuations and its intermittency at both Reynolds numbers are confirmed by the data from these trace points. The frequencies of the shear layer instability normalized by the Karman vortex shedding frequency are in good agreement with those of the previous experimental studies. Interestingly, there exist two distinct types of the shear layer instability: one is a completely 3-D type and the other is a quasi-2-D type. In the case of 3-D type, the intermittent velocity fluctuations exist locally in the spanwise direction, whereas they occur simultaneously at all spanwise positions in the case of quasi-2-D type. The instantaneous vortical structures are also investigated to identify these instabilities. In the case of 3-D type, the shear layer roll-up is confined in some area of the span, whereas the roll-up vortices exist throughout the span in the case of quasi-2-D type. The instability of 3-D type is generated by a strong streamwise vortex underneath the separating shear layer, while the quasi-2-D type instability is associated with disorder of the Karman vortex shedding process.

Keywords: Shear layer instability, Circular cylinder, Wake, LES

Perturbation Analysis of a Meandering Rivulet

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The rivulet is a narrow stream of liquid flowing down a solid surface. When the rivulet's flow rate exceeds a certain limit, it tends to meander exhibiting the instability of its interface. This study performs a perturbation analysis of this meandering rivulet assuming an inviscid flow possessing contact angle hysteresis at the contact line. Without the effects of a solid surface, this problem reduces to the dynamics of a liquid sheet subjected to the Kelvin-Helmholtz instability. However, the pressure jump across the rivulet interface is dependent on the dynamic contact angles at the contact line, and evaluating influences of this aspect is a major focus of this work.

Our analysis yields the dispersion relations for both the axisymmetric and anti-axisymmetric rivulets. We find that the contact angle hysteresis significantly promotes the rivulet instability as compared with a liquid sheet surrounded only by gas. Moreover, when the rivulet velocity is low, it is predicted that the axisymmetric disturbances are amplified more rapidly than the anti-axisymmetric ones, which explains the emergence of the droplet flow at the low velocity regime. An experimental apparatus is constructed to verify our modeling results while using water as a liquid. The experimental measurements, i.e. the wavelengths at each flow speed, are favorably compared with the analysis results for various solid surfaces.

Linear Stability of an Elliptically Strained Vortex Tube Revisited

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We revisit the short-wave instability of a straight vortex tube embedded in a pure shear flow, originally addressed by Moore & Saffman (1975) and Tsai & Widnall (1976). The vorticity is assumed to be uniform over the elliptically deformed core, and thus, without shear, the

basic flow is the Rankine vortex. The Rankine vortex supports neutrally stable three-dimensional waves called the Kelvin waves. A pure shear breaks the circular symmetry, causing a parametric resonance between bending waves of right- and left-handed helical form, being well known as the Moore-Saffman-Tsai-Widnall instability.

The results of Tsai & Widnall (1976) are simplified by providing an explicit expression for disturbance flow field, whereby an improvement in numerical accuracy is achieved. The parametric resonance instability occurs at every intersection point of dispersion curves of two types of bending waves. The amplification rate of non-rotating waves is by far larger than that of rotating waves. Direct relations of this static instability are established with the two-dimensional displacement instability in the long-wave limit (Moore & Saffman 1971) and with the elliptical instability in the short-wave limit (Bayly 1986; Waleffe 1990). An account for this instability is given from the viewpoint of Hamiltonian spectra. The energy of the Kelvin waves is calculated. It is shown that the non-rotating instability mode emerges as a result of collision of eigenvalues of zero-energy waves.

On the Effect of Nonparallel Terms on the Absolute and Convective Instabilities of the Rotating Disk Boundary Layer

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The stability of the flow produced by an infinite rotating disk in an otherwise still fluid has been investigated. This basic flow has long been studied as a convenient model for boundary layer flow over swept wings and turbomachinery blades (it has the same crossflow instability mechanisms producing stationary vortices); it is also a member of a wider class of swirling flows with geophysical applications, and is relevant to rotating magnetic storage media. In certain directions the resolved profile is inflexional and the flow is inviscidly unstable. A fourth order Orr-Sommerfeld (OS) equation can be derived if streamline curvature, Coriolis and nonparallel terms are neglected and only the viscous terms retained. The critical Reynolds number, R_c, for stationary vortices is then 181. If streamline curvature and Coriolis terms are included, giving a sixth order system, then an extra mode appears via a kink in the lower branch of the neutral curve for stationary vortices and R_c becomes 285. This extra mode replaces the OS mode. In addition to the stationary vortices, there exist travelling wave solutions and Lingwood (1995, JFM Vol. 299) has shown that these lead to an absolute instability for $R > 510$.

However, viscous, streamline curvature, Coriolis and nonparallel terms all enter the linearized disturbance equations at the same order (when variables are scaled on the boundary layer thickness). Given the differences between the results when some of these terms are arbitrarily included or excluded, it is of interest to discover what further changes might occur if nonparallel terms are included as well, and this is the focus of this research.

A formulation based on the 'local' version of the parabolized stability equations (PSE) described in Bertolotti, Herbert and Spalart (1992, JFM Vol. 242) that they used for producing initial conditions for their downstream marching scheme, and for pointwise stability results, has been implemented. Malik and Balakumar (1992, in 'Instability, Transition and Turbulence') used a similar approach on this problem, but our nonparallel terms differ from their's. The local PSE formulation (essentially a multiple-scales/WKB analysis) leads to an eigenvalue problem for a set of stiff 12th order linear ordinary differential equations, and these have been solved using expansions in Chebyshev polynomials.

Of great surprise to us, was that we found *two* neutral curves for stationary vortices. When followed to large R, the upper branch of each curve approached the inviscid result, while one mode, which displayed a prominent kink, approached the Coriolis-viscous mode along the lower branch, and the other mode, which has no kink, approached the OS mode. The nonparallel Coriolis mode has $R_c \approx 238$ and the nonparallel OS mode has $R_c \approx 340$. The azimuthal wavenumbers are similar to those in the sixth order parallel case. Nonparallel terms thus destabilize the flow with respect to the sixth order stability equations. Furthermore, the absolute instability now occurs above $R \approx 475$, so its connection with transition is not as close as suggested by Lingwood. At the time of writing, work is continuing on the effect of nonparallel terms on travelling waves and in the derivation of an asymptotic theory for the second unstable mode along the lines of Hall (1986, Proc. R. Soc. Lond. A 406).

Keywords: Nonparallel boundary layer stability, convective/absolute instability.

SESSION T2P
FLOW AND MODELING

Development of Patched Grid Model for a Flow Solver

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Multi-zone mesh techniques are widely used for complex geometry flow problems in computational fluid dynamics. Among these, there are two types of zonal methods depending on whether zonal boundaries exactly match or arbitrarily intersect. The former is named Patched grid approach and the latter the Overlapped (Chimera) grid approach. Major concern in zonal interface treatment lies in the conservation for flow variables. With the patched grid it is much easier to maintain conservation since there is only one boundary across which the two regions communicate. Therefore in this work, the patched grid model has been developed and implemented in a flow solver, i.e. UNIC-UNS. The failure in conservation of common direct interpolation method for dealing with the zonal interface leads to some special treatments to conserve flow variables at zonal interfaces, described as:

- Reconstruct a new interface on the basis of the original pair of interfaces by identifying the interface cells that are bounded by the mesh lines of original interfaces, leading to the best cell resolutions to describe the new interface.
- Integrate mass fluxes at the interface based on the cells identified on the new interface. This ensures that the best resolutions of mass fluxes are preserved.
- Use the new mass fluxes for continuity, momentum and other transport equations.

The high-cell-resolution interface reconstruction is required only once at the starting of CFD problem initialization. Therefore the procedure can still be very efficient. The interface boundary for 2D is determined by all of the face grid points of both adjoining zones as shown in Fig. 1. This enables that all the individual points from both zones lie in the interface line and then the interface is unique and accurate. Cell elements for 3D are defined using the original grid points in both zones and virtual intersection points. So that all grid points are used to construct the interface surface. The intersection point of these two set of grid meshes is defined as the intersection of one grid mesh with the image of the nearby cells of another grid mesh on it. For higher accuracy, the finer mesh is selected as the base mesh and the image of the other mesh is calculated based on every cell of the base mesh. If the interface is planar surface, the image can be calculated only once based on the base surface.

Fig. 2 shows that a planar surface structured mesh intersects with another unstructured mesh. We keep all the grid lines and collect the resulting cells. They may be no longer quadrilaterals or triangular, but polygons with the edge number less than eight (the maximum edge number of a polygon is eight in the case of two structured grids mesh interface). The polygon doesn't need to be triangulated under the memory and speed consideration. Fig. 3 illustrates a cylinder face as a simple example of curved interface in 3-D application. The 6×6 mesh (dark lines) is the base mesh and the 4×4 mesh (light lines) is projected based on every cell of the base mesh to construct the interface mesh. The validating case is 3D fin cooling, the zonal geometry, computational grid and numerical results are shown in Fig. 4

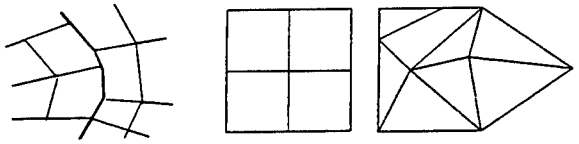


Fig. 1 Interface is defined by all of the grid points in 2-D case

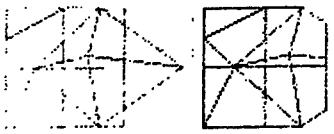


Fig. 2 Patched grid planar surface interface

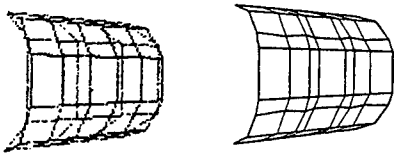


Fig. 3 Patched grid curve surface interface

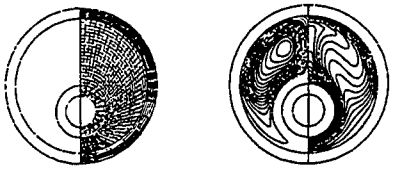


Fig. 4 Fin cooling (geometry, grid, temperature contours and streamline)

Keywords: computational fluid dynamics, multi-block, patched grid, conservation

An Adaptive Wavelet Method for Fluid Flows

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Accurate numerical simulations of multiscale problems require enormous computational resources in terms of memory storage and computing time because a large number of unknowns are necessary to resolve fine scales on a uniform grid. Since a great amount of these resources are waisted in regions where solutions have smooth behavior, the use of an adaptive solution strategy becomes necessary.

Different types of adaptive methods and related algorithms have been the subject of intensive research in recent years. Adaptive Mesh Refinement (AMR) on structured grids, as well as Adaptive Finite Element (AFE) and Adaptive Boundary Element (ABE) methods on unstructured grids have been developed. AMR algorithms are superior to AFE and ABE methods in terms of the cost and simplicity of mesh rebuilding and analysis for mesh rearrangement, but are inferior in their ability to handle complex geometries or moving boundaries.

Most recenlty, adaptive wavelet-based algorithms have been proposed. These methods are either based on Galerkin or collocation formulations. Galerkin methods, though accurate, have difficulties in dealing with general boundary conditions, general geometries, and nonlinear terms. Here we present a new wavelet-based adaptive multiresolution representation (WAMR) algorithm for the numerical solution of multiscale evolution problems. Key features of the algorithm are fast procedures for grid rearrangement, computation of derivatives, as well as the ability to minimize the degrees of freedom for a prescribed solution accuracy. Other main features include: ability of handling general boundary conditions; ease of switching the order of the wavelet basis used; and effective control of error in the numerical solution.

To demonstrate the efficiency and accuracy of the algorithm, we use it to solve the two-dimensional benchmark problem of incompressible fluid-flow in a lid-driven cavity at large Reynolds numbers. The numerical experiments demonstrate the great ability of the algorithm to adapt to different scales at different locations and at different times so as to produce accurate solutions at low computational cost. Specifically, we show that solutions of comparable accuracy as the benchmarks are obtained with more than an order of magnitude reduction in degrees of freedom.

Keywords: wavelet, adaptive, multiscale, fluids.

On Blade Coating Flow of Viscoelastic Fluids

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The complicated problem of blade coating for a large class of viscoelastic (*Oldroyd*) fluids is divided into two regions; downstream of the channel with a fully-developed plane-Couette flow (PCF), and free-surface flow at the front exit of channel. Appropriate analysis of the flow for both regions are of great importance as a change in flow in either region can alter the evolution of the free-surface flow drastically. First, the stability of one-dimensional plane Couette flow is determined for purely elastic fluids with added viscosity. The fluid here represents polymer solutions composed of a Newtonian solvent and a polymeric solute. Next, the obtained velocity profile is introduced as an input profile at the inlet to the blade coating flow. The free-surface evolution of the flow at the outlet of the flow is simulated using the boundary element method (BEM). For the inlet flow, the problem is reduced to a nonlinear dynamical system using the Galerkin projection method. Stability analysis indicates that the velocity profile at the inlet may be linear or non-linear depending on the range of the Weissenberg number (We). The evolution of the free-surface flow at the exit is examined for two cases; precritical $We = 1$ and critical $We = 4$. Using the two methods of spectral and boundary element for studying moving interface problems where the velocity of the free surface is to be explored for the blade coating problem is first introduced in this study.

Keywords: Blade Coating, Polymeric flow, Free-surface flow, Stability

Experiments and Analyses of Water-Filled Geomembrane Tubes as Temporary Flood-Fighting Devices

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Water-filled tubes have been introduced as an alternative to sandbags as temporary flood barriers. However, failures have occurred due to excessive movements of the tubes. The results of numerical and experimental investigations of these tubes are presented here.

Experiments were carried out with sand in a test box. The tubes were 4.5m long and their cross-sections had a

circumference of 1.5m. They were made of coated vinyl, 0.5mm thick, with polyester reinforcement. External water of varying heights was applied on one side. Several methods for inhibiting rolling and sliding were examined.

In one set of experiments, wedges were placed on the downstream side. Measurements of the cross-sectional deformations, underseepage flow rates, and pore pressure beneath the tube were taken. In another set, the tube had an apron that extended under the external water. Pressure on the apron induced friction between the apron and the soil. Two configurations involving multiple tubes were tested also. In the first, two tubes were placed next to each other and a vinyl sleeve was put around them. In the second, a tube was placed on top of two tubes, and they were strapped together.

In conjunction with the experiments, two-dimensional numerical analyses using the finite-difference program FLAC were carried out. The cross sections of the tubes were modeled with beam elements, and the Mohr-Coulomb soil model was adopted. The results compared well with those from the experiments.

This research has demonstrated that water-filled tubes can provide an effective alternative to sandbags for holding back floodwaters.

Keywords: Flood control, geomembrane tubes, numerical modeling, fluid-soil-structure interaction

Simulation of Long-time Evolution of Water Waves in Deep Water

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This paper studies the modulational instability if deep water waves. Benjamin & Feir (1967) showed that weakly nonlinear water waves could be unstable to modulatinal perturbations under certain conditions. Benjamin & Feir's theory describes the onset of the instability and the initial growth of the sidebands. Numerical simulations of the phenomena of modulational instability have typically been conducted on the basis of various forms of the nonlinear Schrodinger equations, the Zakharov equations or fully nonlinear boundary integral methods. Until now, Boussinesq equations have not been applied for this purpose, because of their shallow water limitations. The new high order Boussinesq model proposed by Madsen et al (2001) is used to simulate the long time modulation of water waves with two sideband perturbations in a long numerical wave flume. An absorbing sponge layer is applied at both ends of the model domain to keep reflections to a minimum.

Our first test case is inspirited by Mayer et al. (1998), who solved the 2D Euler equations with FDM in a tank covering about 130 wave lengths. We extend the computational domain to cover 1600m i.e. approximately 250 wave lengths. The computational results show that the recurrence length of the wave train is 141 wave length. In the present simulation there is no sign of energy loss, and although the two pulses are not identical, they do reach approximately the same height. Landrini et al. (1998) used a boundary-integral method with spatial domain to study the BF instability of water waves. Transforming Landrini's numerical results of beat length from the time domain to the spatial domain, the recurrence length is 140 wave lengths i.e. in excellent agreement with our result.

Wind-wave spectra are known to shift towards lower frequencies as the fetch increases. The phenomenon of frequency down shift has been modeled with the Dysthe's fourth order Schrödinger equations by Lo & Mei (1985), who examined the effect of viscous dissipation due to friction; by Trulsen & Dysthe (1990), who incorporated the effect of breaking by introducing a damping term activated for waves exceeding a certain height. Recently, Tuline & Waseda (1999) conducted a number of seeded experiments to investigate the importance of wave breaking for modulational instability. We consider one of their test cases involving a brief event of wave breaking near the first modulational peak. Our computational results show that at the first modulational peak, the carrier mode has a local minimum, while the lower and upper sidebands increase to a local maximum. At this point, the lower sideband is by far the largest of the three. Beyond this point, the lower sideband stars to oscillate around a much higher mean level and never return to its initial very low level, while upper sideband stays at a considerably lower mean level than the lower sideband. This increase of asymmetry between the lower and upper sidebands to vary between two extreme states: a state with dominant lower sideband and insignificant carrier wave and a state where the lower sideband and carrier are of almost equal size.

Theoretical Modelling of the Effect of Drag Reducing Polymer Solution on TBL Induced Flow Noise

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The drag reducing characteristics of certain high molecular weight polymers have been extensively studied

by various investigators. Because of the polymer's ability to reduce turbulent shear stress and the dependence of the boundary layer wall pressure spectral amplitude on the shear stress, polymer addition has the potential to suppress noise and vibration caused by the boundary layer unsteady pressures. Compared to its effect on drag reduction, polymer effects on Turbulent Boundary Layer wall pressure fluctuations have received little attention. Works from the former Soviet Union (1970) (1975) and Barker (1977) showed that drag reducing polymer additives do indeed reduce wall pressure fluctuations, but they have not established any scaling relationship which effectively collapse the data. Some effort has been made by Timothy et.al. at Penn state (July 2000) to develop a scaling relationship for TBL wall pressure fluctuations that are modified by adding drag reducing polymer to pure water flow.This paper presents a theoretical model based on the work of Timothy at.al. team using which one can estimate reduction in TBL flow induced noise and vibration for both smooth and rough surfaces. The author gives a regression relation ship in conjunction with Corcos (1963) model taking into account the effect of polymer addition on wall shear stress and flow noise. Using this theoretical model, low noise as experienced by a flush mounted array of hydrophones will be estimated for various surface roughness values as a function of polymer additive concentration. Effect of non-dimensionalisation of the wall pressure fluctuation frequency spectra with traditional outer, inner and mixed flow variables will also be addressed in the paper.

SESSION T4F
FLOW IN POROUS MEDIA

Prediction of Non-Darcy Flow Coefficients Using Pore Network Modeling

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At high fluid velocities through porous media, Forchheimer's Law is used, which introduces a new porous medium property, the Forchheimer coefficient B. There is not, however, agreement between investigators on the predictive correlation for B as a function of the medium porosity and permeability.

Pore network (PN) models can be used to predict the medium permeability and B. Our PN model consists of a modular simulation that first generates the PN geometry and then simulates fluid flow through it. The porous material is deconstructed into a skeleton of cylindrical pores; each one's length, diameter and orientation are randomly distributed according to user-specified pdf's. The coordination number is also randomly selected. The simulation can construct a random grid of pores satisfying a given porosity. The flow simulation module solves the equations that describe flow through the PN. A Monte Carlo (MC) approach is used to generate a large number of the PN realizations. The medium properties are then estimated from the MC results. When the process converges, the expected values of the medium properties are calculated and the uncertainty about the mean values is quantified with the calculation of the variances. Such a simulation can be run before a full reservoir scale simulation is performed, using as input measurements of porosity and pore size distribution of rock samples for a specific reservoir.

Results from using Gaussian, beta, and experimentally measured pore size distributions are going to be presented. The effect of the porous medium structure on the permeability and on the coefficient B will be discussed. The correlation between permeability and B for each distribution will be presented, and the factors that contribute to non-Darcy flow will be discussed. Finally, the effects of compaction on permeability and on b will be presented.

Keywords: Porous media, non-Darcy flow, pore network modeling

Controlled Granular Segregation in Unsteady Dense Sheared Flows

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Granular materials tend to segregate based on even small differences in particle properties. A prototypical example occurs in a long circular drum mixer filled partway with a granular mixture and rotated slowly about its axis (Figs. 1a, 1b). Here, the particles segregate in the radial direction, perpendicular to the axis of rotation, and sometimes into bands in the axial direction (Figs. 1c, 1d, respectively). This segregation is undesirable in many industrial processes, from pharmaceutical to ceramic production, where a uniform mixture of granular materials is often required. However, there are many situations where it would be useful to have a method for segregating components in a controlled fashion. Presently, there is no universal understanding as to why granular segregation occurs, nor a method for predicting the outcome before it is

experimentally observed, nor systematically controlling it when it is desired. We will present results from new segregation patterns obtained in a circular drum mixer which suggest a method for manipulating segregation in dense granular flows so that they may be tailored to specific applications. When the mixer is rotated at a slow but unsteady pace, the resulting segregation pattern is strongly coupled with the variation of the speed of the flowing layer (Fig. 1e). The results show that the coupling between the flow profile and the instantaneous composition of a granular mixture is important to understanding and predicting granular segregation in dense flows (Fig. 1f).

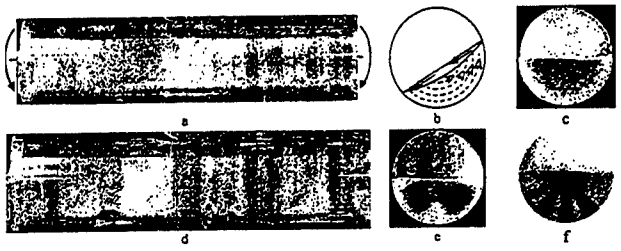


Fig. 1 Segregation in a circular drum mixer. Different sized (1mm and 3mm) glass spheres start out well-mixed in a 75cm-long drum mixer (a). The drum is rotated in the rolling regime: most particles are carried around in solid-like rotation; a small fraction moves quickly down a relatively flat top layer (b). Radial segregation occurs within a single rotation (b). Axial segregation occurs in $\sim$ 100 rev. (c). Figures 1e and 1f show non-traditional radial segregation patterns that appear to occur due to variations in the flowing layer speed (e) and spontaneous flow profile (f).

We gratefully acknowledge the support of the UW-Whitewater Faculty Development Program.

Diffusion of Fluids in Swelling Solids

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We model the slow diffusion of a fluid into a swellingn soid undergoing large deformations. Both the stress in the solid and the diffusion rates are predicted and compared with experimental data for a number of different systems. The approach presented here, overcomes inherent difficulties associated with mixture theory with regard to boundary conditions. A "natural boundary condition" based on the continuity of chemical potentials is proposed here. It is shown that the differential equations resulting from the use of mixture theory can be recast in a form that is identical to that derived here. The flow of a variety of solvents through a gum rubber membrane is studied and the results show excellent agreement with experimental data.

Characterization of Porous Membrane Elements in Microfluidic Devices

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Membranes are common components in many Bio-MEMS tools like sample prep kits or immunoassays. These membrane-based tools provide simple, accurate, and cost effective means for diagnostic devices. However, fluid flow through the numerous tiny, tortuous paths of the membrane is a complex physical phenomenon that presents a significant challenge for the designer. Analytical understanding is limited in terms of flow through the capillaries of a typical membrane. Pore size, pore shape, overall porosity, tortuosity are just a few variables for the membrane. For the fluid, a few important variables include viscosity, surface tension, and flow characteristics before the entrance to the filter. For a microfluidic device with fluid conduits in the 100 m range (and below) and incorporating a porous plug or membrane, computational modeling presents yet a bigger challenge The objective of this paper was to develop a tool capable of predicting hydrodynamic flow through a porous membrane in a narrow channel by varying the membrane properties and the geometry of the microfluidic channels. The developed design tool should lead to the building of robust microfluidic devices with embedded porous elements that behave in a predictable way under a wide range of user applications.

For macro fluidic devices incorporating membranes, it is relatively simple to use experimental methods to optimize the hydrodynamic flow by varying membrane characteristics (pore size, porosity, material, etc.), geometry, fluid path, etc. A combination of experiments and design iterations normally yields an acceptable final design. For microfluidic devices, however, this method is not as effective as it is a lot harder to control environmental effects in microfluidic experiments such as temperature drift and prevent formation of bubbles.

FIDAP and FLUENT were the first commercial finite element software packages that introduced a "porous element" that allowed the modeling of porous membrane behavior. This porous element was used to validate the performance of air filters [1]. Permeability can be non-homogeneous, anisotropic and non-linear (as a function of location and fluid flow characteristic). This nonlinear feature was used in the finite difference code PHOENICS to predict the dust build-up in an air filter [2]. Unfortunately, this feature of simulating flow characteristics in the presence of a membrane is not yet commercially available for designers of microfluidic devices.

In this study, we have used CoventorWare(tm), through specialized function calls to simulate pressure-driven liq-

uid flow through a membrane in a microfluidic device. A porous membrane embedded in a tee-joint was uses as a simple microfluidic model device. Modeling was based on a non-linear Forchheimer-Brinkman model [3], rather than the simpler, linear Darcy model which account for the key features of permeability and porosity. From the simulation runs it was shown that the flow through a tee-joint with a built-in membrane depends on the characteristics of the membrane. By varying the permeability, the fractional flows in the tee joint can be significantly varied. It is also shown that the overall porosity does not affect the flow pattern for a steady state condition. The results provide a useful design tool to predict the flow characteristics and geometry needed in the design of a desired microfluidic device.

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An Application of Flow through Parallel Porous Plates

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Malfunctioning of the kidney has now become a common problem . Hence external help is required to remove metabolic wastes and other unwanted chemicals from our blood.Dialysis acts as an artificial kidney. There are two types of treatment: hemodialysis and peritoneal dialysis. About 90 percent of dialysis patients receive hemodialysis, in which the blood is circulated outside the body and cleaned inside a machine before returning to the patient. Hemodialysis for the treatment of renal failure has become a very common practice in the medical field. Currently, there are thousands of patients who have been alive longer than 10 years with hemodialysis. A problem with hemodialysis is that treatments are required two to three days a week and each treatment lasts four to six hours. This is in any case a very painful process. One layered magnetohydrodynamic models for the flow of blood have been investigated by many researchers[1]. A two layered model for parallel plate hemodialyser under the influence of a uniform transverse magnetic field has been investigated by Chaturani et al.[2] Here the fluid mechanical aspects of flat plate type dialyser has been dealt.The present study deals with the steady flow of blood between two permeable stationary plates. This is an extension of [2] where the walls are considered to be impermeable. As suggested by the authors a more realistic way is taken up by considering the walls to be permeable. This leads to diffusion through the membrane. The problem is approximated to the one dimensional flow between two infinite parallel plates. Further blood is assumed to be newtonian. Analytical expressions for physiologically important fluid dynamic quantities have been obtained.It is observed that the results are in good agreement with [2]. Investigations reveal that the time taken for the dialysis process is greatly reduced. Our next attempt is to take up the problem by treating blood as a non-newtonian fluid.

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SESSION T2R
FLUID FLOWS

Numerical Simulation of the Deformation and Breakup Process of Agglomerates in Polymer Melts

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Mixing is one of the most important components of polymer processing because the material formability and the product properties of the compound are highly influenced by mixing quality. The mixing mechanism associated with the dispersive mixing which is the reduction of size of one component within a continuous liquid phase. In the dispersive mixing, the agglomerates are broken into smaller fragments and down to aggregate size into the matrix of a fluid. It is generally recognized that this is the most difficult step of the mixing processes, and therefore, the kinetics of the dispersion process is important. In this work, we attempt to develop the dynamic predictive model of the deformation and breakup process

of agglomerate in polymer melts. The Discrete Element Method (DEM) is employed to predict the behavior of particle-agglomerates on the dispersion process. Here, an agglomerate in a polymer melt compound is represented as an assembly of small spherical particle elements. The model is developed by taking into consideration the hydrodynamic drag force and the particle-particle interaction forces which induce flocculation and yield stresses in suspensions. During the mixing of agglomerates in polymer melts, agglomerates are dispersed and distributed in the matrix depending on the local stress fields in the fluid. This deformation and breakup process of coagulated particles is numerically investigated by using the DEM. It is observed that the agglomerate is deformed and split into many smaller fragments under shear and extensional flows. However, it is also indicated that the coalescence of particles occurs during the dispersion process. Erosion, breakup, and coalescence phenomena of the agglomerates in various flow fields are discussed.

Depicting Random Velocities in Suspension Flows with the Helmholtz Theorem on Vector Fields

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Our studies track fluorescent particles over long lengths by collecting images on a camera while the flow conduit moves at a fixed speed (Eckstein, 2000). Measurements made with such images are called "apparent." Data were collected for flows of concentrated (25%) and dilute suspensions with a variety of tracers. With x as the flow direction, a quantity like $i \cdot U$ was traced. Observations began at times when the apparent axial velocity was nil, i.e. $i \cdot U - Uc \sim 0$; time intervals were measured for tracers to move selected net apparent distances (NAD). These increments captured the erratic evolution of axial position. Information to fully describe the stochastic process was captured in a transformed way (Feller, 1966). The data are viewed within a stochastic model of axial dispersion for dilute materials (VDB model, Van Den Broeck, 1990) and Helmholtz's theorem, which showes that vector fields decompose into divergence-free (A) and curl-free (B) parts. The VDB model uses "axial tracks" that were chosen as the instantaneous speed at the initial time. Two state variables report the current and future conditions; they are a Poisson-distributed time interval on the current track and the speed of the next track. By the theorem, all motions must result from two separate parts that combine orthogonally. These parts occur as velocity integrals that are summed in the measured time intervals. A transformation would provide complete information but the increments can be considered as ratios for ensembles. Let the NAD to the m-th fence be lm and the average time increment from the nil value of apparent speed until crossing the fence be ¡tm¿. Then the times are length/velocity ratios of Data fitted well to an equation for persistent random walk in the VDB model. As a limit, this equation has $lm^2 \sim< tm^2 >$. Interpretations in terms of fluxes and incremental motions are available.

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SPH applied to Hydrodynamic Ram

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A wide class of engineering problems including impact, penetration and large deformation of solid materials causes a severe numerical diffusion when Eulerian or Arbitrary Lagrangian eulerian (ALE) formulation is used. Smoothed Particle Hydrodynamics (SPH) is a pure Lagrangian and meshless approach which overcomes the inaccuracies due to meshing or remeshing operations. It is an attractive method due to its simplicity.

Hydrodynamic ram phenomenon consists on the complicated sequence of energy and momentum transfer from a projectile to fluid- filled container. Additional difficulties appears when the materials considered are thermodynamically different.

In this paper, the basic concept of SPH method is described and some 2D and 3D numerical results from simulations are shown.

Introduction:

The smoothed particle hydrodynamics method (SPH) is widely used in astrophysics and in gas dynamics simulations: Lucy[1], Gingold and Monaghan[2], Benz[3] and others. Recently the method has been extended to problems of solid mechanics including impacts and penetrations: Libersky and Petschek[4], Benz[5], Johnson[6], Swegle, Hicks and Attaway[7], Randles and Libersky[8] .

More recently, Liu et *al* [9,10,11] initiated the Reproducing Kernel Particle Method (RKPM). Other Normalisation technique are introduced by Johnson and Beissel [12] and Randles and Libersky [8].

In this paper, the standard SPH method is used to simulate a hydrodynamic ram and two equations of state were tested for water.

Basic Concepts:

Any observations or mesurements made upon a physical system result from the interaction (of the 'observer' or 'Detector') with the system at some length-time scale. The convolution principle reproduces this interaction and it is the key of the SPH formalism.

Any exact physical field depending on space position and on time is estimated by its smoothed value, given by:

$$\langle \psi(r,t) \rangle = \int_{Dw} \psi(x).W(r-s,h).\left(\frac{\rho(s,t).ds}{\rho(s,t)}\right) \quad (1)$$

and

$$\begin{cases} Lim\, W(z,h) \overrightarrow{h} \rightarrow 0\delta(z) \\ Dw = \{z \in \mathcal{R}^N / W(z,h) \in \mathcal{R}^{1^*}\} \end{cases} \quad (2)$$

In the above equations $\rho(s,t)$ is the density $W(z,h)$ is a kernel distribution and h is a geometrical quantity or smoothing length describing the scale of the resolution.

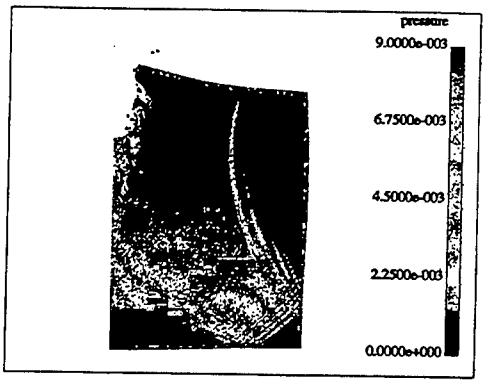


Fig 1: Pressure Distribution at $t = 50\mu s$

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On a Cavitation in Spherical-Particle Slow Motion in a Liquid Along a Wall

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A gravity-induced rolling of a solid spherical particle down along an inclined plane in quiescent fluid is studied experimentally and theoretically for a slow (creeping) flow. The particle is several millimeters in size. The roughness of the particle surface is fairly small and the wall roughness is much smaller.

It is shown that, for fairly large plane inclination angles, when the gravity- force component directed toward the plane is small, the particle can travel without contact with the wall. The lifting force required for this motion is not associated with fluid inertia, i.e. is not the Magnus force. The distance between the particle and the wall is of the order of micrometers. As the plane inclination angle decreases, the particle-wall gap decreases and, at a certain critical angle, the particle touches the wall by the roughness top.

It is shown that to use ordinary hydrodynamic parameters is not enough to describe the particle motion observed. Additional physical mechanisms, such as anomalous viscosity and cavitation, which may be important in a small particle-wall gap, should be considered . The possibility of cavitation was noted in [1].

In our experiments, in which static pressure was varied, we observed a change in particle motion.

On the basis of the Stokes equations, the minimum of the pressure in the gap is calculated. The minimum is displaced relative to the symmetry axis of the particle-wall system. By comparing the calculation and the experiments, it is shown that, for creeping flow of the fluid in the particle-wall gap, cavitation ma y take place. Within a traditional consideration of the particle motion along the wall, the lift force is absent. If a cavitation zone arises in a small region, practically no negative pressure is realized; this results in a decrease of the normal stresses on the particle surface in this region and the onset of a lifting force.

Keywords: cavitation, creeping, particle, wall.

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Motive Thermodynamics of Multiphase Flows

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The purpose of this communication is to firstly unite the thermal and mechanical descriptions of sunlight powered direct propulsion systems at an elementary level. By this approach, any element of new mechanical energy by conversion from thermal one is considered to be as the result of work conducted by two motive forces, which are principally equal in magnitudes and have opposite directions according to the law of momentum conservation. This provides the complex format of work to unit thermal and mechanical properties of liquids by direct conversion of sunlight on a joint elementary energy balance equation. The novel complex format of work to unite mechanics and thermodynamics on motive thermodynamic concept is introduced to right explain the mechanisms of gigantic motive forces firstly created experimentally in multiphase flows. By using both laser and solar optical pumping, the new vibration and capillary motive forces for mechanical propulsion were created to transport liquids in multiphase flows directly by continuous light. The outline of both branches of motive thermodynamics is given within the laws of energy and momentum conservation and non-equilibrium entropy of sunlight having terms responsible for both 1) renewable and 2) non-renewable processes to solve the problem of maximum light available for conversion. The elements of motive thermo dynamics are experimentally found by laser simulation of sunlight in laboratory condition for effective generation of vibration and capillary propulsive forces in multiphase liquids by renewable volume of system as a hole. There are two branches of application of such renewable motive forces of light for solar engineering: a) direct conversion of solar light with high effective up to 100g acceleration of bodies for elevating and vibration engineering and solar capillary extraction purposes b) building new kinds of solar renewable power systems

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SESSION W3J
FLUID MECHANICS

Real Time, 3-dimensional Imaging of Gas-Liquid-Solid Flows using Electrical Capacitance Tomography with Neural Network Based Multi-criterion Optimization Image Reconstruction Technique

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In this study, a 3-dimensional image reconstruction technique for imaging two- and three-phase flows using electrical capacitance tomography (ECT) has been developed for the first time. A 3- dimensional sensitivity matrix is constructed to replace the 2- dimensional sensitivity matrix commonly used in Linear Back Projection (LBP) for electrical capacitance tomography. The 3-dimensional image reconstruction problem is then solved based on multi-criterion optimization using an analogue neural network, referred to as neural network multi-criteria optimization image reconstruction technique (3D-NN-MOIRT). NN-MOIRT, early developed in this work, has also capability of three-component identification in three-phase systems using a double-sigmoid function. The technique has been tested on a capacitance data set obtained from simulated measurement as well as experiments using a 12-electrode sensor. The performance of the technique has been analyzed, and has shown good accuracy and consistency. The technique is then applied for real time, 3-dimensional imaging of gas-liquid-solid flows in bubble column reactors. The hydrodynamic characteristics of the three-phase flow system including the bubbly

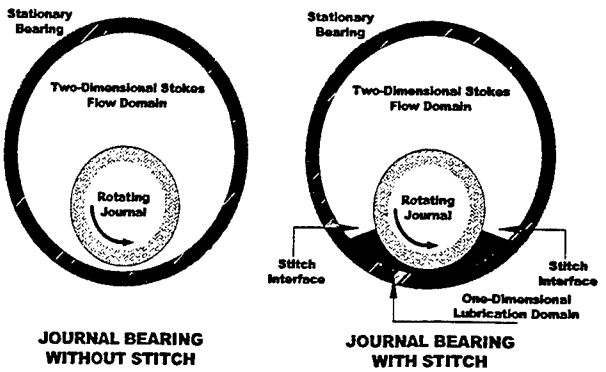
flow structure, bubble velocity, and gas and solids concentrations' variations are deliberated based on the ECT images obtained in this study.

Selective Model Domain Reduction in Fluid Systems with Complex Geometry

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Today's commercial and research finite element codes solving the mass and momentum balances of a fluid or fluid-solid system neglect any simplifications that can be made based on local geometry and solve either the full three- or two-dimensional governing equations (depending on what simplifications have been made before the numerical analysis) over the entire domain. This method is robust and works successfully for most systems, however, is not well suited for domains in which there are regions with a dimensional length much larger than the others- i.e. a planar region connecting two non-planar geometries. Typically, these regions contain critical information to the understanding of the complete system dynamics and require heavy local discretization of the finite element mesh. This intense discretization results in the obvious increase of computational time, can lead to a poorly conditioned matrix problem, and in the case of moving surfaces, makes the prediction of contact impossible.

To combat this problem, we propose using lubrication theory to perform a local dimensional reduction in the fluid's governing physics and then match the stress and mass flow at the boundaries of the lubricated region with the rest of the domain. We term this domain reduction "lubrication-stitching" and apply it to a journal-bearing system (see figure below) for which an analytical solution is known. With the analytical solution for comparison, we develop "stitch" performance metrics to determine when and how the "stitch" fails. We then use this technique to model the more interesting problem of microscale peristaltic pumping.



A Closed Form Solution for A Falling Cylinder Viscometer

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The paper presents a theory of the flow of a viscous fluid in a falling cylinder viscometer. The falling cylinder can be subjected to a magnetic force, in addition to gravity, for speeding the data collection of highly viscous fluids, or for the determination of a possible yield stress. Experimental data are obtained with a microrheometer, which is a device that requires only a tiny amount of fluid (a major requirement for some biological fluids).

The velocity profiles for the flow in infinite tube and finite tube are obtained in finite forms. That allows us to determine quite easily the influence of various parameters involved on the fluid flow and on the motion of the cylinder [as densities (may be variable), geometry of the cylinder-tube, pressure gradient, magnetic force, etc.]. Several examples are given. Also a formula written in finite form is obtained for the determination of the viscosity coefficient. All these formulae contain a term that describes the influence of the magnetic field on the motion of the falling cylinder. A comparison of the viscosities determined according to the present theory and falling cylinder experiments, and with a cone-plate viscometer shows a good agreement.

Keywords: viscometer, microrheometer, viscosity coefficient, biofluids.

Modeling Flow-Induced Suspension-Head Vibrations in Disk Drives

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A numerical investigation is performed on the flow-induced vibrations of suspension-head units (SHUs) in hard disk drives (HDDs). The 3D flow around a SHU in a HDD is simulated by the 2D flow in a channel with sliding walls and appropriate inlet/exit boundary conditions. In this configuration, emphasis is placed solely on resolving the flow around the suspension portion of the SHU at air flow velocities corresponding to 25 and 50 m/s. The suspensions are modeled as prisms of rectangular or U-shaped cross-sections that are symmetrically oriented with respect to the channel midplane. Flows

past single prisms are also investigated. Figure 1, below, shows typical contours of vorticity. The time-dependent drag and lift forces obtained for the prisms are used to force the vibration modes of the suspension of a SHU. Figure 2 shows values of the drag and lift coefficient for the conditions of Figure 1. In this regard, because of the small displacements involved (stiff suspension), the flow drives the suspension but the suspension does not alter the flow. The dynamics of the SHU is approximated employing Euler-Bernoulli beam theory for a beam (the suspension) of constant cross-section with a point mass, representing the slider, located at the tip of the beam. Non-dimensional forms of the equations describing the beam dynamics are especially revealing. Together with the numerical results obtained they explain the relative roles of beam inertia and drag/lift forces. Predictions of in-plane slider trajectories show that the shapes of these trajectories correlate strongly with the SHU dynamics and can be used to diagnose some characteristics of the flow-structure interactions. Figure 3 shows drag-induced displacements of the beam tip. A more detailed, comparative, discussion will be provided of the various cases explored.

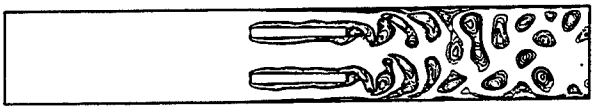


Figure 1

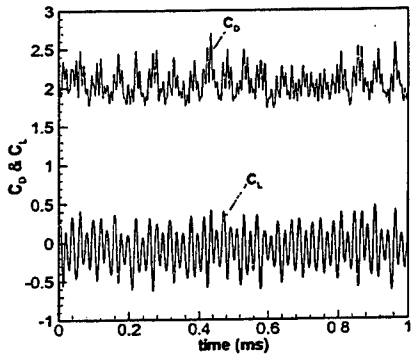


Figure 2

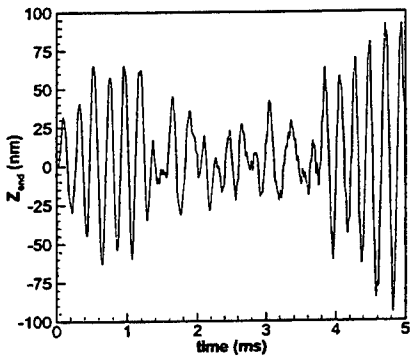


Figure 3

Keywords: disk drive, suspension, magnetic head, flow induced vibrations

Injection-Ejection Influence on Velocity Field and Laminar-Turbulent Transition of Unsteady Boundary Layer on Porous Contour for a Great Decelerating Fluid Flow

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The behaviour of a boundary layer in the presence of a positive or negative pressure gradient along the surface, is particularly important for the calculation of the drag of an aerofoil as well as for the understanding of the processes which take in a diffuser, because there is transition from laminar to turbulent flow which determines the dividing line between a region with low drag and one where drag is dramatically increased. So one can control laminar-turbulent transition and shear stress distribution by fluid which has been ejected or injected through the porous contour, because the separation reduce is very important goal of flow manipulation. Apart from shear stress we are interested in knowing whether the boundary layer will separate under given circumstances and if so, we shall wish to determine the point of separation. Generalized similarity method is used for calculation of this complicated phenomena.

Similar solutions of the boundary layer equations play an important role in the investigation of the stability of hydrodynamic flows and in developing semi-empirical criteria for the transition to turbulence.

Through the porous contour in perpendicular direction, the fluid of the same properties as incompressible fluid in basic flow, has been injected or ejected with velocity which is a function of the contour longitudinal coordinate and time. The corresponding equations of this unsteady boundary layer, by introducing the appropriate variable transformations, momentum and energy equations and two similarity parameters sets, being transformed into so-called universal, i.e. generalized form. These parameters are expressing the influence of the outer flow velocity, the injection or ejection velocity, and the flow history in boundary layer, on the boundary layer characteristics. The numerical integration of the universal equation with boundary conditions has been performed by means of the difference schemes and by using Tridiagonal Algorithm Method with iterations in three once localized approximation, where the first unsteady, dynamic and porous parameters will remaine, while all others and derivatives with respect to the first porous parameter will be let to be equal to zero. So obtained universal solutions are used to calculate the characteristic properties, i.e. shear stress, momentum and displacement thickness of unsteady bound-

ary layer on porous aerofoil when center velocity changes in time as a degree function and when potential external velocity on aerofoil is measured in free flight. It's found that for both in confuser and in diffuser aerofoil regions the decelerating flow reduces the shear stress and favours the separation of flow. In comparison with the steady flow the separation is occurring at lower contour values, i.e. to the 47.6% of contour for a great decelerating flow, when there are no fluid injection or ejection through the porous contour. The ejection of fluid postpones the boundary layer separation, i.e. laminar-turbulent transition, and vice versa the injection of fluid reduces the shear stress and favours the flow separation, so the separation is occurring at lower contour values, about 38% of contour for a great decelerating flow. Shear stress distribution and laminar-turbulent transition are found directly, no further numerical integration of momentum equation.

Keywords: Boundary layer theory; Velocity field; Laminar-turbulent transition; Porous contour; Similarity solutions;

The Characteristics and Dynamics of Vortex Dislocations in Wake-type Flow with Local Spanwise Non-uniformity

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Numerical analyses of the vortex dislocations and their effect on flow transition in the wake-type flow with a local spanwise non-uniformity are made by DNS approach. The dimensionless streamwise velocity profile of the wake-type coming flow in computation is

$$U(y,z) = 1.0 - a(z) \cdot (2.0 - \cosh(by)^2)e^{-(cy)^2},$$

where $a = 1.1 + 0.4e^{-z^2}$ imposed represents a local spanwise change in momentum defect. The numerical method used to solve 3-D incompressible N-S equations is the compact finite difference-Fourier spectral hybrid method. Reynolds number is 200.

Numerical results have shown that the nonlinear development of the flow instability and nonuniform evolution in space lead to three-dimensional vortex streets whose phase and strength vary with the span caused by the local nonuniformity. A series of symmetric twist vortex dislocations are generated in the middle downstream as shown in fig. (1), where we also can see the streamwise vorticity and vertical vorticity branches are connected to the large distorted spanwise vortex rolls. Isosurfaces of vorticity, vorticity components' contours and fluctuating velocity distributions are used to describe the generation and the configuration of the vortex dislocations. Representative vorticity lines emitting from different part of a vortex roll located at different downstream positions are investigated. Their directions and tracks describe clearly how the vortex dislocations generate and what the real vortex linkages are in vortex dislocations. A sample is shown in fig. (2). Spanwise spreading and vertical enlargement of the vortex dislocations are shown. The effects of vortex dislocations on velocity field, frequency are analyzed. The flow transition behaviors are discussed too.

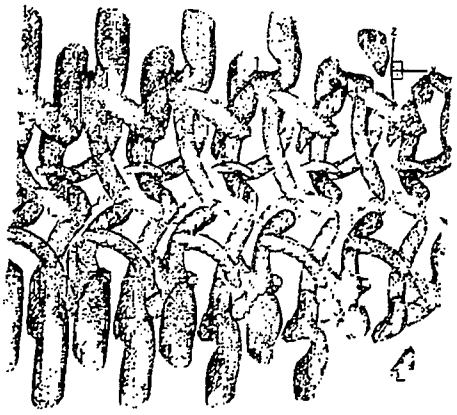


Fig. 1. Iso-surface of $|\vec{\omega}| = 0.12$ at $t = 300.0$

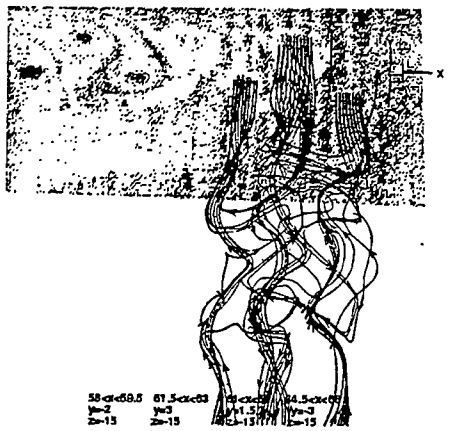


Fig.2. Vortex lines

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SESSION M2S
FRACTURE MECHANICS I

How Fast can Cracks Propagate?

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The dynamic behavior of crack propagation has been investigated by a combination of molecular dynamics and elasticity. This work was motivated by recent experiments by Ares Rosakis's group in Caltech on intersonic shear crack propagation. We simulate intersonic and supersonic cracks by the molecular dynamics method of integrating Newton's law for individual atoms. The simulation results are used to test and develop continuum theories of intersonic and supersonic fracture. For linear elastic solids characterized by a harmonic potential, mode I cracks are limited by the Rayleigh wave speed, in consistency with the existing theory of fracture. In comparison, mode II cracks can reach the longitudinal wave speed via a mother-daughter crack mechanism. We also find that, while the initiation of the mother crack is controlled by the Griffith criterion, the nucleation of the daughter crack is controlled by the cohesive stress criterion. Another finding is that the limiting crack speed is governed by the local wave speed near the crack tip, rather than by linear elastic wave speeds. For harmonic solids, the local wave speeds coincide with linear elastic wave speeds. For anharmonic solids, the local wave speeds can be lower or higher than the linear elastic wave speeds depending on the material properties. Increasing local wave speed near the crack tip by elastic stiffening results in supersonic crack propagation. Similar dynamic behaviors have also been found for dislocation propagation at intersonic and supersonic speeds under sufficiently large stress field.

Redistribution of the Cohesive Stress and Variations in Microstructural Properties Associated with Quasistatic Crack Extension

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A tri-axiality dependent cohesive zone model for a stationary and a quasistatic crack is proposed. The model is rooted in the mesomechanical approach to Fracture Mechanics and it is inspired by the quantum law concerning emission of light, which was postulated by Max Planck at the end of 19th century.

The model provides an extension of the early concepts of Barenblatt, Dugdale and the Bilby-Cotrell-Swinden team. It also incorporates the experimental observations of the pre-fracture states due to Panin and his school in Tomsk. Relations between micro- and macro-parameters that characterize the deformation and fracture processes in dissipative media are described in detail.

The analysis suggests that the ratio of the "true" work of fracture to the total energy dissipated during the course of the irreversible deformation contained within the end zone can be used as a measure of material resistance to a quasistatically propagating fracture. This ratio, evaluated for various sets of mic rostructural parameters that define the distribution of the restraining stresses within the cohesive zone, provides both conceptual and quantitative foundation for a better understanding of the phenomena essential during the early stages of fracture in non-elastic solids. Some of the by-products of the analysis are novel physical interpretations of the fracture toughness enhancement that leads to a developed R-curve.

As it turns out, when we consider deformation, local pre-fracture states as defined by Panin, and finally, the fracture processes at the micro- or meso-levels and the associated dissipation energies that characterize these irreversible events, none of the Continuum Mechanics standard concepts seem to work. They all break down at the distances less than a certain critical length, which equals the size of the process zone and cannot be determined by the macroscopically measured material constants alone. The very fact that one must introduce into the mathematical model the finite entity, called "process zone", adjacent to the crack front, provides an evidence of breakdown of the classic field theories. Therefore, in this work a link between the Mechanics of Fracture, as it is known to most engineers, and the Mesomechanics of Fracture is proposed and put to work, so that certain essential nonlinear phenomena for either stationary or quasistatically moving cracks can be better understood and mathematically justified.

This is the domain of mathematical modeling founded on the premises of Mesomechanics. Development of new concepts and mathematical approaches compatible with Mesomechanics that departs from substantially from the "classic" continuum approaches, is the primary objective of work.

Keywords: cohesive zone, J-integral, specific work of fracture, cohesive tractions, microstructure, triaxiality, local constraints, ductile-brittle transition, surface tension, plastic work, ductility, overstress, dissipation.

Analysis of Slant Fracture in Specimens Under Nominal Mode-I Loading Conditions

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Slant fracture often occurs in specimens made of ductile materials (e.g. aluminum alloys) under nominal Mode-I loading conditions. For example, an initially flat crack (Fig. 1) in a single-edge specimen loaded in Mode I will tend to tilt its crack surface and turn into a slant crack (Fig. 2). In this study, the crack-front stress and deformation fields around a flat and a slant crack are analyzed using the finite element method.

The purpose of this analysis is to understand why a flat crack loaded in Mode I prefers to grow in a slant fashion under nominal Mode I loading conditions. To this end, Arcan specimens made of Al 2024-T3 are considered. These specimens show a slant angle of about 38°. Finite element results were obtained based on the Arcan specimen geometry and the stress-strain curve for Al 2024-T3. A major finding of this study is that the effect of turning a flat crack into a slant crack is to lower the constraint value in the mid-plane of the specimen and raise the constrain value near the specimen surfaces. Furthermore, the effective stress in the case of a slant crack is much higher than those in the case of a flat crack under the same loading conditions. These observations seem to suggest that slant fracture promotes a shear-type failure mode instead of a tensile-type failure mode associated with flat crack growth.

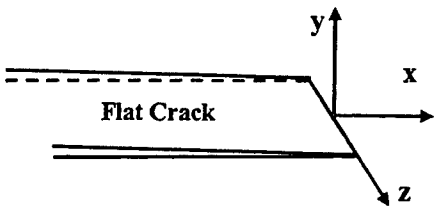


Fig. 1. A flat crack with its surface parallel to the z axis; loading is along the y axis

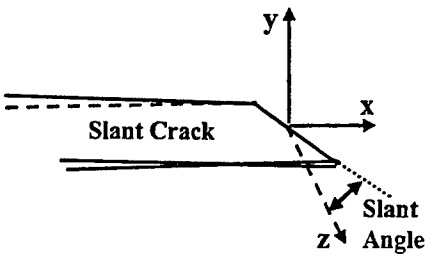


Fig. 2. A slant crack with its surface forming an angle (the slant angle) with the z axis; loading is along the y axis.

Keywords: Slant fracture, crack-tip fields, constraint, finite element analysis

Financial support from AFRL (Contract No. 00-3210-27-1), NASA/EPSCoR (Grant No. NCC5-174), and the SC Space Grant Consortium are gratefully acknowledged.

Mixed Mode I/III Fracture of Solids: Tensile-Shear Transition

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The mixed-mode fracture of fatigue pre-cracked PMMA and 7050 aluminum alloy specimens are studied in combined tension-torsion loading. Circumferentially notched cylindrical bars are pre-cracked in uniaxial cyclic tension to introduce a concentric mode I fatigue crack. Afterward, the bars are quasi-statically loaded to fracture under mixed I/III loading conditions. Fracture mechanisms, which are examined from the fracture surface morphology, reveal that, one type of failure (tensile type) is observed for brittle material (PMMA), while *two distinct fracture types* are observed for ductile materials (7050 aluminum alloy), i.e. a shear type and a tensile type of failure. A fracture criterion based on the achievement and competition of a critical tensile fracturing stress τ_C (MNSC) and a critical shear fracturing stress σ_C (MSSC) at a characteristic distance r_C around the crack tip is proposed. Material strength ratio is incorporated into the fracture criterion using the ratio τ_C/σ_C. The prediction of the fracture type is determined by comparing τ_{max}/σ_{max} at $r = r_C$, for a given mixed-mode loading, to the material strength ratio τ_C/σ_C, i.e. $(\tau_{max}/\sigma_{max}) < (\tau_C/\sigma_C)$ for tensile type of fracture and $(\tau_{max}/\sigma_{max}) > (\tau_C/\sigma_C)$ for shear type of fracture. It is shown that the transition of fracture type from tensile to shear, as observed for ductile materials but not observed for brittle materials, can be properly explained and predicted by the theory.

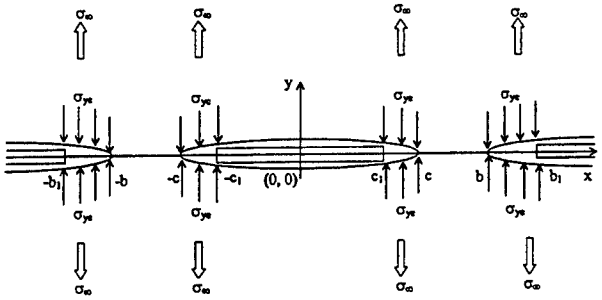
Keywords: mixed-mode I/III fracture, transition of fracture type, critical stress, material strength ratio

Crack Arrest Model for Internal and External Cracks Weakening a Plate - a Dugdale Model Approach

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A crack arrest model is proposed for infinite elastic perfectly -plastic plate weakened by two external and an internal collinear hairline straight cracks. Uniform constant tension, σ_∞, applied at the infinite boundary of the plate in a direction perpendicular to the rims of the cracks opens the faces of the cracks in Mode-I type deformation. Consequently a plastic zone is developed ahead each tip (situated at finite distance) of the cracks. To arrest the cracks from further opening each rim of the developed plastic zone is subjected to unidirectional uniform cohesive normal stress distribution, σ_{ye}.



Configuration of the Problem

Solution of the problem is obtained under certain constraints from the solution of an Auxiliary Problem appropriately derived from the above problem. **Auxiliary Problem:** An infinite elastic perfectly-plastic plate is weakened by three hairline collinear straight cracks. Unidirectional tension, σ_∞, applied at infinite boundary opens the faces of the cracks, in Mode I type deformation, forming a plastic zone ahead each tip of the cracks. In turn, these plastic zones are closed by normal cohesive yield stress distribution (ye. Complex variable technique is employed to find Dugdale model solution for the problem. A case study is carried out to study the qualitative behavior of load required to close the developed plastic zones with respect to affecting parameters. Results obtained are reported graphically and analyzed.

Keywords: Internal crack, external cracks, plastic zone and Dugdale model.

Shear Fatigue of Cross-Linked and Linear PVC Foams

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An investigation of the fatigue behavior of two closed-cell cellular PVC foams, Divinycell HD130 (linear) and H130 (cross linked), with a density of 130 kg/m^3, under in plane shear was undertaken.

Static tests reveal that HD foams are more ductile, have almost twice the energy absorption capability, and an extraordinary crack propagation resistance when compared to the H130 foams. The fracture toughness of both foams, on the other hand, was very comparable. The shear modulus and shear strength of both foams were determined and showed a good correlation with the values obtained from tests conducted in a Rheometer in torsional shear mode.

Shear fatigue tests were conducted at room temperature, at a frequency of 3 Hz and at a stress ratio R=0.1. S-N curves were generated and shear fatigue characteristics were determined. The fatigue strength and shear elongation of linear foams was substantially higher than cross-linked PVC foams. Shear deformation occurs without volume change and both materials fail by shearing of the foam in the vicinity of the centerline along the longitudinal axis. In both cases numerous 45° shear cracks formed along the width of the specimen immediately prior to the final failure event. Details of the experimental investigation and the evaluation of the fatigue performance will be presented.

SESSION M3S
FRACTURE MECHANICS II

The Dynamic Growth of A Single Void in a Viscoplastic Material Under Transient Hydrostatic Loading

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We have examined the problem of the dynamic growth of a single spherical void in an elastic-viscoplastic medium, with a view towards addressing a number of problems that arise during the dynamic failure of metals. Particular attention is paid to inertial, rate-dependent and

thermal effects. The effects of inertia are quantified, and it is demonstrated that inertial effects are small in the early stages of void growth and are strongly dependent on the initial size of the void and the rate of loading. Under supercritical loading, voids of all sizes achieve a constant absolute void growth rate in the long term. Thus, smaller voids appear to "catch up" with their larger counterparts in the long term. For dynamic void growth, the effect of rate-hardening is to reduce the rate of void growth in comparison to the rate-independent case, to reduce the final relative void growth achieved, and is stronger at the early stages of void growth but gives way to the effects of inertia in the long term if under supercritical loading. Thermal softening has the effect of lowering the critical stress for unstable growth of the void in the quasistatic case. It is shown that the effects of thermal diffusion strongly depend on the initial size of the void and the rate of loading.

Keywords: dynamic fracture, voids and inclusions, shock waves, viscoplastic materials

On Three-Dimensional Singular Stress Field at the Front of a Crack/Anticrack in an Orthotropic Plate

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Three-dimensional stress field at the front of a crack or anticrack weakening an orthotropic plate has remained a challenge to the researchers in the field of solid mechanics. A novel eigenfunction expansion technique based in part on separation of variables and partly on the Stroh type formulation, is developed to derive three-dimensional asymptotic stress fields in the vicinity of the front of a semi-infinite crack or anticrack weakening an infinite plate made of homogeneous orthotropic material. Explicit expressions for singular stress fields at the crack front are derived, and the order of stress singularity is computed.

Keywords: Three-dimensional, Stress Singularity, Orthotropic, Crack

Physical Significance of Fracture Criterion in GYFM and EPFM Zone

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In certain design problems, (e.g., components of airplanes, rockets and spaceships) using plane strain fracture toughness as material property may be too conservative because structural materials are mostly used in plane stress. Adopting a too conservative approach is against the philosophy of engineering profession. We as engineers should always strive to obtain numbers close to reality. In aerospace applications where factor of safety is of the order of 1.1 for many components, using material toughness properties of plane strain is likely to make the machine heavy with poor payload. In such a situation, stress intensity factor is determined by preparing test-specimen of thickness same as of sheets used in the actual application.

In EPFM zone the fracture toughness increases as thickness decreases; this continues till a critical point thickness BCP (Figure 1), after which the fracture toughness increases with increase in thickness and fracture behaviour becomes reversible. The critical point thickness BCP is the thickness up to which component is in predominantly plane stress condition. The present attempt is to find out a responsible parameter for the opposite fracture behaviour in these two zones. Finite Element method is proposed to find out a critical point thickness. The experimental determination of the critical point separating the two zones is a difficult task as experimental tests are expensive for tough materials.

Experimental and FE results (Table 1) are generated on fracture behaviour of effective deep drawn (EDD) steel sheets with CT specimens and using CTOD criterion. Using FE analysis stress components at the crack tip are determined. These values are used to draw Mohr's circles for a thickness range of 1.18 to 2.1 mm. From Mohr's circle diagram it has been found that, maximum shear stress; an indirect measure of fracture toughness is the responsible factor for this opposite fracture behaviour. At the end it is concluded that determination of a critical point thickness using Finite Element method is a simpler task than the experimental method.

Table 1. Assessment of critical point thickness (Experimental and FE Results on Different Fracutre Parameters)

Specimen Code No.	Thickness B (mm)	Crack-Tip Opening Displacement $CTOD_c(\delta)$ (mm)		Fracture Toughness K_Q (GYFM) and K_c (EPFM) MPa $m^{1/2}$	
		Experiment	FEM	Experiment	FEM
S1	1.18	0.552	0.567	197.06	199.72
S2	1.58	0.593	0.601	204.25	205.62
S3	1.64	0.671	0.684	217.27	219.36
S4	1.69	0.802	0.816	237.53	239.60
S5	$B_{cp}=1.8$	0.988	0.997	263.64	264.84
S6	1.85	0.885	0.898	249.52	251.35
S7	1.90	0.823	0.831	240.62	241.79
S8	2.00	0.726	0.734	225.99	227.24

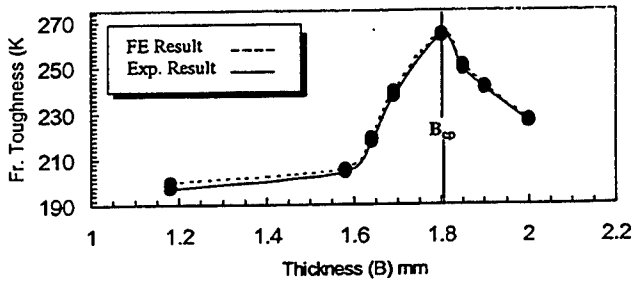


Figure 1. Variation of fracture toughness for EDD (0.06%C) steel sheet and critical point thickness

Keywords: critical point thickness, EDD steel sheets, EPFM and GYFM zone, CTOD criterion

The SIF for Deep Semi-elliptical Surface Crack in Finite Thickness Plates Determined by the Nodal Displacement Method

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It is well known that structures often have imperfection. In steel structures, these imperfections may take the form of cracks especially at the welded joints. Under the actions of fatigue loadings, propagations of cracks may occur. The consequence of these crack propagations could be a catastrophic collapse of a structure in the worst case. Therefore, an accurate prediction of the growth of either an existing crack or a hypothesis crack becomes a critical part in design and maintenance especially for structures subjected to cyclic loading. To have an accurate prediction, knowing the severity of the crack is the first necessary step. Of all parameters, the stress intensity factor (SIF) is the most widely one adopted to measure the severity of a crack.

In practice, the common flaws in many structural members are three dimensional surface cracks in the shape of semi-ellipse which may propagate and break through the members. Exact solution of SIF for this crack is not available due to the complexity of the problem itself. Reliable computational solutions for SIF of surface cracks have been reported by many research workers such as Newman. And yet, all serious solutions have a limited range of validity for the crack depth ratio (the ratio of crack depth to member thickness, a/T, is less than 0.8). For cracks grow beyond this barrier, SIF are obtained by extrapolation e.g. BS7910. Precision of this approach is still questioning. To investigate the detailed process of crack growth until breaking through occurs, solutions for SIF not available in the reported literature are necessary.

In this work, the distributions of the SIF along the crack front of deep semi-elliptical surface cracks ($a/t > 0.8$) have been investigated. Due to the corresponding importance in fatigue calculation, SIF at two points, namely, the surface point and deepest point have been checked in extra detail. Based on the severity concern, a flat plate subjected to a tensile remote stress, namely the case of mode I defined in fracture mechanics, has been considered. Finally, the SIF obtained in this work was used to fill up the lack part of the existing SIF for cracked plate and to produce comprehensive equation or table which extended the range of the size of crack with reliable SIF.

It has been common to calculate the SIF based on the J-contour integral. However, in the case of deep surface crack, ligament left for carrying out the J-countour integral is very limited and leads to a questionable accuracy of the obtained SIF. Consequently, a localised approach, nodal displacement method, was adopted. All computational works were carried out based on finite element code ABAQUS in which the node displacement close to the crack tip were determined. Post-processing of these extracted nodal dispacement was then carried out to determine the desired SIF. In order to simulate the singularity at the crack tip, the quarter point element was adopted.

Keywords: nodal displacement, elliptical surface cracks, J-contour integral, SIF

Failure Mechanism of Thermal Barrier Ceramic Coating

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The paper presents the experimental investigation on the fracture of thermal barrier ceramic coating (TBC) at high temperature. The fracture was induced by temperature gradient along TBC system thickness direction and oxidation between TBC and bond coat. Laser heating method was used to simulate the operating state of TBC system. Micro-observation and acoustic emission (AE) detect both revealed that fatigue crack was in two forms: surface crack and interface delamination. One can understand the failure mechanism from the plane of TBC surface temperature and substrate surface temperature. It was found that the life of thermal fatigue was reduced by the formation of alumina at interface. On the other hand,

it was found that the temperature gradient between inner and outer surface of specimen accelerates the growth of alumina layer.

Keywords: Thermal barrier ceramic coating, thermal fracture, temperature gradient, oxidation

SESSION M4S
FRACTURE MECHANICS III

Dimple Fracture Simulation of Cracked Specimen Under Different Constraint Conditions

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Three kinds of fracture specimens are tested under different constraint conditions. They are 3PB (Three Point Bending) specimen, CCT (Center Cracked Tension) specimen, and so-called CCB (Center Cracked Bending) specimen. Material of test specimen is A533B steel, which is ductile material, and the dimple fracture occurs. It is shown that the difference of the constraint condition results the difference of the apparent JIC value, and it is also shown that the fracture surface roughness is largely different from each other. The number of dimples and the diameter of dimples are measured experimentally. It is shown that the global constraint condition affects the local dimple fracture process, such as void nucleation and growth, strongly. The dimple fracture process is simulated by the finite element method using Gurson's constitutive equation. The effect of the large particles on the void nucleation, growth and coalescence are evaluated numerically. It is shown that the difference of the constraint condition results large differences of the dimple fracture process. It is also shown that the non-uniform distributions of large particles affect the fracture surface roughness largely, and the numerical results agree well with the experimental observation qualitatively. The distributions of stress triaxiality components explain the experimental results well. The J-R curves are obtained by the numerical analyses. The critical J value, JIC, is evaluated numerically, and the results also agree with those of experiments.

Keywords: Dimple Fracture, Void, FEM, Curson's equation, HRR field

Experimental Study on Ductile Crack Growth of Aluminum 7050 Alloy by Rubber Impression Method

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In order to study the ductile crack growth behavior of Aluminum 7050 alloy, Rubber Impression Method is applied to surface cracked specimens with different crack geometry under tension loading. Rubber Impression Method is an experimental technique which makes it possible to estimate the three-dimensional crack growth profile by inserting liquid-state rubber into the crack, and taking out the solid-state rubber. During the test, three stages of fracture are found and characterized as successive stable crack growth, fast fracture, and final ductile rupture. Successive crack growth profiles are measured by the Rubber Impression Method and compared with the crack geometries obtained by optical microscope from the broken fracture surfaces. Generally both profiles show good agreement except the crack tip region near the free surface. At the center plane of the specimen, Crack Tip Opening Displacement (CTOD) is approximated by examining the development of crack tip opening with crack extension. It is revealed that shallow cracked specimen has relatively high value of CTOD. Also, it is found that there is a unique tendency in change of aspect ratio of surface crack during the stable crack growth. The effectiveness of Rubber Impression Method to the study of ductile crack growth is verified through this study though there are some limitations for the quantitative evaluation of fracture parameters.

Keywords: ductile crack growth, Rubber Impression Method, surface cracked specimen, Aluminum alloy

Mode III Crack Growth in Elastic-Plastic Strain Gradient Solid

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The flow-theory version of couple stress plasticity developed by Fleck and Hutchinson [1] is employed to investigate the asymptotic fields near a crack-tip steadily propagating under mode III loading condition. By incorporating a material characteristic length l, typically of

the order of few microns for ductile metals, the adopted constitutive model accounts for the microstructure of the material and can capture the strong size effects arising at small scales and experimentally observed.

The present investigation shows the remarkable influence on the asymptotic crack-tip fields of the elastic characteristic length le, which has been introduced by Fleck and Hutchinson in order to split the deformation curvature rate tensor into elastic and plastic parts. In particular, the results obtained shows that, as the ratio le/l tends to vanish, the singularities of the stress and couple stress fields increase substantially and approach the values obtained in[2] for the purely elastic behaviour with strain gradient effects, also for a small hardening coefficient. Moreover, an elastic unloading sector is found for $le/l < 0.18$ and a further plastic reloading zone appears near to the crack flanks for $0.1 < le/l < 0.18$. By contrast, the crack-tip zone turns out to be fully plastic for $le/l > 0.18$. In agreement with the purely elastic solution with strain gradient effects the symmetric stress field is found to be not singular, whereas the skew-symmetric stress field dominates the asymptotic solution, although it does not contribute to the effective stress, which appears to be as singular as the couple stress fields.

Therefore, the performed asymptotic analysis can provide useful predictions about the increase of the traction level ahead of the crack-tip due to the strain gradient effects, which have been found relevant and non negligible at the micron scale, namely for $r < l$.

Keywords: crack-tip plasticity, crack propagation, strain gradient effects, asymptotic analysis.

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Fracture Initiation at Sharp Reentrant Corners in Elastic Plates in Bending

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We present an approach to correlate fracture initiation at sharp reentrant corners in elastic plates. The approach is based on a rigorous stress analysis and reveals the universal nature of the asymptotic elastic fields at a reentrant corner. Specifically that the stresses are singular in the context of linear elasticity with magnitude scaled solely by scalar stress intensities. These stresses are of the form stress $= K * r^{(lamba-1)} * f$. Here lambda is the order of the stress singularity, f describes the angular variation of the stress fields and K is the corresponding stress intensity. These quantities depend on the applicability of either Kirchhoff or Reissner/Mindlin plate theory. Both lambda and f are functions of the material and corner angle, and K depends on the far-field loading and geometry. We can express the stress intensity in the form $K = stress * a^{(1-lambda)} * Y$, where stress is the nominal stress in a uniform plate, a is the notch depth and Y is a nondimensional calibration function determined from numerical analyses. In order to demonstrate the approach, we consider a specific reentrant corner angle and material, namely ninety Degree corner in PMMA for which we compute the asymptotic stress and displacement fields. From full-field finite element analysis, we compute the corresponding stress intensities for a given far-field geometry and loading. Experimentation reveals that the measured failure loads show a systematic variation with specimen size; however, the corresponding stress intensities do not, suggesting their use to correlate fracture initiation.

Crack Tip Fields in Ductile Single Crystals: Experiment and Theory

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We compare extremely detailed experimental studies of "plane strain" crack tip deformation fields for several symmetric crack orientations in a ductile single crystal of low hardening copper with new asymptotic analytical solutions employing single crystal elasto-plasticity. The pioneering analysis by Rice[1] of crack tip fields in nonhardening ductile single crystals showed that, in contrast to crack tip fields in isotropic (polycrystalline) ductile materials, the single crystal crack tip fields consist of angular sectors of constant Cartesian stress components joined by rays of stress and displacement discontinuity. Rice's solutions assume yield is attained at all angles about the crack tip, which requires radial shear bands of both slip and kink type. The new experiments confirm many of Rice's predictions; however, there are several important differences. Our experimental observations and measurements[2] show: an absence of kink-type shear

bands; some sector boundary locations differing significantly from Rice's predictions; different near-tip fields for a 90° crack orientation change (in contrast to the theoretical prediction); and angular regions exhibiting no evidence of plastic slip and very low strain (as measured by Moiré microscopy). Based on these observations, we[3] have derived new asymptotic analytical solutions that do not exhibit rays of kink-type shearing and that possess near-tip sub-yield angular sectors. Direct comparison of these solutions with the experimental observations and measurements shows quite good agreement. We have also been studying the development of single-crystalline tensile crack tip fields as a function of the loading history. Our experiments show that such fields in general develop in an asymmetric manner, even though the final near-tip field is symmetric. We are in the process of modeling this analytically. We will give a progress report on the experiments and our analytical modeling to date.

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Molecular Process in Creep and Fracture of an Oriented Linear Crystalline Polymer

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The interrelation between elementary creep and fracture molecular processes of a crystalline polymer - slippage through crystallite and ruptures of passage molecular chains is offered.

The biphase model of a linear highoriented crystalline polymer of fibrillary microstructure with alternating amorphous and crystalline regions type of linear polyethylene is considered. The crowdion Frenkel-Kontorova's for mechanically stimulation of linear chain slippage.

According to of the molecular model in polymer sample creep the leading elementary process is mechanically stimulation of thermofluctuation slippage of passage macromolecules. It is valid for flexible chain polymers at least.

The system of nonlinear kinetic equations for the description of creep process has been written.

The different kinetic dependences for creep by number calculation have been found.

The creep processes are complexely dependent on load, conformation structure, concentration of chain ends,entanglements and cross -links, and on other molecular and supermolecular parametrs of polymer sample.

It is taken into account complex interaction between slippage and rupture of polymer chains. It is considered conditions under which thermofluctuational rupture of a chemical bond of the stressed macromolecular chain takes place.

SESSION T3S
FRACTURE MECHANICS V

Application of Ring Dislocations to Penny Shaped Crack Problems under Combined Tension and Torsion

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Two problems have recently been considered by the authors, namely a penny shaped crack subjected to torsion and a penny shaped crack subjected to tension. The problems were motivated by a need to study the behaviour of shrink-fitted assemblies. Two types of dislocation solution were utilised - special axi-symmetric dislocations giving a relative twist displacement over the end plane were used for the torsion problem and prismatic ring dislocations for the tension problem. The mode III and mode I stress intensity factors were determined by the requirement that the faces of the crack remain traction free. This yielded a relationship between the dislocation density along the crack faces and the imposed loading at the surface, the bilateral solution. For torsion problems, the imposed surface tractions were assumed to lie between two bounding solutions, namely the Reissner-Sagoci solution, where the tangential displacement of the surface, u_θ,

increased linearly with radius, r, or that the shearing stress distribution, $\sigma_{z\theta}$, increased linearly with r. Equivalent bounding solutions apply to the tension problem, namely that vertical displacement is constant over a circular region or that σ_{zz} is constant over a circular region. In this presentation, tension and torsion will be applied simultaneously to the surface of a half-space and the behaviour of a penny shaped crack will be analysed. The loading will be applied in a non-proportional manner. Mathematically this requires the solution of two coupled integral equations expressing the requirement of traction free crack faces. The two pertinent stress intensity factors will be calculated and comparisons between the magnitudes of the stress intensity factors under combined and non-combined loading.

Keywords: Dislocations, cracks, non-proportional, elasticity

Explicit Analysis of Stochastic Fracture Processes at the Microstructural Level

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Variations in constituent properties, phase morphology, and phase distribution cause deformation and failure at the microstructural level to be inherently stochastic. Deterministic analyses do not characterize the range of outcome in terms of quantities such as fracture path, crack speed and failure resistance. It is important to characterize the degree of variation of material response and its dependence on microstructural uncertainties. In this research, we focus on the influence of material property variations on fracture processes in two phase microstructures under dynamic loading. The framework of analysis integrates the second order perturbation method for stochastic processes (Liu et. al., 1986) and the cohesive finite element method (CFEM) (Needleman 1987, Zhai et. al. 1998)). Explicit account of random crack development and arbitrary microstructural morphologies is obtained. The calculations yield both the deterministic behavior and a characterization of the ranges of stochastic variation of fracture initiation time, energy release rate, and crack lengths. This combination of determinism and stochasticity is achieved by introducing stochastic variability to material properties over their expected values through the perturbation analysis and by requiring the satisfaction of all field equations. This presents an application of a stochastic method to micromechanics for explicit failure analysis. Calculations show that a variation of 10constitutive properties in an Al2O3/TiB2 ceramic composite system can result in a comparable range of change for fracture energy release rate. The calculations also yield ranges of variation for fracture initiation time and crack lengths. The influence of property variations and phase morphology on fracture initiation and crack speed will also be discussed.

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A Study on the Delamination of a Ductile Film on an Elastic Substrate

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Numerical studies of indentation induced interface delamination are described for a system consisting of a ductile film on an elastic substrate. Special attention is paid to the properties of the film-substrate interface, and their influence on the indentation response [1]. The interface is characterized by a cohesive zone (CZ) model with the CZ strength and energy as interface parameters. The modified-Riks method is used to solve the boundary value problem. The CZ model is incorporated into the finite element approach via CZ elements and a traction-separation formulation.

Past studies of similar systems assumed the presence of initial delaminations of length larger than the film thickness and plastic deformation induced by the indenter was considered to be present only remotely from the delamination tip. Here, no initial defects are assumed. The formation of the delamination occurs in mode II due to the shear displacements caused by differences in deformation plastic deformation in the film and elastic deformation in the substrate. For weak interfaces the mode mixity changes as buckling occurs. This event is dependent on the CZ properties, and is described by use of modified the solutions from [2] accounting for inelastic buckling. For strong interfaces buckling is excluded, and the initiation of delamination, is connected to distinct pop-in

events. Growth of delaminations occurs under mode II only. The final delamination length is reached at maximum load with no further growth during unloading. Consequently, the maximum load is also dependent on the CZ properties. The dependence of these events on film thickness, film yield strength, residual stresses, and the presence of elastic super-layers, is discussed. Based on the findings of the investigation calibration charts are described that allow the use the present predictions to determine the CZ properties from experimental measurements of indentation response.

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Peridynamic Modeling of Interfaces and Fracture

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The peridynamic theory of solid mechanis [1] reformulates the fundamental equations that describe deformation and motion of a continuous body. The theory uses integral equations rather than partial differential equations to model forces between material particles. The main advantage of the reformulation is that the validity of the equations is unaffected by the presence of cracks or other discontinuities that may appear spontaneously as a result of deformation of the body.

In this talk, application of the theory to material interfaces will be discussed. Because the peridynamic theory allows material particles to interact through a finite distance, rather than through contact forces, it permits particles on opposite sides of an interface to interact according to a force law that may be different from that described in a mathematically and physically richer setting than would be possible in the classical theory.

Progress to date on modeling interfaces in the peridynamic theory will be described. Examples of how failure occurs along and around interfaces will be shown, including numerical simulations of interface cracking.

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Nucleation and Propagation of an Edge Crack in a Uniformly Cooled Epoxy/Glass Bimaterial

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An epoxy/glass bimaterial beam test configuration has been used to study cooling-induced crack nucleation and propagation. This effort extends a nucleation criterion [1], previously applied to tensile-loaded, adhesively bonded butt joints, to another geometry and type of loading. Loading by thermally induced straining complicates the application of a nucleation criterion based upon parameters defining the asymptotic stress fields at the interface edge (i.e. at the edge discontinuity defined by the intersection of the interface and stress-free boundary). In contrast to the tensile-loaded butt joint, where the magnitude of asymptotic stress state is fully characterized by a single interface-edge stress intensity factor Ka, an additional, non-negligible r-independent regular term $Ka0$ always exists for thermally induced strains. In the present work, a direct extension of the previously used nucleation criterion is applied: crack nucleation occurs when $Ka = Kac$, but with the stipulation that interface-edge toughness Kac depends on Ka0.

Acknowledgment
Work performed at Sandia National Laboratories, a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. DOE under contract DE-AC04-94AL85000.

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SESSION T4S
FRACTURE MECHANICS VI

A Study on the Use of Cohesive Model in Ductile Fracture

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Energetic methods to characterize ductile fracture have gained in popularity because of the limitations of conventional parameters. However the separation of the actual work of fracture within the process zone of a growing crack tip, from the surrounding plastic dissipation, is a very difficult proposition. The development of the cohesive zone model, where an explicit fracture mechanism is incorporated into the continuum of the cracked structure, is an important step in overcoming the above shortcoming of continuum mechanics. The fracture process is assumed to occur in an infinitesimally thin strip ahead of the crack tip, whose details are given by a cohesive traction-separation law. This study is an attempt at using this model to predict ductile crack growth and failure based on existing experimental data available in the literature. Three sets of experimental data are used as the basis for the study. In each set one experiment is used to experimentally fit the parameters of the model and then the remaining experiments are used to judge predictions made with the model, such as the load-deflection plot (Fig 1) and the crack history data. The results indicate that the model in its present form does not always yield accurate results. The study also discusses various issues involved in the model that could affect the predictions, such as the choice of parameters and shape of the cohesive law.

Keyword: Cohesive model, plastic dissipation, traction-separation law.

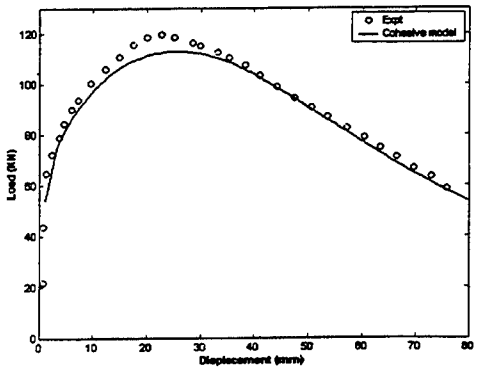


Fig 1: Load-deflection plot for a compact tension specimen

Transient Dynamic Response and Fracture Mechanism of Brittle Spheres Under Impact Loads

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This paper presents a new model for dynamics fracture and damage of a brittle sphere subjected to compression under diametrical impact loading. Based on the superposition principle proposed by Valanis, exact and explicit general solutions for the transient response in the interior of a solid sphere is obtained for displacements and stresses induced by the propagating and reflected waves. The dynamic solution is reduced in the form of a double series involving Legendre polynomial and spherical Bessel function of first kind, in which the integration constants can be determined by the initial conditions. The numerical results are given graphically to show the displacement and the stress variations verse time in the solid sphere. Moreover, the previous calculated local stress distribution is imposed on the pre-existing pores and flaws given by a randomly distributed damage model to analysis the fracture of a sphere with cracks, the crack growth velocity is established in terms of the static stress intensity factor, the dynamic fracture toughness, and the dilatational and shear waves speed. The analysis is still on-going, the preliminary results show that the present framework is useful to investigate the dynamic fragmentation of spheres under impact dynamic loading. More elaborated numerical analysis and application remains to be done and present at a later time.

Keywords: Solids spheres, Transient stress, Dynamic crack growth, Impact loads, Compression and fragmentation.

Fracture Model for Spalling of Titanium Alloy Based on the Mesoscale Approach

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Study and modeling of physical mechanisms of spalling observed via plate impact experiments for a ti-

tanium alloy are the subject of this paper. Different time of loading and level of stress are tested in order to obtain the incipient stage of spalling in our material. Because spalling is a specific kind of fracture, which is loading history dependent, the aspects of the initial microstructure and its evolution during plastic deformation are very important. In order to understand better the physical mechanisms of spall, numerous scanning electron microscopy (SEM) pictures of the free surface created by spalling have been taken for this material. It has been confirmed that the microstructure has a direct influence on the mechanism of nucleation, growth and coalescence of micro-cavities or micro-cracks by means of distribution of nucleation sites and decohesion between the harder particles and the softer lattice. The results of measurements in the form of statistical distribution of horizontal micro-segments of fractured surfaces of targets, corresponding to quasi-brittle fracture, and vertical micro-segments, corresponding to ductile and/or adiabatic shear banding, all along the entire cross-section of a targets, are reported. A meso-macro model developped to study the spall fracture of two others materials is tested and modified in order to traduce the fracture mechanism which take place during dynamic loading. These model allow us to determine the macroscopic stress necessary to obtain a fixed leved of damage from the modelisation of damage and fracture meso-mechanisms.

Estimation of Dynamic T-Stress Using a Domain Version of Interaction Integral

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The limitations of a single parameter characterization (K or J based) of elastic-plastic crack tip fields under quasi-static loadng is well recognized. In order to overcome these limitaions, two parameter theories based on elastic T-stress or constraint parameter Q in addition to K or J are proposed. Since T-stress is an elastic parameter, its estimation is easy as compared to Q, and hence, K-T (or J-T) approach is more useful. Recently, similar studies are reported which demonstrate severe constraint loss in dynamically loaded fracture specimens. Since Q and T are related under small scale yielding when loading is quasi-static, it is reasonable to expect similar changes in T also. Several computational procedures are reported in the literature to estimate the elastic T-stress in fracture specimens. However, these methods are restricted to quasi-static conditions. Hence, an accurate method of estimating dynamic T-stess is warranted. To this end, a domain version of the interaction integral is developed. Its accuracy is ascertained by performing benchmark problems. Also, the accuracy of this method is compared with other T-stress estimation techniques under quasi-static loading conditions. Finally, the evolution of T-stress is studied in a typical dynamically loaded fracture specimen. The results show that the biaxiality parameter ($\beta = T\sqrt{\pi a}/K$) has a large negative value during the initial stages of loading and it slowly approaches the static limit.

Keywords: T-stress, Dynamic fracture, Fracture toughness, Constraint loss

Creep Crack Growth Under Nonsteady Load

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The loading environment that a high temperature component is subjected to in service may be varying with time. The crack growth behavior under changing load has not been studied significantly. This paper addresses some observations on the transient crack growth behavior made on a 12% chrome steel under two-step loading and constant-rate loading. Two-step loading tests include step-up tests and step-down tests. The creep crack growth tests are performed at 545 C using 1/2T CT specimens. The crack growth process is simulated using elastic-plastic-steady state creep finite element analysis to examine the transient crack tip field. The experimental crack growth history is used in the simulation. The results are compared with those under constant loading. In step-up loading, crack growth accelerates greatly after load change due to the effect of prior creep damage and reduced stress relaxation. In step-down loading, further creep-damage at the crack tip nearly ceases after load change due to a sharp drop in crack tip stress, leading to crack arrest for a substantial period of time. Crack growth eventually resumes as the crack tip stress increases by redistribution of the creep strain. The period of crack arrest is dependent on when the load is changed. In general, earlier changes lead to a longer arrest, which can be explained in terms of creep strain and damage at the crack tip under prior load. Crack growth rates are found to correlate well with $C^*(t)$ both in step-up and step-down loading other than the arrest period. Constant rate tests are currently under way and the results will also be discussed.

Keywords: Fracture mechanics, Creep crack growth

SESSION W2S
FRACTURE MECHANICS VII

On the Trajectory of a Crack Near a Graded Interface in a Ductile Material

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The trajectory of an initially straight crack lying parallel to a graded layer between two plastically dissimilar materials was studied using the Exclusion Region (ER) theory of fracture. The ER theory represents a theoretical framework for surface separation within which a broad range of fracture phenomenologies can be modeled. In the specific separation model used in the present study, the instantaneous crack direction is such that the normal-opening force in the near-tip region is maximized. The crack-advance criterion, on the other hand, relates to the intensity of plastic deformation near the tip. A computational study was undertaken using the ER theory as implemented in a special-purpose finite element analysis platform. The problem under consideration involves two plastically dissimilar, but elastically identical, materials joined by a thin, graded interface layer. The fracture parameters are such that extensive plastic deformation accompanies crack advance. It was found that the plastic heterogeneity of the body causes substantial curvature in the crack trajectories, and that the presence of the interface leads to an initial toughness considerably greater than that exhibited by either of the two materials individually.

Mixed Mode Stress Intensity Factor Computation for Cracks in Functionally Graded Materials

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A new interaction energy integral method for extracting mixed mode stress intensity factors in functionally graded materials is described. In the formulation, the general crack-tip contour integral is recast into an equivalent area integral for the purpose of accurate numerical computation. The integrand of the contour integral involves the actual stress, strain, and displacement fields that come from the solution of the particular boundary value problem of interest. It also involves auxiliary fields that are necessary for the extraction of the individual mixed mode stress intensity factors. The auxiliary displacement and stress fields are chosen to be the well-known near-tip fields for cracks in homogeneous solids. The auxiliary strain field is related to the auxiliary stress field through the spatially varying compliance tensor of the functionally graded material. It turns out that this auxiliary strain field is not compatible with the auxiliary displacement field. While the terms that give rise to lack of compatibility are not sufficiently singular in the asymptotic limit to contribute to the value of the crack-tip integral, it is important not to neglect these terms when evaluating the equivalent area integrals because the auxiliary fields are not just defined asymptotically close to the crack tip but are extended throughout the entire domain of integration. Similar issues have been borne out in the development of interaction energy integral methods for axisymmetric and three-dimensional bimaterial interface crack problems, see Nahta and Moran [1] and Gosz, Dolbow, and Moran [2]. In order to assess the validity of the method, we consider several benchmark problems and compare the numerical results to available analytical solutions. In the numerical examples, the boundary value problems are solved using the extended finite element method (X-FEM). The resulting domain integrals are computed as a post-processing step. In particular, we consider the problem of an inhomogeneous edge cracked plate subjected to remote tensile and shear loading. We also consider the problem of a functionally graded plate with an angled center crack. Excellent agreement is obtained between the numerical and analytical results.

Keywords: Functionally graded materials, fracture mechanics, domain integral, X-FEM.

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Effect of the Boundary Conditions on the Theoretical Stress Concentration Factors For Short Members

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Theoretical stress concentration factors (TSCF) are widely used in both analysis and design of loaded members especially when subjected fatigue. It has been recently established [1] that for members with geometric discontinuities considered from the point of view of notches, holes, shoulders, etc. [2], the magnitude of the TSCF below the region defined by the Saint Venant Principle could vary appreciably from the well accepted published values [3]. In this work, the values of the Finite Element calculated TSCF are presented for the case of shouldered plates when subjected to different types of Boundary Conditions (BC) The novel concept of transition length which defines the threshold between long plates and short plates is discussed. The 8 node quadratic quadrilateral element in the context of plane stress elasticity is used throughout the calculations. It is shown that the magnitude of the TSCF could be notably different than the published values with important consequences in fatigue applications. In some cases the computed TSCF were smaller than existing results with the possible consequence of over sizing, and in others the computed TSCF were found to be larger than the existing values with the possible consequence of under sizing a condition that may potentially result in unexpected failure.

Keywords: Theoretical Stress Concentration Factor, Short Members, Boundary Conditions, Finite Elements

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A Theoretical and Numerical Study of Axisymmetric Blistering Film under Elastic Deformation and Delamination in the Presence of Residual Stress

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The mechanical characterization of a thin film in terms of its intrinsic (or residual) membrane stress and delamination mechanics is important in assessing the reliability of encapsulated electronic components and understanding of mechanics of bio-capsules and bio-membranes. In this paper, we propose several ways of measuring residual stress, N_0 , and derive the strain energy release rate, G, of several axisymmetric blister configurations either under a uniform hydrostatic pressure or a central load via a cylindrical punch. Analytical constitutive relations are derived based on an average equi-biaxial membrane stress approximation and are shown to be consistent with finite element analysis (FEA) results. The film is allowed to span wide spectra of film thickness and flexural rigidity so that both bending moment and tensile stretching membrane stress are present. The elastic response of the blistering films are shown to be $\varphi \propto (W_0)^n$, with φ and W_0 the normalized load and blister height respectively, and n is a function of φ, W_0 and N_0. When the film is thick and rigid under a small residual stress, $n = 1$ and $\varphi \propto W_0$; and when the film is thin and flexible under a large residual stress, $n = 3$ and $\varphi \propto (W_0)^3$. The intermediate film thickness and rigidity lead to a linear-cubic transition with $1 \leq n \leq 3$ and an analytical elastic solution is formulated. If the blistering film is now allowed to delaminate from the substrate, n plays a critical role in defining the strain energy release rate and the crack growth stability. The various forms of constitutive relations for a delaminating film are derived and confirmed by FEA.

Keywords: Residual stress, thin film, blister, delamination

A Disc-Shaped Interface Crack in a Laminated Plate Subject to Uniform Temperature Change

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We present solutions to a model problem in order to elucidate the effect of temperature change on local delamination buckling and growth in layered plates on the basis of the theory of small deflection of plates. The model plate is formed by bonding two isotropic and linearly elastic circular plates and it contains a concentric disc-shaped delamination, or interface crack. Axisymmetric bending occurs by a uniform temperature change due to thermal expansion misfit. Radial in-plane forces are induced in the parts of the constituent plates above and below the disc-shaped crack, the determination of which becomes a key to the solution of the problem. A nonlinear equation for determining the in-plane forces is derived by modeling the cracked part as two lapped discs which are hinged along their rims and by imposing the compatibility condition of the deformations of the two plates. Numerical solutions are obtained for some model plates. It is shown that crack faces are always open and relative displacement at the center of the crack increases gradually with the increase in temperature. However, at a critical temperature, the relative displacement begins to increase very rapidly, i.e., local delamination buckling occurs. For the couple of relatively compliant and nearly rigid plates, energy release rate is nearly zero for temperatures below the critical value, but it takes a large value when the temperature is increased above the critical value. Energy release rate also increases with the increase in the radius of the crack and hence the buckling driven delamination grows unstably under constant temperature condition.

Keywords: Disc-Shaped Interface Crack, Thermal Stress, Buckling, Energy Release Rate

The J-Integral and the Strain Energy Release Rate G for the Double Cantilever Beam Specimen

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The double cantilever beam (DCB) test has been used extensively for the determination of the fracture toughness of adhesive joints and the inter laminar fracture toughness of composite materials. The load, load point displacement, and crack length were measured during the test. The material was assumed to be linear-elastic, and the strain energy release rate G was calculated using beam theory. The fracture toughness was defined as the critical strain energy release rate - the traditional fracture criterion. Measurements of the load and load point displacement were usually automated, but measurement of the crack length was often difficult and done manually. The method for calculating G and the inaccuracy of the crack length measurement yielded inaccurate or imprecise results. Hence, the evaluation of alternative test methods was appealing.

Paris et al [1] applied the J-integral to the DCB test specimen and developed an analytical result for J in terms of the load and the load point rotation. No material properties such as the elastic modulus or specimen geometry such as crack length appeared in the equation. The critical value of the J-integral was proposed as the fracture criterion. The proposed method offered several advantages. (1) The crack length did not need to be measured. (2) The proposed fracture criterion could be used to evaluate non-linear-elastic, elastic-plastic, and anisotropic materials within the usual conditions for J-controlled crack growth. (3) Upon substitution of linear-elastic material properties and classical beam theory, J reduced to the traditional equation for G. (4) The only limit upon the volume of test data that could be taken was the speed and capacity of the data acquisition equipment. In addition, this approach could be used for creep-crack growth and fatigue tests. In this study, the feasibility of the J-integral for the DCB test was evaluated.

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SESSION M2K
FRICTION AND WEAR I

Friction-Stir Welding Process Simulation: Material Flow and Microstructure Issues

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Friction stir welding (FSW) is a new solid-state joining process. In this process, a rotating tool (a pin with a shoulder) is made to move between two parts being welded. Material joining is achieved through friction-induced heating and a mixing-extrusion action introduced by the tool, as shown in Fig. 1. FSW has advantages over traditional fusion-welding processes because (a) there is no melting and hence no melting-related joint imperfections, (b) the joint has a high mechanical efficiency, and (c) FSW can be applied to many "hard-to-weld" alloys (e.g. aluminum alloys). The purpose of this study is to develop solid-mechanics based finite element models of the FSW process in order to understand and predict thermo-mechanical phenomena associated with this new joining process.

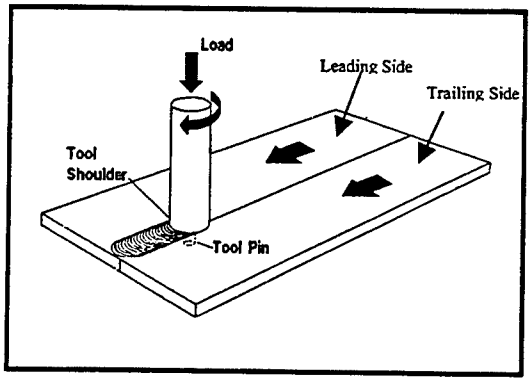


Fig. 1, FSW process for a butt joint

In this presentation, finite element simulation results based on both 2D and 3D models of the FSW process for butt welds will be described. These models have been developed based on several advanced options in a general-purpose finite element code and on limited experimental data available in the literature. An Arbitrary Eulerian-Lagrangian finite element formulation with adaptive meshing is utilized, with considerations of large elastic-plastic deformation and temperature-dependent material properties. The interface between the rotating tool and the workpiece is modeled explicitly. It is found that predicted material flow patterns compare well with experimental measurements, and that a good correlation exists between post-weld effective plastic strain zones and experimentally measured microstructure zones across a welded butt joint.

Keywords: Friction stir welding, finite element simulation, material flow, microstructure

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Vibration and Stability of Frictional Sliding of Two Elastic Bodies With a Wavy Contact Interface

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The stability of steady sliding, with Amontons-Coulomb friction, of two elastic bodies with a rough contact interface is analyzed. The bodies are modeled as elastic half-spaces, one of which has a periodic wavy surface. The steady state solution yields a periodic set of contact and separation zones, whereas the stability analysis requires consideration of dynamic effects. By considering a spatial Fourier decomposition of the vibration modes, the dynamic problem is reduced to a singular integral equation for determining the eigenvectors (modes) and eigenvalues (frequencies). A pure imaginary root for an eigenvalue corresponds to a standing wave confined to the interface, while a positive/negative real part of the eigenvalue indicates instability/dissipation. A complex eigenvector indicates a complex mode of vibration.

For the limit of zero friction it can be demonstrated analytically that the problem is self-adjoint and the eigenvalues, if they exist, are pure imaginary (no energy dissipation). These roots are found for a wide range of material properties and ratios of separation to contact zones lengths. For the limiting case of complete contact, the solution found corresponds to a superposition of two slip waves (generalized Rayleigh waves) traveling in opposite directions and forming a standing wave. With increasing separation zone length, the vibration frequency decreases from the slip wave frequency to the smaller surface wave frequency of the two bodies. With a non-zero separation zone, solutions can exist for material combinations which do not allow slip waves.

For non-zero friction and sliding velocities, unstable solutions are found. The degree of instability is proportional to the product of the friction coefficient and the sliding velocity. These instabilities may contribute to the formation of friction-induced vibrations at high sliding speeds.

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Dynamic Tribological Response of Engaged Fracture Surfaces

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A good understanding of the tribological response of engaged fracture surfaces is important for analyzing shear cracking in materials under high-velocity impact or other loadings resulting in high confining stresses. Several models have been proposed for estimating the effects of interfacial friction and wear of fracture surfaces on shear cracking. However, there is a lack of direct experimental measurements to validate the models. A combined experimental and computational investigation is undertaken to study the dynamic tribological response of as-fractured tribo-pairs. Experimentally, a new dynamic tribometric technique has been developed utilizing a modified Kolsky torsion bar device. Transient tribometric measurements have been obtained for annular as-fractured surfaces of two materials: 7075-T6 aluminum and polycrystalline silicon carbide (SiC). The surface topographies of each specimen before and after the test are examined using an optical profilometer to correlate the tribometric measurement with the evolution of surface wear. The results for 7075-T6 indicate a highly nonlinear response affected strongly by compression and wear while those for SiC indicate a basically linear response with weak sensitivity to wear. Computational simulations based on realistic fracture surface topography and material microstructure are performed to investigate the underlying mechanisms for the observed tribological response. An elasto-plastic model is used in the simulations for 7075-T6. For SiC, the crystal anisotropy and polycrystalline structure are modeled using a three-dimensional Voronoi tessellation. Numerical results will be presented and compared with the experimental data. Issues related to better modeling for shear cracking in materials under high confining stresses will also be discussed.

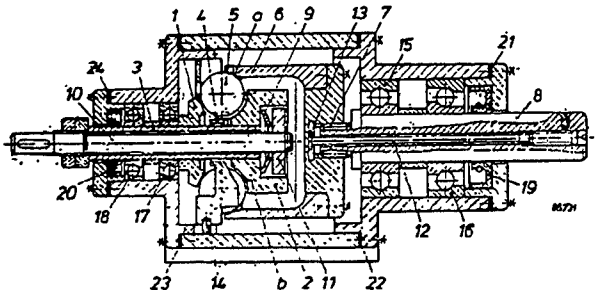
Keywords: Shear cracking in compressed solids, tribological response of engaged fracture surfaces; dynamic tribometry; fracture surface modeling

Steady Power Continuously Variable Speed Traction Drives

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The advancement in understanding the rolling contact phenomena, the development of new synthetic lubricants with increased values of the traction characteristics and the high contact dynamic capacity materials has given a new life to the elasto-hydrodynamic drives. The automobile industry understands that an important way to enhance the fuel efficiency is incorporating a CVT into their products' power train.



The author recognizes that in field of the CVTs a lot of valuable research and many original products were developed, tested, and re-tested. These devices were built in many alternatives and each one of them has its advantages and disadvantages

An original continuously variable speed traction drive is presented. The device is capable to automatic adjust the transmission ratio according to the value of torque delivered. The device is able to control and sustain a steady power transmitted. A study of the transmission ratio and of the power transmitted by device is performed using the "Mathematica 4.0". The results of the study show that the device can be designed for a large range of power transmitted, making it suitable to be incorporated into the automobile's power train. The complex geometric configuration generated by simple geometric shapes offers a great potential of optimization for different applications.

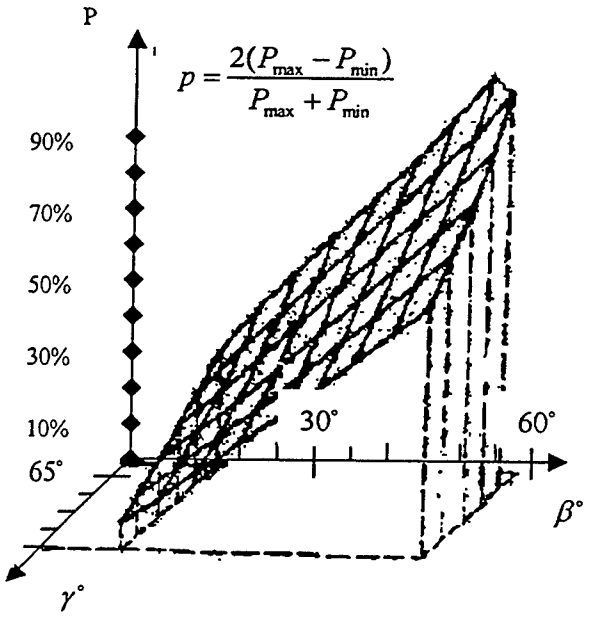
Usually the continuously variable speed devices are characterized by maintaining a constant torque. A few of them could sustain a steady power transmitted for the entire transmission ratio range or a large portion of that

range. The family of traction drives presented can accomplish this desire goal.

The past experience and recent investigations show that this type of CVT presents high potentials and deserve further research. A more profound theoretical study using "Mathematica" will allow a better understanding of the dependence between the internal configuration (geometry, couplings placement, springs' stiffness coefficient) and variator's performance.

This type of CVT offers the advantage of minimizing the friction losses from axial bearing. This increases the overall efficiency. Furthermore the possibility of using a "tandem system" completely eliminates the loss of power in the main bearings.

CVT, Traction, Power-train, Drive, IVT.



Predicting Mechanism of Energy Dissipation in Mechanical System With Dry Friction

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Determination of the energy dissipative mechanism in mechanical system composed of two sub-structures in dry contact, is presented. The analysis is based on the measurement of displacement ratio of the contacting sub-structures as a function of frequency due to light impulse excitation at a single point on any of the two sub-structures. The theoretical analysis depends on a very simple model of two-degree-of-freedom system with elastic coupling. Two different models o f the friction interface are adopted. Several experiments are presented to illustrate the dominant friction mechanism of contacting surfaces within the micro slip regime in a frequency range of oscillation up to 500 Hz It is shown that the energy dissipated due to dry friction during micro slip regime does not depend on the relative velocity between the two contacting surface and is proportional to their relative displacements. The damping friction coefficient is determined from the displacement ratio curve.

On the Analysis of Thermo-Visco-Elastic Frictional Contact Problems

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Almost all devices are made up from an assemblage of different parts, which are mechanically joined resulting in contact interfaces. As is well known, the analysis of contact problems is a very important item for engineers. Yet the thermo-visco-elastic frictional contact between two deformable bodies is rather under developed in comparison to continuum mechanics. It is necessary to take into account the micro-friction effect. Thermal and elastic deformations are considered simultaneously. The contact non-linearities, the thermo-visco-elastic complexity, and friction process make it impossible to attain an analytical solution for the practical case. These why a numerical treatment of the problem is necessary. Since the non-linearities and the imposed boundary conditions are located at the boundaries, the finite element method appears to be a suitable technique for the analysis of these kinds of problems. In this paper a technique, based on the finite element method for the treatment of the two dimensional thermo-visco-elastic contact including friction is developed. An iterative schema is presented based on adaptive convex programming model to linearize the problem of thermo-visco-elastic contact.

Keywords: Finite element method, incremental convex programming, thermo-visco-elasticity, friction contact

Research on the Damping Characteristics of Metal Rubber Material

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The nonlinear hysteretic isolators with dry friction damping performance have been applied in engineering. The non-linear restoring force of hysteretic isolators is history-dependent, i.e., it depends not only on the instantaneous deformation, but on the past history of deformation. As a result, the restoring force cannot be described by an algebraic function of the instantaneous deformation and velocity. This memory nature renders the hysteretic systems more difficult to model and analyze than other non-linear systems.

Metal Rubber (MR) is one of materials with hysteretic characteristics performance. It has been used in spacecraft engine and other equipments as the key elements of isolation construction in Russia and in China recently, such as the flexible supporting of the bearings of engine rotor, and the pipe-line supporting of engine.

Different from the other materials with hysteretic damping, the characteristics of dry friction damping of MR are unique. Because of the special and complex shaping technology of MR, it is difficult to obtain the elements with good performance, despite of its wide application and importance. So it is necessary to make a stable and strict technology process to produce the MR products.

Processing technology of Metal Rubber is complicated. For different uses, the chemical component, diameter, and the heat treatment of metal wires, which are used to produce Metal Rubber product, are often different. All these factors make the inner dry friction status of Metal Rubber material distinguished from each other. So it will be very difficult to get the numerical solution of the motion equation of isolation system of Metal Rubber isolator by the help of experiments.

Masing hypothesis and its derivation are introduced to describe the hysteresis loop of Metal Rubber material. This will reduce the numbers of experimental points and the numerical solution with enough precision can be obtained.

By the help of a test rig, one- and two-dimensional loading experiments are exploited to research the damping characteristics of Metal Rubber. Primary loading line, which is the essential part in Masing model and used to describe the full hysteresis loop, is experimented with different changing steps. By the help of primary loading line and Masing hypothesis, full hysteresis loop is obtained. After that, the relationship between relative deformation and friction force is researched.

To analyze the experimental phenomena, an end-contact surface model of multi-layer beams is used.

It is shown that Metal Rubber has unique nonlinear characteristics from the experimental results. When the isolator with Metal Rubber damper elements is loaded by two-dimensional force, it shows different stiffness and damping coefficients in different direction. The energy dissipation depends on the property of external force. The resonant frequency and energy dissipation can be changed by changing the force direction and amplitude of the force.

This research is supported by the National Science Foundation of China (number of the project: 50075017) and partly by the Youth Science Foundation of Heilongjiang Province (number of the project: Q00C0025). These supports are gratefully acknowledged.

Contact Interaction of Thin-walled Elements and Bodies with Coating Including Wear and Friction

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This work is devoted to the questions of mathematical bases relating to contact interaction mechanics including wear and tear and the development of effective methods to calculate contact connections. The research topic concerns transversally isotropic thin-walled construction elements and protective coatings.

The theoretical basis of this research is the general theory of thermal elasticity and heat conductivity of plates and shells. On this basis a series of investigations, important for practical problems, concerning the wear of plates by hot stamp was carried out and included frictional warming and changes to plate thickness during the process of wear.

To study contact interaction and wear in the system:

- a rigid stamp - cover - elastic base mathematical model of the problem was formulated
- decisive integral equations were accepted
- an asymptotic analysis of these equations was carried out
- solutions of certain-new problems were obtained.

Research was carried out on the effect of :

- anisotropy physicomechanical and thermophysical characteristics of contact pair concerning the magnitude of wear,
- the phenomenon of mutually effective separate rough projections,
- the saturation effect of the actual area of contact
- the division of maximum tangential stresses in undersurface layers of contacting bodies with rough surface.

Keywords: contact problems, thin-walled elements, coating, transversally isotropic materials, wear, frictional warming, coarseness, integral equations.

SESSION M2M
HEAT TRANSFER AND THERMODYNAMICS

A New Method for the Estimation of Heat-Transfer Coefficients in Quenching Problems

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Accurate prediction of thermal and mechanical field variables in quenching models depends on accurate estimation of surface heat flux histories in the parts being quenched. The surface heat fluxes are, in general, estimated using a combination of experiments and inverse heat transfer methods. In this work, a new, noniterative, finite element-based inverse method is presented. The technique takes advantage of the linearity between computed temperatures and the instantaneous surface heat flux distribution, and sequentially minimizes the least squares error norm between corresponding sets of measured and computed temperatures. Results from a validation against a simple analytical inverse heat-transfer problem indicates that the method is capable of predicting surface heat-transfer coefficients very accurately. Results from a quenching experiment on a cylindrical bar are also presented and comparisons with previously reported results in the literature on similar experiments are also made.

New Thermodynamic Cycle For Heat and Mass Transfer

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The Maisotsenko Cycle is revolutionizing the way we see potential energy. The Cycle provides for 10 times the heat and mass transfer for the same surface area as previously realized, with very low-pressure drops. The Maisotsenko cycle uses the latent heat differences to create large heat fluxes that can only be realized with this cycle and can be used wherever heat and mass transfer is needed.

The ranges of uses vary greatly, from cooling fuel cells, to humidifying the hydrocarbon in a fuel cell, cooling turbine inlet air, humidifying combustion air in turbines, cooling buildings, chemical production. The product being cooled can be any fluidized flow. The cooling fluid must be a gas able to absorb an evaporate and thereby use latent energy to cool and/or humidify.

The Maisotsenko Cycle is comprised of passing the cooling gas over the dry side of a plate, passing the gas through the plate to a wet side where the cooling gas absorbs the evaporate embedded in the wet side of the plate. The wet side is in heat transfer contact along with the dry side. This causes the cooling gas to be precooled pass the wet bulb toward the dew point temperature. This precooled gas is then passed over the wet side of a plate in heat transfer contact with the product on the dry side of the same plate. The cooling gas continues to be warmed by the product fluid and therefore evaporate additional fluid from the wet side of the plate.

In practice we have incorporated material design and component configuration to make the exchanger produce more for the surface area given. In addition we will demonstrate the Maisotsenko cycle and show our test results.

Keywords: Energy, Turbine, Cooling, Humidify, Maisotsenko

To Numerical Modeling of Some Processes in a Nonlinear Moving Media

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We consider the degenerate type quasilinear parabolic equation

$$\frac{\partial u}{\partial t} = div(|grad\, u^k|^{n-1} grad\, u^k) - div(uv) + \epsilon\gamma(t)u^\beta, \quad k > 0,\ n, \beta \geq 1 \qquad (1)$$

The equation is basis for describing a processes of a heat conductivity, diffusion, polytropical filtration not submitting to a law of the Newton, in a moving with velocity $v(t)$ a nonlinear media, at the presence of a volumetric absorption ($\epsilon = -1$) or source ($\epsilon = +1$) a power of which is equal to $\gamma(t)u^\beta$. It describes many other processes too. We analyze the influence of the various factors to the velocity of the distribution of a temperature waves. In special cases of the equation (1) ($n = 1$ or $k = 1, v(t) = const, \gamma(t) = const$) it was shown as the presence of absorption or source influences to the velocity of the distribution of a temperature waves. Thus the volumetric absorption reduces to the finite velocity of the distribution of perturbution of a temperature waves. It is clear, that the action of convective transfer and absorption in (1) simultaneously reduses to the new phenomena and influences to the velocity of the distribution of front of temperature waves. It was shown, that the action of the convective transfer and absorption (source) may be reduced to a new effects: an arising of "a wall" for a front; an arising of a back front; a localization of the limited and unlimited weak solutions. It was established conditions, in which these phenomens have placed. It is found, that the behaviours of the solutions are diferent that depend of cases $0 < kn < 1, kn = 1, kn > 1; \beta \geq 1$. Estimations, asymptotics of the solutions ($t \to \infty$) and of the front ($kn > 1$) are established. The numerical modeling of the studied process on basis of these estimations of the solutions carried out.

Unsteady Heat Transfer Problem in Functionally Grading Wood-based Board for Higher Insulation

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Much wood-based materials are used as building materials and much waste of them are also discharged every year in Japan. Recently, the concept of sustainable development has been taken seriously and recycle use of wooden building waste has been desired. The long use of wood-based materials is effective against the global warming because that it can put off the return of wood into carbon dioxide. The boards made of powders and/or particles of wooden waste are prospective recycled products. In this paper, we treat the unsteady heat transfer problem in functionally graded material (FGM) plate to seek the more effective grading pattern of structure in the wood-based board with higher insulating property.

The analysis of unsteady heat transfer problem of arbitrary inhomogeneous material is not so easy. We use the analytical method combined of the Laplace transform, the suitable transform of variables and the perturbation method. We proposed the analytical method and applied it for the problem whose surface temperatures were given as boundary conditions in [1]. In this paper, we apply it for the convection transfer problem with different Biot numbers and surrounding temperatures at surfaces. It means the state that the FGM board is used as a wall between inside and outside of house. The numerical calculations are tried for several grading patterns and the better grading patterns are discussed for the higher insulating property. These discussions can be useful from the viewpoint of energy saving for the sustainable development.

[1] Y. Obata and N. Noda, "Transient Thermal Stresses in a plate of functionally gradient material", Ceramic Transactions Volume 34, The American Ceramic Society, pp.403-410 (1993).

Modeling for the Hot Section Structures by Genetic Algorithm

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The genetic algorithm is applied for the parametric identification of thermal responce analysis model of reentry vehicle structure. It is very difficult to apply controlled, strong thermal load for the large structure. Then, there are severe limitations for the ground test evaluation of thermo-resistive structure of re- entry vehicle. Therefore the computational evaluation is very important. The improvement of numerical model is required for the excellent evaluation of the thermal responce predictions. The nose cone model and the leading edge model are chosen

for the target of modeling test. These are the hot sections of the vehicle. In addition, ground test results are available for these section, which were conducted under the japanese re-enrtry project - HOPE. The recent rapid progress of multi processor system prepares good environment to genetic identification algorithm. In addition, we pay special attention to reduce the number of identification parameters in our computer algorithm. The small parameter number leads to the computational time reduction, which is very important to the practical genetic algorithm application. The numerical simulation results are compared with experimental data. The modified models show better simulation results than the original ones.

Keywords; GA, Modeling, Re-entry, Hot section

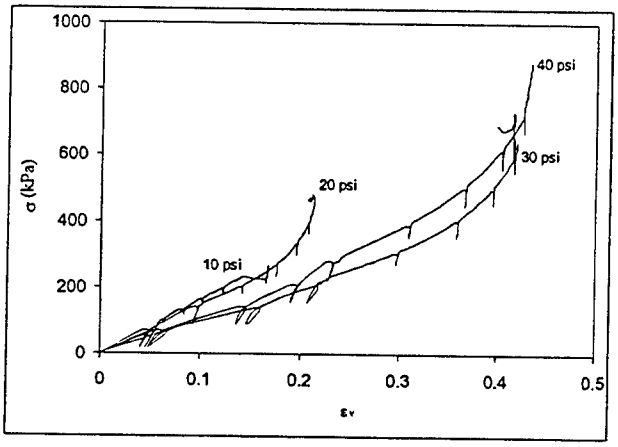
SESSION M1I
MATERIAL BEHAVIOR I

On the Mechanical Behavior of Microcrystalline Cellulose During Compaction

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Microcrystalline cellulose is a highly compressible, relatively free-flowing powder, which is widely used in industry. Significance of applications inspires the experimental and theoretical studies of the mechanical behavior during compaction for different brands of this powder. The main objective of this study is to obtain accurate and reliable experimental data characterizing the complex mechanical response of microcrystalline cellulose, which can be employed for formulation of the constitutive model. A new volume change triaxial tester has been developed for measurement of the stress and deformation of the dry cohesive powders under different loading paths. The data have been obtained for microcrystalline cellulose powders with average particle sizes 20 μm and 40 μm. The triaxial tests have been performed in two stages: hydrostatic tests have been followed by deviatoric tests (under confining pressures 10, 20, 30, and 40 psi) until failure at different confining pressure. The mechanical response of the material on the loading is essentially inelastic and depends on the loading history as well as time effects. At different stress levels, after short-time creep (keeping the stress constant for about 10 minutes), partial unloading-reloading cycles have been performed in order to obtain the elastic moduli. It has been shown that the elastic moduli are not constants and vary with the stress state. The volumetric behavior of the powders strongly depends on the particle size. It has been determined that the microcrystalline cellulose powder with particle size 40 μm starts to dilate longer before failure than the microcrystalline cellulose powder with particle size 20 μm. In the last case the material does not exhibit perceptible dilatancy. The presented figure shows the stress-strain relations (mean stress against volumetric strain) in the triaxial tests obtained for the microcrystalline cellulose powder with particle size 20 μm under different confining pressures in the deviatoric part of tests.



Keywords: Microcrystalline cellulose, Compaction, Mechanical response, Experimental results

Effect of Grain Size on the Shear Localization of Iron

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We have investigated the effect of grain size on the shear localization of iron, with grain size ranging from microns to submicrons (nanoscale). Pure iron powder was ball milled in protective atmosphere to obtain nanocrystalline powder, followed by consolidation under different conditions to obtain fully dense samples with varied grain size. Both quasi-static and dynamic (Kolsky bar) mechanical testing indicate strong effect of grain size on the mechanical behavior of the samples. When the grain size is in the micron range, plastic deformation takes place uniformly, whereas those samples with submicron and

nanocrytalline structure exhibit shear localization. Transmission electron microscopy reveals several features in the microstructure of the shear band. The grains in the band have experienced severe plastic deformation, giving rise to elongated grains with an aspect ratio of ~ 10. Electron diffraction of the crystals in the shear band shows strong texturing, corresponding to the $< 111 > /\{110\}$ slip systems. No obvious recovery or recrystallization can be established in the shear band, implying a non-adiabatic process. Our observations of the mechanical behavior are related to current dislocation-mechanism based constitutive models for bcc metals.

Keywords: grain size effect, shear localization, bcc metal, constitutive model

An Elastic/Viscoplastic Constitutive Model for Microcrystalline Cellulose

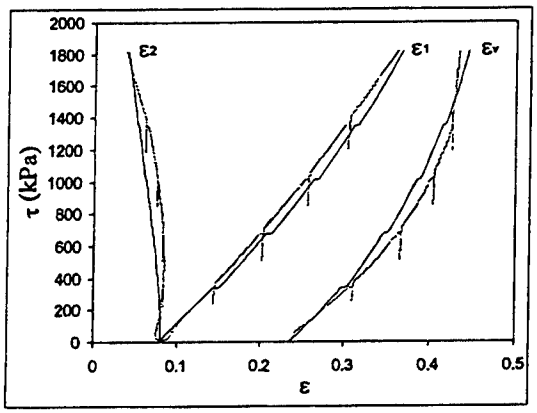
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The focus of this study is development of a suitable rheological model for the microcrystalline cellulose powder PH-105 with particle size 20 μm that recognizes complex mechanical response of the material to the loading history. The experimental data obtained in the hydrostatic and deviatoric tests were used for derivation of the model, which is based on the three-dimensional general elastic/viscoplastic constitutive equation obtained by Cristescu

$$\dot{\epsilon} = \frac{\dot{\sigma}}{2G} + \left(\frac{1}{3K} - \frac{1}{2G}\right)\dot{\sigma}\mathbf{1} + k_r \left\langle 1 - \frac{W^I(t)}{H(\sigma,\tau)} \right\rangle \frac{\partial F}{\partial \sigma}.$$

This equation describes elastic and viscoplastic behavior of the material, and the irreversibility (the last term of the equation) is due to transient creep. The problem of developing the model reduces to the determination of all the constitutive functions and coefficients in this equation. We have obtained expressions for elastic parameters, the yield function, the viscoplastic potential and short-failure condition. Note that the experimental data shows that microcrystalline cellulose with particle size 20 is practically compressible. A small dilatancy may occur just before the failure. With regard to this we propose the model that describes only the compressible behavior of the given material. It has been determined that the yield surfaces (stabilization boundaries) and viscoplastic potential surfaces do not coincide. This implies different orientation of the stress and irreversible strain rate tensors and proves the importance of application of the non-associated flow rule in the used constitutive equation. Validation of the obtained elastic/viscoplastic model has been performed by comparing the theoretically predicted stress-strain curves with those measured in tests. For example, the presented figure shows stress-strain relations (effective stress against components of strain) in the deviatoric test under confining pressure 40 psi, obtained both theoretically (black lines) and experimentally (gray lines).



Keywords: Constitutive model; Viscoplasticity; Flow rule; Microcrystalline cellulose

Thermo-mechanical Study of Dynamic Shear Band in Bulk Metallic Glasses and Composites

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Bulk metallic glasses (BMGs) are amorphous metals that became potential structural materials due to recent development. However, applications are limited by their lack of plasticity. Actually, BMGs fail by the formation of localized shear bands. The incorporation of a ductile crystalline second phase (β-phase) stabilizes the shear band formation and hence improves the failure behavior. In this work, we present an experimental thermo-mechanical investigation of dynamic shear band in BMGs using two apparatus: a modified split Hopkinson tension bar system and a high-speed infrared camera.

The specimen has dog-bone geometry with a gauge section of 3×3 mm^2 and loaded by a split Hopkinson tensile bar system made of maragin steel C350 of 20 mm diameter. The incident bar (1850 mm length) is impacted by the

hollow striker (200 mm length) at a speed of 8 to 25 m/s, which results in a strain rate up to 10^3 /s in the specimen. The classical transmitted bar is replaced by a rigid bulk block to avoid any movement of the specimen during the experiment while the camera is focused on it.

The high-speed infrared camera is an instrument capable of measuring 2D thermal fields at rates of up to 1 million frames per second. A double Schwarzchild optical focusing lens collects IR radiation emitted by the area of interest of 1.1×1.1 mm^2. Behind the lens, an array of 8×8 HgCdTe IR detectors is cooled with liquid nitrogen in the dewar and allows to detect radiation with temperature sensitivity of 2 K. The time resolution of 1 million FPS is achieved by multiplexing the 64 signals from the detectors with 8 multiplexing circuits at a frequency of 10 MHz. Finally the signals are captured using 4 data acquisition boards (2 channels each) and stored in a computer.

Several experiments have been performed and the results are discussed including the differences between the thermal fields of a monolithic BMG and a β-phase composite. Also, the failure mode under tension loading is compared with the compression results as well as shear banding at different strain rate. Investigations have been conducted to confirm the discrete regions of high temperature ("hot spots") along the shear band instead of a laminar process.

Keywords: shear band, metallic glass, infrared temperature measurement, dynamic tension test.

Mechanisms of Inhomogeneous Cyclic Plastic Deformation of 1045 Steel

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Inhomogeneous localized cyclic plastic deformation of 1045 steel was experimentally investigated. Solid round specimens were subjected to cyclic tension-compression and torsion. Local strains were measured by using small strain gages. Local deformation was studied under fully reversed loading as well as asymmetrical loading with a mean stress. For tension-compression cyclic loading with the maximum stress lower than the lower yield stress of the material, cyclic plastic deformation was initiated in local areas of the specimen and it propagated into the whole gage section with increasing cyclic loading after a period of incubation. Inhomogeneous cyclic plastic deformation was observed within the gage section even after the saturation state. Under asymmetric cyclic loading with a mean stress, the cyclic plastic deformation was accompanied by noticeable inhomogeneous ratcheting deformation. When a solid specimen was subjected to cyclic torsion, the local cyclic plastic deformation not only propagated in the axial direction but also from the specimen surface into the interior of the specimen. The inhomogeneous cyclic deformation was dependent on the loading magnitude and evolved with continued cyclic loading. TEM was used to analyze the distribution and evolution of the dislocation substructures at different locations of the specimens. Because of the stress concentration at the grain boundary, micro plastic deformation occurred initially near the grain boundary in ferrite grains and then accumulated, aggravated, and propagated into the central zone of the grain. With increasing loading cycles, the dislocation substructures evolved in a sequence of uncondensed veins, condensed veins, uncondensed cells, elongated cells and equiaxial cells. The interaction of grains through grain boundaries resulted in the propagation of the experimentally observed inhomogeneous cyclic plastic deformation.

Keywords: 1045 steel, dislocation substructure, inhomogeneous cyclic deformation, ratcheting.

SESSION T2I
MATERIAL BEHAVIOR II

Modeling of Fatigue Damage

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Fatigue life consists of two qualitatively distinguishable but quantitatively vague stages: crack initiation and growth. Generally, macroscopic continuum mechanics concepts are used to assess the fatigue damage of crack initiation and fracture mechanics concepts are used to determine the crack growth.

The current work attempted to unify the modeling of the two stages with one general fatigue damage model. The goal was to predict fatigue crack propagation by using the fatigue constants and cyclic plasticity properties obtained from a smooth specimen. A recently developed incremental multiaxial fatigue model was used to assess fatigue damage. An attractive feature of the model is the elimination of a cycle counting method. This makes it possible to predict fatigue crack growth when the cyclic material deformation near the crack tip is known. The cyclic elastic-plastic stress-strain field near the crack tip was analyzed using the finite element method with the implementation of a robust cyclic plasticity theory. The

fatigue damage model was used to determine the crack growth based upon the detailed stress-strain histories near the crack front obtained from the finite element analysis.

Mode I, Mode III, and mixed Mode I and III fatigue propagation experiments were conducted using 1070 steel at room temperature. In addition to constant-amplitude loading conditions, experiments were also conducted for the overload effect on crack propagation. Modeling results obtained by using the new theory were compared with the experimental observations including overload effect, R-ratio effect, and crack initiation on a sharp notch. An excellent agreement was achieved.

Keywords: Cyclic plasticity, crack propagation, fatigue damage, multiaxial fatigue.

Observation of Failure Mechanism and Development of Model for Predicting Strength of Resistance Spot Weld

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Spot weld made of resistance welding has been used extensively in auto body assembly for thin-gauged sheet metals. It is ironic however that despite its importance in safety related issues a generally accepted failure criterion for spot weld does not exist.

To develop a theoretical model for predicting the strength of spot weld, failure tests were first performed to reveal the failure mechanisms of spot weld in lap-shear and cross tension test samples. Experimental observation during the tests shows that while the lap-shear (cross tension) sample is subjected to shear (normal) load at the structural level the failure mechanism at the materials level is tensile (shear) mode. Based on the observed failure mechanism, stress distribution is assumed and related to the far field load for the lap-shear and cross tension test samples. Strength of the spot weld obtained from tests is then correlated with the predictive models. The theoretical model is further extended to the mixed normal/shear loading condition. Data from test as well as finite element numerical method are used to validate the model. Finally, the practical utility of the model in accessing the failure strength of spot weld is discussed.

Risk Based Design Criterion of Welded Details in Marine Structures With Case Studies

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Current design methods applied to ship structures are suffering from several handicaps. The most important of those problems are that the severe environmental conditions, e.g., abnormal wave loading, are either intimately ignored or that due to the lack of information with regard to load distributions. Also, the frequencies of the occurrence are of non-useful provisions or incomplete informations.

The intent of the present paper is to propose a design approach for the lifetime estimation of ships and offshore strucutres. The suggested procedure involves technique based on probabilistic fracture mechanics and risk analysis. The proposed approach takes into consideration abnormal loading conditions. Nevertheless, the normal load could be of the abnormal one in the presence of fabricating defects. Design faults, i.e., hotspots or the incorrect material choice are the two important considerations that had been taken into account. The improper fabrication processes could jeopardize the good design and thus may lead to the immobilization of the marine structure.

The approach has been demonstrated by the same author on different occasions and has been named by the Fitness for Performance. Fitness for performance approach is simply a tool for reducing faults due to improper design, to minimize defects due to fabrication processes and finally to contribute in the good choice of material cited for the corresponding environment. Thus, the impact of the application of the approach is in the consideration that it is a technical device for assessing the engineering integrity of welded marine structures. In the meantime, it furnishes fundamental requirements of engineering design and risk analysis. The ubiquity of the computer and the development of sophisticated software and testing facilities for ! the lifetime estimation of marine structures, have lead to models which can reliably predict material behavior and performance with a high level of confidence.

Applications of the current suggested approach to the estimation of the lifetime and hence the assessment of design allowable stresses of marine structures have been demonstrated. Have resulted in several practical conclusions. Four cases were demonstrated within this work. Two are of the offshore structures. The third one is for a dry cargo ship. The fourth is for a containership.

The main conclusion drawn from those applications are

that the use of the proposed optimized approach can lead to better assessment of mechanical and marine behavior under abnormal environmental conditions. Also, the concept can furnish economic as well as optimized engineering applications of strategic marine structures.

On the Nature of Surface Modification Produced by Non-planar Hypervelocity Sliding in Tungsten Alloy

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High speed metal-on-metal sliding experiments have shown unique tribological phenomena. Dominant surface modification occurs in the form of tear-drop shaped craters (gouges). Gouges on rocket sled tracks and EM launcher rails are the best known cases of steel-on-steel and aluminum-on-copper sliding damages respectively. We have shown that hypervelocity gouging is amenable to experimental study through the use of techniques that are employed in reverse ballistics experiments. This new technique enables production of gouging in a non-planar geometry. Nevertheless, the gouges produced are strikingly similar to those found in planar experiments. In this paper we present our analysis of gouges caused in a tungsten-steel system due to hypervelocity sliding. The gouges so produced were thoroughly examined to establish the underlying tribological and fractographic behavior. We found that gouging provides an efficient mode of material removal and a probable cause for fracture. A numerical simulation of plate target interaction with a long rod possessing a gouge confirms that the gouge can indeed lead to fracture and subsequent performance degradation.

Fatigue Failure and Repairs in Industry

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In spite of numerous and expensive researches in the field of fatigue, cracks and failures caused by fatigue occur every day in all fields of human activity. The paper presents some typical fatigue damages in industry and transport. The fatigue cracks and failures in large gear wheel of cement mill, fatigue failure of the main engine lateral support (at bulk carrier) and fatigue cracks at large portal crane are described.

After 20 years in service, the great gear wheel of cement mill failed due to fatigue. When the whole mill plant was stopped and inspected, additional seventeen fatigue cracks have been found at the tooth fillets. Numerical method (FEM), was used to determine the stress distribution at the gear rim. Joint efforts of alternating stresses, casting errors (sized several millimetres to several centimetres) and most likely existence of tensile residual stresses caused fatigue cracks initiation and propagation at the critical positions. The cross section of the gear rim where complete fatigue failure occurred was additionally weakened by decreasing the rim thickness due to connecting bolts.

Failures of the main engine lateral supports (top engine bracing) of several bulk carrier vessels occurred after a few months of service. In order to solve the problem and avoid future time and money losses, it was necessary to establish main causes of failures. The strain gage measurements were performed in large scale during the sea trial. Failures were mainly caused by inadequate design of the joint between support and ship (hull) structure and insufficient weld quality.

The paper also presents complete fatigue damage analysis and repair procedure that was carried out in shipyard after the cracks at 250 kN portal crane were detected.

Residual Stress in Electroplated Nickel Coating

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Nickel coating is widely used in many fields, such as wear-resistant, anti-corrosive surface layers. The residual stress will be produced in the preparation and the treatment of the coating due to the thermal-mechanical mismatch of coating and substrate. In the present investigation, the residual stress in the nickel coating is measured by X-ray diffraction method (XRD) and nanoindentation which is a newly method to obtain the residual stress in the coatings. The relationship between the residual stresses and preparing or processing parameters is investigated. In the study, a new method which is named as thermal shock induced by Nd:YAG laser beam was used to treat the coating. The laser beam thermal shock can make the original tensile residual stress become compressive residual stresses. The compressive residual stresses are benefit for the coating in the mechanical processing.

SESSION W2I
MATERIAL BEHAVIOR III

Strain Rate Sensitivity of Epoxy in Tensile and Shear Loading

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Two types of epoxy, E-862 and PR-520, have been tested in tension and shear over a wide range of strain rates from 10^{-4} to 800 s^{-1}. Experiments at strain rates of up to 2 s^{-1} have been conducted with a hydraulic testing machine, and tests at strain rates above 300 s^{-1} have been conducted using the split Hopkinson bar technique. Specimens with identical geometry are used in tests at all strain rates for each type of loading (tension or shear). The specimens in the tensile tests have dog-bone geometry. Strain in these tests is measured (including in the split Hopkinson bar tests) with strain gages that are cemented onto the specimen. The specimens in the torsion tests are short thin-walled tubes, and the strain is determined from the relative rotation of the ends.

The results show that epoxy is very sensitive to the rate of deformation. A stiffer material response (increase in modulus) is observed with increasing strain rate in both, tension and shear loadings. The effect of strain rate on the maximum stress depends on the loading mode. In shear the maximum stress significantly increases with strain rate. The maximum shear stress at strain rate of 700 s^{-1} is roughly twice the maximum stress at strain rate of 10^{-4} s^{-1}. In the tensile tests the maximum stress is about the same in all strain rates. The results show also that the deformation in shear and tension cannot be related to each other by the classical J_2 flow theory. It appears that the hydrostatic component of the stress plays a role in the deformation and failure in tensile deformation. The PR-520 epoxy is stronger and more ductile than the E-862 epoxy.

On the Characterization of Material Repeated-impact States using a Pattern-recognition Approach

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This paper deals with the design procedure of computer based pattern recognition (PR)classifiers when a nondestructive experimental technique, e.g. Acousto-ultrasonics (AU),is used for the identification of mechanical repeated-impact states in engineering materials. For this purpose, material specimens presenting different residual impact states are processed to retrieve AU signals in the form of digital records. The retrieved AU data are, then, grouped in distinct classes, each pertaining to a known mechanical response state of the material under consideration. These AU data are subsequently identified by pattern vectors, the components of which represent values of characteristic features in particular domains of description. PR-classifiers built from these pattern vectors are then employed to determine unknown mechanical impact response states of the material by identifing their pertaining AU signals as belonging to one of the predefined classes. The procedure is further illustrated in this paper by the determination of low energy repeated impact states in both homogeneous and heterogeneous (composite) materials. The pattern recognition and classification methodology, as introduced in this paper, can be extended to utilize a large number of nondestructive experimental techniques, and the procedure can be effectively used for the purpose of health monitoring of engineering assemblies and structures in general.

The operating research grant of Natural Sciences and Engineering Council of Canada (NSERC)to the first author is gratefully acknowledged.

Failure of Aluminum Honeycombs in the W-T Plane: Phenomenological and Micro-structural Analysis

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The response of an aluminum honeycomb to a combined state of normal and shear stresses relative to its "out-

of-plane" or "strong" direction (direction perpendicular to the cross-section of honeycomb cells) is not understood, despite being of practical significance. The challenge lies in the development of a size-independent test method capable of measuring the intrinsic mechanical properties of the honeycomb. Here, a new test procedure involving the enhancement of the Arcan apparatus is proposed and developed. This apparatus subjects a central section of a "butterfly-shaped" honeycomb specimen to a uniform state of plane stress. The stresses have local maxima at the central section, thus ensuring that failure occurs there. It is found that the honeycomb collapses plastically, developing parallel and complex "fold lines" initiated at the central section. A micro-structural based model is used to explain the observations. An anisotropic failure phenomenology which directly relates to the collapse process is then proposed from the measured stresses and strains.

Identification of the Dynamic Properties of Candidate Materials for the Spent Nuclear Fuel Container

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Spent nuclear fuel container has to meet strict design objectives including maintaining its integrity in case of accidents, where it may be subjected to high loads over very short period of time. Simulating accident scenarios using finite element analysis requires knowledge of material characteristics under these circumstances. Materials usually exhibit different behavior under dynamic loading conditions than under static ones. While behavior of materials under static loads is well-documented, their behavior under strain rates associated with accident scenarios ($\dot{\varepsilon} < 200\text{s}^{-1}$) has not been adequately investigated. Three candidate materials, Stainless Steel 316, Titanium Alloy Grade 7, and Alloy C22 were considered for the research. Literature review failed to find any relevant data on mechanical properties of these materials in the strain rate range of interest, ($10^{-4} \leq \dot{\varepsilon} \leq 200\text{s}^{-1}$).

This paper presents a study of the behavior of these three materials under dynamic loading at room temperature. To cover this broad range of strain rates two testing machines were used in the research:

- Axial/Torsional Testing Machine (MTS Model 319.25).
- Impact Testing Machine (Istron Dynatup 8250).

A custom fixture was designed and manufactured to conduct impact tensile testing of standard cylindrical specimens, Figure 1. Data interpretation procedures were developed to obtain mechanical properties of tested materials and produce stress-strain curves such as the curve of Figure 2. These procedures were based on conducting numerous tests. Results compared well with those of materials with close chemical composition.

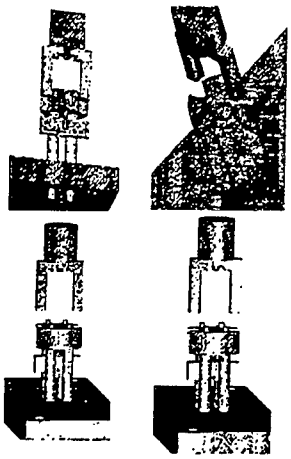


Figure 1. Tensile Impact Test Fixture

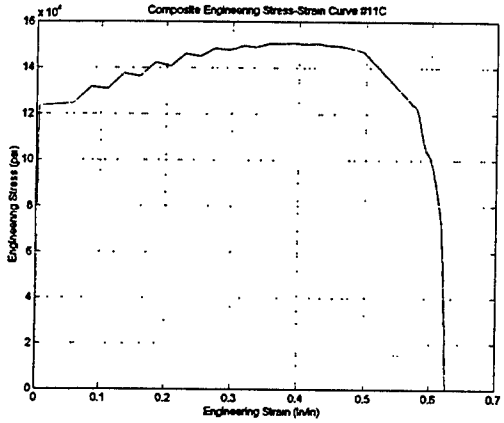


Figure 2. Engineering Stress-Strain Curve for Alloy C22, Strain Rate Equal to 123 sec^{-1}

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Acoustic Emission Monitoring of Contact Induced Damage in Ultra-small Volumes

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Present study evaluates initial stages of plasticity and fracture under normal and sliding contacts. A special design of Acoustic Emission sensor integrated into an indenter tip provided a greatly enhanced sensitivity to indentation and scratch induced transient processes. This enabled detection of AE events for the ultra-light contacts below 1 mN and provided an adequate basis for the AE signal analysis. Evaluations involved thin films ranging from several nanometers thick native oxides on metals to 100-200 nanometers thick metal and ceramic films on ceramic substrates. Evaluated phenomena included cohesive film fracture, film/substrate delamination and yield initiation in oxidized metal surfaces. Indentation curves and in-situ images of the indented areas were correlated with the AE waveforms. Acoustic energy analysis assisted in the evaluation of the mechanisms and kinetics of contact induced fracture and plasticity.

Inverse Analysis for Determining Embedded Delamination in Composite Laminates

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Carbon fiber-reinforced plastic (CFRP) has excellent mechanical properties such as light in weight and strength. In order to extract a merit of CFRP, a layered panel structure is often adopted. However, the strength of the CFRP layered panel structure is greatly degraded by an embedded interlaminar delamination. In order to predict residual strength of the composite panel, it is important to detect a location and a size of delamination if it exists. Therefore, several researches are performed such as ultrasonic inspection, electrical impedance tomography and vibration response.

In this research, outputs of strain gauges obtained from three-point bending tests are adopted to estimate the location and the size of a crack in a four-layered composite panel. The eight strain gauges are mounted on the top surface of the specimen. The location and the size of a crack cannot be measured directly. Therefore the inverse analysis should be performed. The inverse analysis is an iterative procedure to estimate the length and the size of a crack by comparing the FEM analysis and the experimental measurements of strain gauges. The FEM analysis can be the bottleneck of the inverse analysis. Therefore, the approximate functions of the outputs of the strain gauges with respect to the location and the size of a crack are introduced.

The inverse analysis is performed using the eight outputs of the strain gauges when load is applied in the center of the specimen. In this case, the estimated location and the estimated size have large errors. In order to reduce the errors, the results from three separate loadings are considered. The positions of loadings are in the left half, in the right half, and in the center of the specimen. Furthermore the three cases of the deflection at load points are used to the inverse analysis. The estimated location and the estimated size of a crack are improved by this method.

SESSION R2I
MATERIAL BEHAVIOR IV

Microstructure Influence on the Surface Heat Treated Steels Characterization by the Drilling Test

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In order to characterize the heat treated steels, we develop a method based on the thrust measured during a drilling test. Indeed, it is shown that the penetration resistance by drilling is coarsely proportional to the material hardness. Nevertheless, it is observed that the correlation between the hardness and penetration resistance more or less depends on the material properties and particularly its ductility. Different metals with various microstructures have been studied. Then, hardness test, tensile test, drilling and analysis of chips were carried out. The evolution of the drilling thrust over material hardness ratio allows to distinguishing two material sets. The first set concerns the major part of the materials on which a constant drilling thrust over hardness ratio is observed. That confirms the proportionality between drilling thrust and hardness. The second set concerns all globulized and austenitic steels for which one observes drilling

thrust over hardness ratio increases when the hardness decreases. The study of the chip morphology allows us to demonstrate that during the drilling test, the behavior of the first material set is more brittle than that of the second one. Moreover, the microhardness achieved from chips, shows that the higher the increase of hardness between basic material and chip, the higher the ratio between the drilling thrust and the hardness. For very ductile materials, results show that the hardness is not the most influential parameter for the cutting forces. For these materials, the increase of the dissipated energy during the chip plastic deformation, explains the increase of the drilling thrust over hardness ratio when the hardness decreases. On the other hand, for the more brittle materials, the chip formation requires low energy and the ratio between the drilling thrust and the hardness remains coarsely constant regardless of the material hardness.

Keywords: Drilling test, Treated steels, Hardness, Ductility.

Effects of Foreign Object Damage on High-Cycle Fatigue Life of Ti-6Al-4V

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High cycle fatigue (HCF) related failures are the primary cause of major engine failures in the commercial airlines as well by military air fleet. This type of damage is important to the designers and maintainers of aircraft engines since the design methodology of blades presently lacks sufficient understanding to predict the HCF life of a turbine blade after suffering FOD. To establish engineering based criteria for these decisions, a scientific knowledge is needed about the relationship between FOD and the fatigue life under HCF conditions.

This study is a step in this direction where a hybrid experimental-numerical approach was used. Laboratory specimens were tested to establish their HCF behavior after suffering initial damage representative of FOD, and these experimental conditions were modeled numerically. The test material was the titanium alloy Ti-6Al-4V. The damage simulation technique involved a quasi-static, displacement controlled indentation of the specimens with chisel-pointed tools made with various profiles to create different shapes of damage. This technique has advantages in its cost and ability to control the depth and shape of damage.

The high cycle fatigue behavior of the damaged specimens was established by testing these specimens. The fatigue strength needed to cause failure at a life of 107 cycles was measured. An electromagnetic shaker was used to fatigue the specimens at 350 Hz. These HCF tests were used to generate Haigh diagram for a fatigue life of 107 cycles. Specimens were examined by various fractographic techniques to record the size and shape of the damaged region and the location of the crack initiation sites. Three-dimensional nonlinear finite element method was used to estimate the plastic zone and residual stresses around the FOD in the vicinity of the FOD which were then used to explain the reduction in the high cycle fatigue life due to FOD.

Thermography Detection on the Fatigue Behavior of Reactor Pressure Vessel Steels

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Fatigue experiments on reactor pressure vessel steels were conducted using an advanced electrohydraulic machine, which has a frequency range from approximately 1 Hz to 1,000 Hz. Increasing the test frequency from 10 Hz to 1,000 Hz will increase the specimen temperature, which, in turn, will decrease the fatigue life.

A high-speed and high-sensitivity thermographic infrared (IR) imaging system h as been used for nondestructive evaluation of temperature evolutions during fatigue testing of steels. The temperature sensitivity of the camera is 0.015°C at 23°C.

Five stages of specimen temperature evolutions were observed during fatigue testing: an initial increase of the mean temperature of the test sample, a followed decrease of the temperature, an equilibrium (steady-state) temperature region, an abrupt increase of temperature before final failure, and the final drop of the temperature following the specimen failure. The measurements of temperature oscillations within each fatigue cycle at 20 Hz have been attempted. During each fatigue cycle, the specimen temperature was detected to oscillate within approximately

0.5°C depending on the loading conditions and test materials.

A theoretical framework was attempted to predict temperature evolutions based on thermoelastic and inelastic effects, and heat-conduction models. Temperature oscillation during fatigue resulted from the thermoelastic effects, while the increase in the mean temperature derived from the inelastic behavior of the materials. The predicted temperature evolutions during fatigue were found to be in good agreement with the thermographic results measured by the advanced high-speed and high-sensitivity IR camera. The temperature profile along the specimen gage length during low-cycle fatigue was also predicted. Furthermore, fatigue testing on specimens with different geometries has been compared. The differences of temperature evolutions from these tests are normalized by theoretical modeling.

Discrete Modeling of Transformation Toughening in Heterogeneous Materials

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In recent years, there has been an increasing demand for the development of lightweight, high temperature structural materials in industry. However, the use of such materials is currently limited by their low room-temperature ductility and fracture toughness. It is well known that the fracture toughness of materials can be enhanced by stress-induced martensitic transformation mechanisms. When the particles are surrounded by a growing crack, the high stress concentration will trigger the transformation of particles near the tip. As the crack grows, a zone of transformed particles develops around the crack tip and induces a crack closure.

In this work, a hybrid finite element approach to discrete modeling of the transformation toughening mechanism is presented. As opposed to the continuum approach, detailed microstructural features including individual particle size and distribution are incorporated into the discrete model. Based on thermodynamics, size dependent critical stresses required for transformation of the particles are evaluated. These are then utilized in the numerical analysis. The model utilizes a local transformation criterion that includes the influences of particle interaction and residual stresses in order to predict the process zone evolution and resistance-curve behavior. The transformation height, distribution of the transformed particles, and transformation toughening are predicted as a function of crack propagation through an iterative numerical procedure. The results obtained from the numerical analyses are compared with resistance-curve obtained from experiments conducted on a model nickel aluminide composite reinforced with yttria-stabilized zirconia particles. The numerical predictions are shown to be an excellent agreement with the measured resistance-curve when the actual particle distributions are modeled.

A Rate and Damage Dependent Constitutive Relation for Polymers at Strain Rates from 10^{-4} to 10^{-3} s^{-1}

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Using the Split-Hopkinson-Pressure-Bar (SHPB) technique and a Back-Propagation (BP) Neural Network program, the rate-dependent constitutive relation at finite deformation and in a wide range of strain-rates from 10-4 to 103 s-1 were investigated in the authors' laboratory in the recent 15 years. It was found that for a variety of engineering plastics and polymer-matrix-composites the nonlinear dynamic viscoelastic constitutive response could be well described by the so-called Zhu-Wang-Tang (ZWT) nonlinear thermo-viscoelastic constitutive equation [1] by taking account of damage evolution.

Based on the main results obtained, the following characters are emphasized in the present paper. (1) The physical or constitutive non-linearity comes from the pure elastic equilibrium response, while all the rate/time dependent responses are essentially linear and consequently can be still described by linear viscoelastic elements even when the apparent, overall response is nonlinear, if strain is less than about 7%. (2) At high strain rates the total dynamic response, in fact, consists of a rate independent nonlinear elastic response and a high-frequency linear viscoelastic response. The dispersion and attenuation of nonlinear viscoelastic waves thus mainly depend on the effective nonlinear elasticity and the high-frequency relaxation time of materials. Correspondingly, an "effective influence distance/time" is defined to characterize the rate-dependent wave propagation domain. (3) With increase of strain, for example if strain is larger than about 7%, the internal damage evolution accompanied with the deformation

process of polymers should be taken into account. Correspondingly, a damage modified ZWT nonlinear thermo-viscoelastic constitutive equation is proposed.

Keywords: Nonlinear viscoelastic constitutive model, polymers, high strain rates, damage evolution

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Use of Resolved Shear Stress Criteria in Design Applications Involving Material Damping Under Combined Stresses

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Resolved shear stress cumulative probability functions developed by S.G. Cupschalk for random polycrystalline metals and alloys have been applied to Lazan's method by means of which simple laboratory tests can be used in determining the contribution of materials to the observed damping of vibrations in structures and components. The overall problem is considered at three levels. First the damping behavior of actual components and specimens is determined under service conditions where, in general, the stress is not uniform. Next, damping is calculated for the same components assuming that they are subjected to a homogeneous cyclic stress which is equal to the maximum applied shear stress. Lastly, the material's damping characteristics are determined based on an assumed homogeneous cyclic resolved shear stress that is equal to the component's maximum applied shear stress. Lazan's procedure for obtaining information concerned with the second level has been modified so that it is based on the weighted average of damping values within regions of the specimen rather than on the simple average of such parameters at the boundaries of these regions. The third level is common to all cyclic states of stress having a zero mean stress, and thus its presentation constitutes a "master curve." It can be related to theoretical treatments of damping associated with microscopic dislocation theory which are based upon resolved shear stress criteria. Numerical procedures have been developed which enable transformations to be performed among these three levels. These are then applied, sequentially, to demonstrate that inverse torsion pendulum results obtained from wire specimens, which only involve cyclic shear stresses, can be utilized in predicting the damping behavior of axially loaded members, within which the alternating stresses are tensile and compressive in nature. Also, as long as the mean stress is zero, a method is outlined whereby master curve information can be used to calculate the damping characteristics of engineering components that are subjected to a variety of realistic cyclic loading conditions.

Keywords: Damping, Design, Resolved Shear Stress

SESSION R4G
MATERIAL BEHAVIOR V

Optimization of a Materials Microstructure through Microstructure Sensitive Design

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Microstructure Sensitive Design (MSD) provides a mathematical framework within which a materials microstructure can be expressed in a spectral representation along with processing routes and material properties. Once the relevant mechanics are chosen for particular design requirements, the full range of material properties given the design constraints can be explored using optimization techniques. A solution set of microstructure families can be identified along with processing routes that allow one to reach a particular solution within this set of design solutions. The entire optimization process including the microstructure, the processing, and the property constraints takes place in the Fourier design space defined by the spectral representation. The method is particularly useful when considering the anisotropy of a material. Single crystal and polycrystalline solutions are automatically considered and the solution with the simplest processing will be chosen. Especially in cases where multiple material properties are considered, a polycrystalline microstructure may yield the best properties for the design objectives. Recent applications of MSD include a stress concentration problem where the stress concentration around a hole in a flat Nickel plate was reduced from 3 for the isotropic case to around 2.5 using rolling and annealing processes. A significant increase in the applied stress is allowed by the rolled and annealed material.

Keywords: Microstructure, Optimization, Anisotropy, Design.

Effect of Geometric Distribution on Cellular Solids

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Mechanical properties of cellular solids not only depend on the properties of the cell wall but also the topological structures of the cells. Typical mechanical relations are established in terms of porosity and other characteristics. For open-cell metal foams, Young's modulus and the plateau stress after yielding are approximated[1,2]

$$\frac{E}{E_s} \approx \alpha_1 \left(\frac{\rho}{\rho_s}\right)^n, \ \sigma_{pl} \approx \alpha_2 \sigma_{y,s} \left(\frac{\rho}{\rho_s}\right)^m$$

where subscript s denotes properties of the solid which builds up the foam, E is Young's modulus, ρ the density, σ_{pl} the plateau stress, σ_y the yielding stress, n, m, α_1 and α_2 are constants depending on the structure of the foam.

A question arises here is how these constants depend on the structures. In addition to the variation in topological structures like rectangular prisms and tetrakaidecahedra, statistical distribution of geometry characteristics should also play an important part. Results by Miyoshi et al[3] suggest that reducing the cell size and increasing the aspect ratio of the cell wall thickness against the cell edge length will affect the stress-strain relation of metal foams, even though the porosity is kept identical. Assuming similar topological structures, studies on regularly arranged cellular solids also show that there are two crucial parameters: one is the cell size, and another is the aspect ratio. Here we study the effect of the distribution of these two parameters. A 2D model is proposed to examine the effect on Young's modulus. The result shows that the error is less than 5% for normal distribution. Impact tests are carried out on two ALPORAS samples with similar cell size. These tests also show the effect of the distribution of these two parameters.

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Keywords: cellular solids, microstructure, statistical distribution, impact

Modeling the Variability in Strength in a Turbine Disk

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The development of new structural materials for commercial aerospace applications currently requires extensive experimental design and testing for certification and qualification. One of the key characterizations centers on the material strength behavior. Specifically, an accurate and reproducible description of the stress - strain behavior is critical for engineering design. Because multiple intrinsic variations exist in the production of engineering materials, variability in material properties, particularly strength, is exhibited as well. The resulting variability has been well characterized for production grade materials. Far too often, however, the characterization has been empirically and experientially based. It is no longer economically or developmentally feasible to emulate past practices for the insertion of new structural materials into high reliability engineering applications. The purpose of this paper is to demonstrate the need for mechanistically based probability modeling of structural materials for current and future applications. The efficacy and value of this approach is illustrated by considering a typical material used in turbine disks. The model, based on simple first principles, will highlight the critical material variables and the effect of their variability on strength. The accuracy of the model will be demonstrated by comparison with an extensive set of production data. Adaptation of this approach to the analysis of materials aging and reliability of other engineered structures will be discussed.

Keywords: mechanistically based probability modeling; variability in material properties; characterization of material strength

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Modeling Recrystallization and Grain Growth in 304L Steel

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A model for recrystallization and grain growth is incorporated into the elasto-viscoplasticity theory of Bammann, Chiesa, and Johnson. Grain size and volume fraction of recrystallized material are added as variables, and evolution equations are provided for each. The original theory also includes an isotropic hardening variable to represent the statistically stored dislocation density. Recrystallization is initiated when the stored energy reaches a critical value that depends on temperature. A softening term is added to the evolution equation for the isotropic hardening variable to represent the decrease in dislocation density that occurs during recrystallization. The term is derived from the kinetics of recrystallization, as described by an Avrami-type evolution equation for the recrystallized volume fraction. Grain size effects are included in the initial yield strength and in the hardening behavior of the isotropic hardening variable. Grain growth has a temperature dependence based on Arrhenius kinetics, and grain refinement is activated at the onset of recrystallization.

The theory is implemented into a finite element code to model the multistage forging process. Material parameters are fit to monotonic compression data for 304L steel for a wide range of temperatures and strain rates. These parameters lead to good results when modeling multistage experiments. Microstructural analysis is also used to validate the model. The three-dimensional internal state variable theory is not restricted to uniaxial or isothermal loading conditions. Future versions of the model will incorporate a misorientation variable to represent the geometrically necessary boundaries that form during large deformations.

Keywords: recrystallization, modeling, plasticity, microstructure, steel

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Kinetic Theory For Granular Flow: Effect of Unequal Granular Temperature on Pressure and Viscosity

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Kinetic theory for particles of the same mass and the same granular temperature is well established. However, kinetic theory for particles of different mass and different granular temperature is yet to be established. In this paper we re-derived the equations of solids pressure and particulate viscosity for a binary granular mixture with unequal granular temperature. Here particles are taken as of different size and density. The results indicate significant discrepancies when compared with the theory that is derived by assuming particles of equal mass and equal granular temperature.

SESSION M2N
MATERIAL MODELING AND OPTIMIZATION

Strain Energy Based Homogenization of Elastic Two-dimensional Model Foams at Finite Strain

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Solid foams gain increasing importance in lightweight construction. While the elastic behavior of metal foams is restricted to the small strain regime, non-metallic and elastomeric foams might be subject to large elastic strains. For reasons of numerical efficiency, the analysis of foamed structural components in all cases is preferrably performed in terms of homogenized effective properties rather than by a direct model of the microstructure. The present study is concerned with a general strain energy based concept for homogenization of hyperelastic microheterogeneous solids at finite strain. Within this concept, the macroscopic mechanical equivalence of a representative volume element (RVE) for the given microstructure

and a corresponding volume element consisting of the homogeneous effective medium is assumed, if the strain energy in both volume elements is equal, provided that the deformation gradient for both elements is equal in a volume average sense. To determine the effective stress state, the RVE is deformed according to a given effective strain state and the volume average of the strain energy density is computed. Subsequently, the components of the second Piola-Kirchhoff stress tensor are determined by partial differentiation of the average strain energy density with respect to the components of the Green-Lagrange strain tensor. As a structural example, a two-dimensional model foam under uniaxial as well as biaxial and shear strain states is considered. The microstructure is idealized by a periodic array of hexagonal cells. The dependence of the effective stress components on the microstructure is investigated in detail. The study is closed by a discussion of the effect of cell irregularity which is included by introduction of a RVE consisting of a patch of multiple basic cells with randomized positions of the cell wall intersections.

Keywords: Micromechanics, Homogenization, Solid foams, Hyperelasticity

A Variational Model of Precipitate Growth under the Influence of Elastic Strain

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A continuum variational model has been developed to model microstructural evolution in precipitate systems within which elastic strain plays a significant role. The variational framework readily allows for the incorporation of a number of different competing kinetic processes and thermodynamic driving forces into a numerical model without geometrical restrictions. The driving forces considered here arise from compositional variations, interfacial energy, phase transformations and changes of elastic stored energy. The kinetic processes are lattice diffusion and interface migration.

The model is used to study the precipitation kinetics in steels with particular reference to the evolution of a ferrite precipitate embedded within an austenite matrix and the coarsening of M23C6 precipitate particles. Two-dimensional computational results are presented within this context.

Optimal Shape Design of Cooling Fins with Varying Conductivity Parameters

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Naturally occurring shapes are not simple. Organisms modify their shapes in an attempt to satisfy competing constraints with the objective of increasing survival, while inorganic matter finds shapes that minimize potential energy. Our ability to design better performance devices has not benefited enough from the inspiration offered by the natural structures and shapes. One impediment in designing better shapes is the numerical methods used to model problems in shape optimization of solids.

The Finite Element Method (FEM) has been the usual choice for treating shape optimization problems based on sensitivity analysis and gradient methods. Recent studies [1, 2], however, have shown that in optimization of cooling fins, a meshfree method can provide new solutions that are with at least 50% more efficient that those obtained with the FEM [3]. Moreover, these novel solutions are obtained without remeshing that is normally needed in an FEM discretization when large shape changes occur in the design process.

Area and stress constraints are imposed and the objective is to increase the heat-flux through the base of the thermal fin. Our study uses the element-free Galerkin method for solving the thermoelastic problem posed at every iteration of the nonlinear optimization process. For a constant conductivity parameter used for the conductive boundaries we discover finger-type shapes that were missed by the FEM analysis. The number of fingers, however, increases as more design variables are used [2]. In the present study we consider a varying conductivity parameter. The conductivity parameter changes with position and the orientation of the exposed surface. The thermal boundary layer that forms imposes constraints on the closeness of two adjacent fingers for optimal heat convection. We show that the use of varying conductivity coefficient prevents fingers from being generated too close to one another and thus their number does not increase unlimited with the increase in the number of design variables. Ways to generate additional sets of design variables to capture secondary features similar to tree leaves are also discussed.

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Keywords: thermoelasticity, shape optimization, meshless methods, cooling fins.

Enhancing the Optimization of Composite Structures using Gradient Architectures

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Many structural components encounter service conditions and hence, required materials performance, which vary from location to location within the component. It is now well known that abrupt transitions in material compositions and properties within a component often result in sharp local concentration of stress, whether the stress is internal or applied externally, which compromise structural integrity. It is also known that the stresses concentrations are greatly reduced if the transition from one material to the other is made gradual. This has led to the concept of Functionally Graded Materials (FGMs), which has been the subject of considerable research interest over the past decade. By definition, FGMs are used to produce components featuring a gradual transition in the microstructure and/or composition, the presence of which is motivated by functional performance requirements that vary with the location within the part. With FGMs, these requirements are met in a manner that optimizes the overall performance of the component, and can be easily employed for the design of composite structures. However, structural optimization techniques, such as the homogenization method, have yet to take full advantage of FGM concepts. Many of these structural optimization techniques employ robust mathematical techniques, such as Genetic Algorithms, to solve the structural optimization problem by performing searches over the complete design space. Using gradient architectures, it will be demonstrated that the Genetic Algorithms can be enhanced by substantially reducing the computational effort through the constraint that gradient architectures place on the search that is performed for optimizing the thermomechanical performance of composite structures.

An Integrated Approch of Sensitivity Analysis Applied on Elastic Structure

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Although mathematical programming has proved a popular means of improving structural optimization it is limited by the fact that the problems of structural optimization are usually nonlinear with implicit algebraic structure and it requires a long procedure of numerical operations. Moreover, mathematical programming needs usually numerous iterations. Therefore the efficiency of optimization algorithm depends strongly on the method of sensitivity analysis. In this paper we focus on the elastic behavior of structure and present a method of sensitivity analysis. This algorithm is based on an especial kind of convex, quadratic and separable approximation of the functions. The approximation of each constraint will be effectuated at the intersection of its boundary and a line directed from the origin to the point of approximation(scaling line). The approximation is only applied on the curvature and could be conservative. The structural response and the first and second derivatives of stress and displacement constraints could be evaluated on the scaling line without additional structural analysis. Using this advantage and integrating it with the quadratic approximation of the related functions, it provides an efficient approch of sensitivity analysis for structural optimization. Choosing the coefficients of curvatures non-negative and conveniently, the approximated function will be convex, quadratic and separable and the related substitutive problem could be resolved using lagrangian and a quasi Newton method. The condition of feasibility of approximated problem requires some limitation on coefficient of curvature. The efficiency of the proposed strategy is illustrated through several applications.

Keywords: sensitivity analysis, optimization, optimum design, structural optimization

Airframe Structural Design for Reliability and Robustness

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Quantifying the design parameters of a structural component in a manufacturing environment or its material properties or the operating conditions with complete confidence is difficult or sometimes impossible. However, a designer can claim with complete confidence that the design parameters and operating environment are not deterministic in nature. Therefore, design optimization without including uncertainty would result in potentially high-risk designs because the design point is usually located on active constraints that can easily be violated due to the variance in the design parameters. Traditionally the risk involved in this type of design process was handled by using safety factors generating non-optimal products without any insight into the uncertainties involved in the design.

In the literature, one can find many different methods for uncertainty quantification in design. Even though different communities have approached uncertainty quantification in different ways, the "goal" of all these techniques is to produce robust and reliable products. While probabilistic methods focus on estimating the level of safety of a particular response, the robust design methods focus on minimizing the variance in the response. In recent years, the "Design For Six Sigma" concepts have become more popular and this is the current field of interest in the industry. This procedure does not involve any design process but it investigates multiple designs and selects a design that produces minimum variance for the response subject to variation in the input. However, an optimization procedure that minimizes/maximizes a performance criterion subject to various constraints and bounds that are formulated using the probability theory and robust design principles would produce highly reliable and robust designs.

This paper presents an idea where the design is optimized for reliability and robustness. This procedure optimizes the response to a particular level of quality, measured by the number of standard deviations, selected by the designer. Various numerical examples would be provided to demonstrate the procedure and present the usefulness of the concept. A deterministic optimization solution would be used to discuss the potential risk involved in such designs. And finally a safety factor based example would also be provided to show how the products are over-designed using this procedure.

SESSION F2A
MATHEMATICAL ANALYSIS OF CONTINUUA I

Semigroups and some Nonlinear Fractional Differential Equations

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Equations of the form

$$\frac{d^{\alpha}u(t)}{dt^{\alpha}} = Au(t) + f(t, B_1(t)u(t), ..., B_r(t)u(t)),$$

are considered, where $0 < \alpha \leq 1$, A is a closed linear operator defined on a dense set in a Banach space E into E, $\{B_i(t), i = 1, ..., r, t \geq 0\}$ is a family of linear closed operators defined on dense sets in E into E and f is a given abstract nonlinear function defined on $[0, T] \times E^r$ with values in E, $T > 0$. It is assumed that A generates an analytic semigroup. Under suitable conditions on the family of operators $\{B_i(t) : i = 1, ..., r, t \geq 0\}$ and on f, we study the existence and uniqueness of the solution of the Cauchy problem for the considered equation. Some properties concerning the stability of solutions are obtained. We also give an application for nonlinear partial differential equations of fractional orders.

Green's Functions for Steady-state Heat Transfer and Elastostatics in an Exponentially Graded Solid

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Functionally graded materials (FGMs) are designed with spatial variations in elastic, thermal, magnetic, or optical properties for optimal performance. Some examples of FGMs are thermal barrier coatings, bone implants, piezoelectric sensors, and graded optical index components. Combinatorial materials are also graded solids that are used for exploration of novel combinations of materials. In this talk, Green's functions will be developed for both steady-state heat transfer and elastostatic problems

in FGMs. Both isotropic and anisotropic solids will be considered. We will consider exponential variations in either the thermal conductivity or elastic stiffnesses. For example, the anisotropic thermal conductivities are taken as $k_{ij} = exp(\beta_m x_m)K_{ij}$ where the K_{ij} and the β_m are constant.

Examples of numerical simulations with the developed Green's functions will be shown using the Method of Fundamental Solutions. Results for steady-state heat transfer in isotropic and anisotropic FGMs will be presented, and some recent results on an inverse problem in a graded material will be shown.

An Efficient Reformulation of Duhamel's Integral to Reduce Execution Time

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In time history dynamic analysis of structures, one approach is to employ Duhamel's integral. The draw back of this integral is that its lower bound is zero and for each time step, the integral needs to be evaluated in the domain from zero up to that specified time. This means that for loads with large number of time steps, a large number of intervals should be integrated which is time prohibitive. In this paper, a modified form of the Duhamel's integral is proposed in which for each time step the last time interval is integrated, therefore, it is considerably faster than its original form. In this formulation, at each time, in addition to displacement, velocity is also calculated and both independent variables are used as initial values for the next step. Then, the transient solution is written in terms of these initial values and for the steady state solution, Duhamel's integral is used and displacement and velocity for the next time step are calculated. The method proposes two integrals for displacements and the same two integrals for the velocity in one time step. Indeed, the total number of integration intervals is $n(n+1)/2$ in Duhamel's, while, the total integration intervals is 2n in the proposed method. The computational time in the proposed formulation is significantly less than Duhamel's integral, and the deviation of the computational time for Duhamel's integral compared to the proposed method becomes more significant with increased number of time steps with maintaining the same accuracy. The proposed method enunciates that the savings in the computational time becomes more obvious for MDOF systems due to the fact that the aforementioned saving is the multiple of the number of modes. Finally, numerical examples are presented and compared to Duhamel's method to show the superiority of the proposed formulation.

Analytical Solutions of a Degenerate Diffusion Equation

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Certain nonlinear diffusion equations of degenerate parabolic type display a finite speed of propagation of disturbances. This mathematical behavior can be used to describe a wide range of physical phenomena such as the penetration distance of a thermal layer, the boundary of a reaction zone, or a wetting front in unsaturated soil moisture flow. However, there are two main difficulties in obtaining solutions to problems of this class. One is that the location of the interface is not known a priori and must be discovered during the analysis. The other is the fact that the differential equation is singular in the neighborhood of the interface. The solution technique developed and presented in this work overcomes these difficulties by extracting a local solution of the differential equation in the neighborhood of the diffusion front. One profound result is the discovery that the velocity of the front is entirely controlled by the first term of the spectral series expansion. Also, by capturing the critical behavior of the solution in the region of the singularity and incorporating the behavior as a dominant factor, the series expansion is provided a means for very rapid convergence. The versatility of the solution technique is demonstrated by solving various boundary value problems covering a broad range of physical interest and testing the solutions against published results.

Keywords: Parabolic partial differential equations of degenerate type; analytic methods, singularities; heat equation

Coalescence Due to Gravitational Settling: The Universal Self-Similarity Velocity-Size Law

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A disperse system in which particles coalesce upon collisions because of their different settling velocities can be considered a model of rain. When the particle relaxation

time, τ_p, is much smaller than the average time between collisions, τ_c, the unique particle (settling) velocity-size law is essentially given by the applicable drag law. However, as the particle size increases, τ_p rapidly overgrows τ_c giving rise to the distribution of velocities for particles of the same size.

We have discovered a new *universal self-similarity velocity-size law* emerging for the large particles that grow by scavenging the small ones. We discuss the physical foundations of this law and its implications for modeling of coagulation due to gravitational settling. We compare our predictions with the results of the dynamical Monte Carlo simulations.

SESSION F3L
MATHEMATICAL ANALYSIS OF CONTINUUA II

On Telegraph Reaction Diffusion and Coupled Map Lattices in Some Biological Systems

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It is argued that telegraph equation is more suitable than ordinary diffusion equation in modelling reaction diffusion in biological, economic and social systems. Telegraph reaction diffusion (TRD) is studied in one and two spatial dimensions. Some exact and approximate resultes are optained. A coupled map lattice (CML) corresponding to the spatial prisoner's dilemma game is constructed and studied in the weak diffusion limit. A formula is derived for Lyapunov exponents and it is shown that periodic solutions are dence in the weak coupling regime and that this system is structurally stable.

Kinematic Analysis of Multibody System using the Tool of Multidimentional Matrices

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The features of application the tool of multidimensional matrices for numerical modeling of kinematics of large-dimension mechanical systems with a variable configuration and constraint structure have been considered. Modeling of such systems involves labor-consuming computations of the coefficients of matrix equations on cumbersome algorithms. Conventionally, a numerical, a computational tool based on the use of block matrices and relative indexing is applied when working with their elements.

A proposed algorithm based on multidimensional matrices enables a forward direct indexing when working with their elements. It considerably formalizes the procedures of setting up kinematics relations, their transforming when changing configuration of the system and structure of the constraints imposed. The procedures of forming and completing the multidimensional matrix describing the kinematics of the system, a procedure of operation with its different cross sections and procedures of convolutions have been developed.

The (4×4) transition matrices B_i from the basic sets tied with the i-th bodies to basic sets and their derivatives $\frac{\partial B_i}{\partial q_j}$ and $\frac{\partial^2 B_i}{\partial q_j \partial q_k}$ are conventionally used in kinematics equations

$$r_0 = B_i r_i,\ v_i = \sum_{j=1}^{i} \left(\frac{\partial B_i}{\partial q_j} r_i \right) \dot{q}_j,$$

$$w_i = \sum_{j=1}^{i} \left(\frac{\partial B_i}{\partial q_j} r_i \right) \ddot{q}_j + \sum_{j,k=1}^{i} \left(\frac{\partial^2 B_i}{\partial q_j \partial q_k} r_i \right) \dot{q}_j \dot{q}_k,$$

that determine dependence between generalized and Cartesian coordinates, velocities and accelerations of an arbitrary point of a chain of the bodies.

It is proposed to introduce the B_i, $\frac{\partial B_i}{\partial q_j}$, $\frac{\partial^2 B_i}{\partial q_j \partial q_k}$ elements into the five-dimensional multidimensional matrix C.

Kinematics relationships for the n-bodies chain are derived using operations on the multidimensional matrices. The initial equation given is correspondent to the expression $r_0 =^{2,0} \{C^{\bar{l}_3=i,\bar{l}_4=\bar{l}_5=n+1} r_i\}$, thus enabling to carry out computations using a convolution of a three-fold section of the (l_3, l_4, l_5) orientation of the multidimensional matrix C and the vector r_i. The velocities and accelerations are computed similarly.

The introduced form of writing the kinematics equations enables reducing the amount of program supply by using a direct indexing in numerical modeling. The complexity of reading the programs has been reduced. An access to the models of specific motion due to change in the structure of constraints in the system becomes easier. The models are considerably formalized. The ways of visualization are considered when working with the multidimensional matrices in kinematics analysis.

Keywords: multibody system, kinematic analysis, nu-

merical modeling of kinematics, multidimensional matrix.

Description of Structure of Multibody Mechanical System by the Tool of Multidimensional Matrices

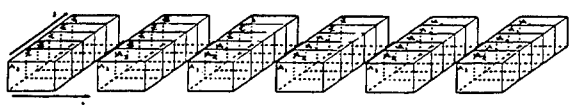
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Myltibody mechanical systems are characterized by mass-initial parameters of each body and topological features that show the rules of linking these bodies into a system. Topology is conventionally described using an oriented graph whose tops are bodies and ribs are hinges, in doing so the direction of the ribs points to the direction of referents when description of system kinematics chain. The graph constructed this way is described by the $(n \times n)$ incidence matrix with $\{0, +1, -1\}$ elements. Here, n is the number of bodies in the system. The conception "weighed oriented graph" implies that the tops and the ribs are assigned some certain relations combined with quantitative characteristics of the system. The 4×4 transition matrices A_i from the system of homogeneous coordinates combined with the i-th body to the system of homogeneous coordinates combined to the j-th body are assigned to the ribs as "weight".

It is proposed by a matrix equivalent of the "weighed oriented graph" assign to the multidimensional incidence matrix $C_{l_1 l_2 l_3 l_4}$. Its dimensions are $4 \times 4 \times n \times n$. A two-fold section of matrix $C_{l_1 l_2 l_3 l_4}$ of the (l_3, l_4) orientationwill be the transition matrix A_i. Let us denote this section by $C^{\bar{l}_3=i,\bar{l}_4=j}$. The $C^{\bar{l}_3=i,\bar{l}_4=j}$ section will: a) coincide with the matrix A_i if the element of the incidence matrix $+1$, i.e. a transition from i-th to j-th body is performed by a direct transition; b) coincide with the reverse matrix A_i^{-1} in case the element of the incidence matrix -1, i.e. a transition from i-th to j-th body is performed with a reverse transition; c) coincide with the unit matrix E, if there are no links between the bodies:

$$C^{\bar{l}_3=i,\bar{l}_4=j} = \begin{cases} A_i, \text{ if the element of the incidence matrix } +1, \\ A_i^{-1}, \text{ if the element of the incidence matrix } -1, \\ E, \text{ if the element of the incidence matrix } 0. \end{cases}$$



Multidimensional matrix of incidence of a Space Shuttle manipulator

Then, in kinematics equations $r_0 = B_i r_i$, where B_i is the transition matrix from the system of coordinates combined with the i-th body to the inertial system of coordinates, B_i is computed by a convolution of the multidimensional incidence matrix. For the Space Shuttle manipulator: $B_i = A_1 A_2 \ldots A_i$. The matrix B_i and its derivatives on generalized coordinates are used in equations of kinematics & dynamics. The introduced presentation form of equations using the multidimensional incidence matrix are allowed the use forward indexing when working with the elements of matrices for computational modeling. The amount of program supply is reduced. The complexity of reading the programs is reduced. Formation of models of specific motion when changing the structure of constraints in the system becomes simple. Formation of the models are considerably formalized. The methods of visualization when working with multidimensional matrix are considered.

Keywords: multibody system, multidimensional matrices, incidence matrix.

Elastic Modulus and Distribution of Local Loads over the Amorphous Sections of Macromolecules in Oriented Crystalline Polymer

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In this work we make an attempt on the base of measurable structural and deformation parameters to estimate the distribution of the local loads on the passing macromolecular amorphous sections of an oriented crystalline polymer . Having defined the sizes and the distribution of supermolecular elements (e.g. of crystalline and amorphous regions) and of passing chains over lengths and conformation structure, having measured the deformation curve and having calculated with help of the curve the elasticity modulus one could find the local load on the chains (or sections) and correspondingly overstrain coefficients.

If the conformation straightening of some part of strained passing chains has taken place, further stretching of the polymer leads to the considerable increasing of the elasticity modulus. Since the value of deformation in tension modulus of macromolecules being in transconformation state is high even when the concentration of such a type of the passing sections is relatively low, then they give remarkable contribution in the elasticity modulus of the sample. Since straightened regions can be considerably loaded then one should take into account the stretching of the chains in the crystalline regions.

Using the kink model of Frenkel-Kontorova's the stress of a chain in long enough crystallits of simple polymer type of linear polyethylene it has been found.

One can find by number computation relationship between molecular structural parameters for the passing chains and elasticity modulus of the polymer sample.

The Distribution Functions of Atoms Escaped from the Surface of the Condensed Phase

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The paper describes the distribution functions of atoms escaped from the surface of the condensed phase by velocities in the Knudsen layer depending on the type of the distribution functions of atoms by velocities in the condensed phase. It has been found that the distribution functions of atoms that have already overcome the potential barrier on the surface of the condensed phase differ from the equilibrium distribution functions of atoms in the condensed phase.

The average values of velocities, energies and z - components of atoms escaped from the surface of the condensed phase depending on the condensed phase parameters, i.e. the temperature of the condensed phase T and the value of the atom connection energy with the surface of the condensed phase U have been obtained. Some obtained results happened to be dependent on dimensionless parameter r=U/kT. It has been found that the values of average velocities and energies in the Knudsen layer exceed similar values in the condensed phase. The formula which is different from the exponential dependence has been obtained for defining the probability of atom escape from the surface of the condensed phase.

The results of theoretical calculations are proved by computer experiments during which Monte Carlo direct method was used. The simulation of 10000000 atoms escape was made for definite parameters of the temperature and the potential barrier.

The angular distributions of escaped atoms for different parameter values of the condensed phase have been obtained. When r=0, the angular distribution of escaped atoms is equiprobable, and when $r \to \infty$ it obeys the law of cosines.

The range of parameter values of the condensed phase for the position of the maximum point of the specific power of the redundant heat flow and impulse from the surface of the condensed phase has been determined. Maximal values are within the range of (0.35;0.38).

The results obtained allowed to explain the decrease in temperature on the surface of the condensed phase during the substance evaporation and some other experimental phenomena. Our computer experiments enabled a new approach to explaining the evaporation process from a microscopic point of view. The way we solve the evaporation problem can be transferred by analogy to other physical processes connected with overcoming the potential barriers, i.e. ions escape from melts, electron thermoemission, atoms escape from relativistic space objects.

On the basis of the results obtained one can create qualitatively new methods of sub-stance distribution, to determine 'true' energy magnitudes of connections with the surface of the condensed phase. By choosing proper substances and temperatures one can create in installations optimal heat mass transfer regimes.

Distance, Size, Volume, Speed, Mass, Energy, Universe are Relative

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Since distance is relative as stated in Einstein's Relativity, then anything moving is in fact shrinking relative to someone else's frame of reference. The concept of relative distance brings a distance dilation process in which speed can be seen as a rate at which objects shrink instead of a rate at which a distance is covered. A meter on the Earth is different from a meter closer to the Sun or a meter in a Black Hole. Therefore it is more logical to talk about shrinking distances. Since distance is relative, there is no very large or very small. There are no infinities and no two theories to be united in order to find a Theory of Everything. The stars are the same thing as atoms. One only appear larger or smaller from our relative point of view. Since both distance and time are relative, any calculations using these variables will bring relative results. We calculate speed by calculating how much relative time it takes for an object to cross a certain relative distance. Therefore the speed of that object is relative and is different for two observers moving at different speed. The speed of light is not a limit and is not constant. If mass is relative from our point of view, then mass will be different depending on your frame of reference. So it is impossible from what we see to establish a correct model of the universe. The only model of the universe we will be able to draw will be a theoretical one. There is equivalence between energy and mass, but it does not mean they are interchangeable and the same thing. This brings new configurations of the universe depending on your speed, making the universe relative and making quantum mechanics applicable to the very large. Relativity proves that the very large is the very small and that Quantum Mechanics is the only thing applicable to the very large and the very small.

SESSION M2O
METAL WORKING AND METALLURGY

Penalty Formulation of Upper Bound Elemental Technique for Shape Rolling of Super Alloy Rings

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The seamless profile ring rolling process offers the designer a unique product with number of advantages over the other methods of manufacturing ring products. Optimization of the profile ring rolling process by simulation techniques can greatly reduce the cost associated with trial-and-error experimental approach which may results in re-machining the rolls and increase in material cost. Complex three dimensional nature of ring rolling deformation and the massive computational time required for simulations usually forces the researchers to develop alternative approaches. These approaches, known as Quasi-3D or $2\frac{1}{2}$D methods, are aimed at reducing complexity of the problem hence down sizing the computational cost. Upper bound methods have made significant contributions in the modeling of complex deformation problems by simplifying the velocity fields associated with the deformation region. The complexity associated with the geometry makes it very difficult to formulate a single velocity field for the complete deformation region. A further step is proposed in this paper to investigate a penalty constant based Upper Bound Elemental Technique (UBET) for modeling deformation with complex three dimensional velocity fields. UBET divides the complex deformation region into elements with fairly simple velocity fields. These elements are assembled to form a system of nonlinear equations while maintaining the incompressibility condition of the plastic defamation with penalty constant formulation. This technique has been applied to the modeling of profile ring rolling process and the model predictions for profile filling, diameter growth, forces on the Mandrel and King rolls, and temperature distribution have been compared with the actual profile rolling data obtained from industry for two widely used super alloys, TI-6AL-4V and IN-718.

This work was funded by the National Center for Excellence in Metalworking Technology (NCEMT), operated by Concurrent Technologies Corporation (CTC), as part of the U.S. Navy MANTECH Program.

Measurement and Simulation of Temperature during Orthogonal Metal Cutting

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Metal cutting is and will remain one of the most important manufacturing technologies. Because of the highly nonlinear nature of metal cutting and the complex coupling between deformation and temperature fields, a complete mechanics understanding of the metal cutting process is still lacking. Finite element studies as well as earlier investigations based on slip-line theories have contributed a great deal to the understanding of mechanics of metal cutting. However, many questions, largely related to the input to such models, remain to be answered before the models can with confidence be used as process design tools.

Thus, instead of asking questions such as: "How can this mechanics problem be solved?" one might now ask: "What parameters should be used to best simulate this metal cutting process, given that the mechanics problem can be solved computationally?" Our hypothesis is that by closely coupling simulation to fine spatial and temporal scale experimental measurements of temperature and strain fields in the region of the cutting tool tip, along with macro scale measurements such as cutting forces, we can resolve questions related to the choice of parameters needed in finite element simulations of cutting.

Impact-Oscillator Model for Low Radial Immersion Milling

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When a machine tool works on a surface that has already been machined, as is usually the case in practical

metal-cutting operations, it is well known that, in many circumstances, the dynamic interaction of the tool with the wave left on the surface can cause the system to develop unstable vibrations. This type of self-excited tool oscillation is called regenerative chatter. Because chatter vibrations can cause poor surface finish on the workpiece and rapid tool wear, much work has been done on the modeling and analysis of the dynamics of regenerative chatter in machining. We have developed a theory for the study of chatter in highly interrupted machining operations. These operations are becoming more and more prevalent in modern manuacturing processes, such as the high-speed machining of contoured surfaces and difficult to machine materials, as well as finishing operations on flexible components. Our theory makes the useful prediction that, in comparison to full-immersion milling, there is a doubling in the number of optimally stable cutting speeds. We show that the predictions of the thoery are supported by experiment and numerical simulations.

SESSION R3D
MULTIPHASE AND SUSPENSION FLOWS

Revaluation of the Validity of Oseen's Approximation in Microhydrodynamics

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A new superposition method of Oseen's flow field around each solid particle or air-bubble,where the deformation of the air-bubbles is considered,is proposed here to estimate the hydrodynamic interaction among solid particles or air-bubbles at low Reynolds numbers below 0.5 in fluid flow. The experiment is carried out using a large glycerol tank and high-speed video-cameras with 10000 frames/s. Equal solid spheres located vertically with the same spacing at the initial time in a quiescent glycerol showed an interesting motion to make pairs of solid spheres from the preceding two solid spheres successively in turn. Equal-sized air-bubbles located vertically with the same spacing at the initial time showed the same motion as the motion of solid spheres, but in these pairs of air-bubbles the two air-bubbles contacted and coalesced finally. In the coalescent motion of two air-bubbles,there were recognized an occurrence of several micro-bubbles. During the approaching motion of two air-bubbles the shape of the preceding air-bubble became oblate, while the following air-bubble became prolate. The numerical results predicted by using the superposition method of Oseen's flow field agree well with the experimental results. It should be noted that these interesting motions are not predicted under the assumption of Stokes's approximation.

Keywords: Multiphase Flow, Solid Particle, Air-Bubble, Hydrodynamic Interaction

Blood flow in Small Curved Vessels

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Blood can be considered as homogeneous in large blood vessels, but in the microcirculation the rheology shows considerable non homogeneous behavior. Due to the particulate nature of red blood cells, there is an almost cell-free layer of plasma near the vessel wall. The major effect of this layer is to decrease the apparent viscosity or resistance, especially in the moderately smaller blood vessels. For vessels 50-1000 microns, the phenomenon can be adequately described by the two-fluid model. First proposed for general suspensions, the model assumes a homogeneous fluid core enclosed by a fluid annulus of lower viscosity. The theoretical derivation of the resistance formula of this model and its substantiation with blood flow data in small straight tubes are given.

On the other hand, in the microvasculature there are numerous instances where the blood vessels are curved or tortuous. The aim of this study is to investigate the effect of curvature on the wall shear and the resistance of the flow through a small curved tube.

The Stokes equation is written in Dean's curved tube coordinates for the two fluids and solved by perturbation in the small curvature parameter. The zeroth order velocity is a blunted parabola. The first order correction causes an increase in velocity (and thus shear) near the inner wall while the effect is opposite near the outer wall. The effect of the curvature of the vessel may increase or decrease the net flow rate through the second order velocity.

Keywords: Curved tube, blood flow, microvascular

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Hydrodynamic Model of the Guidance of Motion of Two-Phase Mixtures When Transported in Pipes

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A two-dimensional non-stationary pulsing flow of viscous two-phase medium in a round pipe with account of variability of volume concentrations of phases and transverse pressure gradient is considered in this paper on the basis of the model of interpenetrating motion of the mixtures.

The aim of this paper is to numerically study the characteristic peculiarities of dynamic behaviour of the parameters of mixture at pulsing mode of flow; and to state the criteria characterising the domains of expected optimal parameters of mixture transportation.

According to results of design it was stated that in the range of Womersley's frequency parameter for the first phase  1 = 1 4 the profiles of the phases have a parabolic form. Here in near-wall layers of the pipe an increase of volume content of transporting medium was observed.

In velocity change along the live section of the flow a determinant role is played by a dimensionless frequency parameter  i and hence a volume content of phases and tangent stresses on the wall are changed. This allows to consider  i as one of the basic criteria of non-stationary pulsing flow.

So with modulation of the gradient of the pressure (or expenditure) in wide range of the parameter  i it is possible to regulate the parameters of the flow from the point of view of its effective transportation.

It was stated that at  i  5 in near-wall domain of the pipe there appears a low-concentrated mixture, and in a core - a high-concentrated flow. The stated hydrodynamic effect provides an effective transportation of the mixture thanks to reduction of the friction force between an alien phase and the walls of the pipe.

Rising Bubbles Testing Water Contamination

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Bubbles of air or gas rise faster in pure than in even slightly impure water. The reason has long been known: small amounts of many impurities (surfactants) lower the surface tension by a large amount, but when a bubble moves, surfactant has to get onto it at the front and off at the rear. Diffusion and slowness of adsorption both imply that the front has a lower concentration of surfactant than the rear, and thus a higher surface tension, which opposes the motion. Smaller bubbles are more sensitive than large ones. It is also well known that many different experimenters used 'pure' water that slowed down bubbles of a given size by the same amount, as if they all had the same amount of the same impurity. Many years ago the speaker gave an order-of-magnitude analysis for bubbles large enough to have almost free surfaces, which suggested that the impurity might have been atmospheric carbon dioxide. Since then, enough computational work has been published for the idea to be tested quantitatively. The test is actually easier for nearly rigid than nearly free surfaces, and carbon dioxide now seems insufficient to account for the experimental results. The 50-year-old question of what did affect everyone's water in the same way therefore remains open.

Models for Stratification of a Sedimenting Suspension

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In a sedimenting suspension the variability of the settling velocity depends crucially on the spatial variations in the particle distribution. Large, container-size-dependent fluctuations in the sedimentation velocity are commonly found at the beginning of the sedimentation process due to fluctuations found in the initial particle density. As the suspension settles, the suspension stratifies and density fluctuations seek their own levels. Accordingly, velocity fluctuations decay and loose their dependence on the size of the container. We present and compare various theories for the transition from an initially homogeneous particle distribution to a stratified distribution. These theories are based on approximate dynamical models that emphasis the action of large collections of particles over large distances. The need for approximate dynamics arises from the complex nonlinear phenomena expected in sedimenting systems which certainly include Reyleigh-Taylor instability.

The approximate dynamics is intended to capture the effects of the strong nonlinearities inherent in the stratification processes without attempting to follow the details

of this complex dynamics. These theories all give qualitatively similar results for the time scale and effect of the stratification process.

SESSION M2H
PLASTICITY I

Microstructure Influence on Deformation and Failure Mechanism of Composite Tungsten

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Recent experiments have shown that the microstructures of tungsten heavy alloys (WHA), such as the shape and orientation of tungsten grains, have significant influence on the deformation and failure mechanism of WHA, especially on the initiation and development of adiabatic shear bands under impact conditions. Ballistic experiments have demonstrated that appropriate microstructures can result in self-sharpening effect induced by adiabatic shear band in WHA penetrator head and eventually enhance the ballistic performance of WHA penetrators. These motivated us to numerically study the microstructure influence on the initiation and development of adiabatic shear band in tungsten composites under dynamic loadings. The deformation mechanism of WHA blocks impacting rigid target and the penetration mechanism of WHA penetrators impacting thick 4340 steel target are investigated numerically in this presentation. The initiation and growth of shear bands in prismatic bodies of rectangular cross-section made of WHA in plane strain compression are also investigated. The simulations are performed with the ABAQUS and MSC/DYTRAN implemented with Johnson-Cook constitutive models. The material of the blocks and penetrators are modeled as a mixture of Fe-Ni-W elements interspersed periodically among the W-elements and several different distributions are considered. The simulation results show that the arrangements of weak matrix have significant influence on the initiation, development of adiabatic shear bands in WHA. For a fixed volume percentage of Fe-Ni-W particles, different distributions result in different deformation modes and patterns of shear bands.

Keywords: Tungsten heavy alloy, Adiabatic shear band, Penetration, Impact

Simulation of Plastic Strain Localization in Polycrystals

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Physical mesomechanics pays much attention to the influence of stresss concentration of various scale in the arising and development of the sites and zones of localized shear. The Relaxation element method[1] allowed one to connect the stress drop within the local region of the solid with the value of plastic deformation in it. Based on the relaxation element method and in combination with the boundary element method the computer model, allowing to analyze the influence of various factor, such as the number of sliding systems in crystallites, the influence of work-hardening and softening, the presence of inclusions on the development of the sites of localised plastic deformation was elaborated.

In the given paper it was analyzed the influence of the value of the coefficient of work hardening, the value of stress relaxation in crystallite, involved into plastic deformation and the influence of free edge on the patterns of the development of the sites of localized plastic deformation. The linear dependency for the crytical shear stress of a separate crystallite on the number of ist consequent involvement into plastic deformation was taken into consideration. The account for free edge was conducted by boundary element method, relieving the normal and tangential stresses at the edges of plane specimen. The results shown that on one hand increasing in the coefficient of work hardening results in attenuation of strain localization. On the other hand, increasing in the number of sliding system in each crystallie results in the inhancement of localization. Increasing in the value of stress relaxation in separate grain, involved into plastic deformation results in inhancement of the plastic strain localization. The physical principles, laid down in the model allow one to simulate and predict the development of the zones of localized plastic deformation which is in good agreement with experimental data.

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Thermomechanical Cyclic and Creep Loading Behavior of Pressure Vessels Under Kinematic Hardening

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Structures such as pressure vessels are required to operate under thermal and mechanical loading and fatigue conditions. Design of these structures is related to their response under these conditions. This work considers the cyclic plastic and creep behavior of a thick-walled sphere and a cylindrical pressure vessel subjected to cyclic pressure and/or temperature. We investigate the steady state behavior of the vessels using linear kinematic hardening in the plastic condition and Norton power law in the creep condition. Each loading cycle consists of four steps: Loading, Creep, Unloading and Creep. The analytical equations developed let us to calculate the final stresses and strains in these structures and a numerical program has been developed to calculate final stress-strain state. The load-controlled cyclic loading under Prager's kinematic hardening model including creep results in ratcheting behavior and deformation-controlled thermal stresses results in ratcheting behavior. Using Chaboche's nonlinear kinematic hardening model and return-map algorithm for a beam subjected to deformation or load-controlled cyclic loadings leads to the same results. Thus, with these conditions secondary stresses lead to the ratcheting in the same way as the primary stresses when creep is including.

Keywords: Pressure vessel, Cyclic plasticity, Creep strain, Ratcheting

Element-size Independent Analysis of Elasto-Plastic Damage Behaviors of Framed Structures

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The first author[1] derived the relation between the location of a numerical integration point and the position of occurrence of a plastic hinge in the linear Timoshenko beam element, considering the equivalence condition for the strain energy approximations of the finite element and the computational discontinuum mechanics model composed of rigid bars and connection springs. The computational method identified as the adaptively shifted integration technique [2],[3] (abbreviated to the ASI technique) was developed, based on this equivalence condition. The ASI technique, in which the plastic hinge can be formed at the exact position by adaptively shifting the position of a numerical integration point, gives accurate elasto-plastic solutions even by the modeling with the minimum number of elements.

In the present study, a new computational method is formulated for the elasto-plastic damage analysis of framed structures, based on the ASI technique for the linear Timoshenko beam element and the concept of continuum damage mechanics. The non-layered approach, in which the stress-strain relation is expressed in terms of the resultant forces and the corresponding generalized strains, is employed in order to reduce the computing time for the large-scale framed structures. A new form of damage evolution equation, which is expressed in terms of plastic relative rotational angles instead of plastic curvature changes, is proposed in order to remove the mesh-dependence of solutions in the damage analysis. The present method is applicable to the collapse analysis of framed structures including elasto-plasticity, damage initiation, its evolution and fracture. Numerical studies for simple frames are conducted to show accuracy, efficiency and the mesh-independence of the proposed method.

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Symmetry Limit Theory and Steady-state Limit Theory; A General Theory for Critical Behavior Prediction of Elasto-Plastic Structures under Cyclic Loading

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We present recent developments by the authors in a general theory for predicting the critical phenomena,

called the symmetry limit and the steady-state limit, observed in elastoplastic structures under quasi-static cyclic loading. The response of a beam-column under the cyclic loading with increasing amplitude in the presence of a compressive axial force can be classified as follows: (1) convergence to a symmetric steady state, (2) convergence to an asymmetric steady state, and (3) ratcheting, or divergent behavior. The symmetry limit bounds the first and second classes of the response. The steady-state limit bounds the second and third classes of the behavior. The focus of the presentation is placed on a proper treatment of the plastic shakedown in predicting the steady-state limit. For elastoplastic truss structures under quasi-static cyclic loading, a method is presented for finding the steady-state limit that bounds the plastic shakedown and ratcheting regions. In the plastic shakedown region, an assumption employed in the previous approaches can be invalid in many circumstances. Although strain reversals were assumed to occur only at load reversals, yielding of an element exhibiting the plastic shakedown may cause strain reversals in other elements. This difficulty is overcome by relaxing this assumption so that the strain reversals due to yielding are taken into account. Through numerical examples of two- and ten-bar truss structures, we demonstrate that the present method is capable of finding the steady-state limit between the plastic shakedown and ratchetting regions even when strong effects of geometrical nonlinearity exist. Extension to two- and three-dimensional solids is also discussed.

Keywords: Symmetry limit theory, Steady-state limit theory, Elastoplastic solids, Cyclic loading

SESSION T2H
PLASTICITY II

On the Method of Calculation of Complex Loading in Plasticity

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The investigations of strength and deformation of elastic plastic materials andconstructions at complex state of stress and under complex loading are connected with development of theory of complex loading. One of way for reaching this aim is development of Ilyushin's theory of processes. This way allows to solve plasticity problems with using of experiment's data on standard specimens. The using of theoretical experimental methods of investigations is actual matter. This is especially important at calculation of responsible structures and designs. For modern stay of investigations are characteristic also the search of ways of creation the theoretically and experimentally based equations of mechanical state of bodies for wide class of complex loading processes. All this investigations directed to more precise account in calculations the plastic properties of material and rational using them, improvement of designs' functional characteristics. But the development has to be following by development of applied engineering numerical methods with using recent advances in the theories. In this report offers to use the boundary element method's technique for calculation of plastic problems with taking into account a complex loading effects. Techniques of calculation of plastic bodies on the base of straight boundary elements method with using of Ilyushin's relation between stresses and strains are developed in the given work. As the realization of this method the calculation of bodies with stresses concentrations are accomplished and this results are compared with calculation by classical plasticity theories.

Keywords: Stress, strain, plasticity, complex loading.

Cyclic Loading and Accumulation of Damages of Carrying Elements of Thin-walled Constructions

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Elastic and plastic deformations under cyclic loading lead to arising of new qualitative effects which impossible to observe under unloading condition. Hereto possible concern the Baushinger's effect, arising secondary plastic deformations, changing the diagrams, cyclic hardening and softening properties and anisotropy, accumulation of damages etc. Take into account those properties allowed more effective to calculate on strength and deformability.

The analytical solution of series problems so as cylinder and sphere, braced with elastic thin-walled shell and conical tube included the secondary plastic deformations are presented in this work. Further, the stress-strained state of compound construction, consisting from cylindrical shell, connected with conical shell and annular plate; jack and reservoir under variable loading with take into account cyclical properties of materials are investigated.

Keywords: stress, strain, plasticity, cyclic loading

Computer Simulation of Plastic Strain Propagation at Localized Shear

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Some results of an investigation of plastic strain localization in metal at antisymmetric shear at impact loading are presented. The investigation was fulfilled using numerical simulation of plane strain in a thin layer of metal. A strain localization in its center was initiated as some nodes were with decreased (on 20%) yield stress. The developed Jonson-Cook's equation of state [1], that take into account viscosity effects, was used in the simulation: ó = óst + ìå, where óst is a stress of metal under static loading, ì is linear viscosity of metal, åis effective strain rate. The óst includes effects of strain hardening, thermal softening and linear viscosity. A nonlinear temperature dependence of shear modulus was also included in the computation. Propagation rate of plastic strain level along the layer depends on strain level and increases with distance from the initiate defect to the elastic shear wave velocity in metal.

Keywords: numerical simulation, simple shear, thin layer, impact loading.

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Multistage Deformation of Microcrystalline Al-Li Alloy under High Strain Rate Superplasticity

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The structure and phase states of rods subjected to the equal-channel angular (ECA) pressing under different conditions have been studied. A fine-grained structure has been shown to form in the process of pressing. The mechanical behavior has been studied for ECA-pressed samples having different structural states. Temperature and strain rate conditions to attain ultimate strains to failure have been defined for samples of each structural state. Mechanical behavior of the 1420 alloy has been studied under superplastic (SP) conditions. Three stages of SP deformation (SPD) have been shown. Dependencies of true strain rate on temperature, true stress and true strain for the deformation during hardening stage and stage of the monotonic decrease of true stress by increase of true strain have been established. The parameters, which characterize these stages of SPD have been determined. It has been shown that a strain up to 1900% may be attained in this alloy, and $n = 2$ and $m = 0.45$ for both stages. Structural behavior under SPD conditions has been studied. The data shows intra-grain slip during the hardening stage and dynamic recrystallization with participation of grain boundary sliding and grain boundary migration during the stage of the monotonic decrease of true stress have been obtained.

Keywords: high strain rate superplasticity.

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Structure - Kinetic Principle for Superplasticity of Solid States

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Mechanical and structural behavior at creep and superplasticity of amorphous cobalt alloy, micro-crystalline zinc- and aluminium-lithium alloys under tension and of coarse grain aluminium under torsion are discussed from unified positions. It is shown that realization of their uperplasticity requires fulfilment of structure-kinetic principle, in other words, necessity to create a sufficiently non-equilibrium dynamic structure, on the one hand, and kinetic conditions for the maximum manifestation of its dynamics, on the other hand.

Keywords: superplasticity, structure - kinetic principle.

The support of INTAS (project 1997-1243) and RFBR (project 01-02-16505) is greatly appreciated.

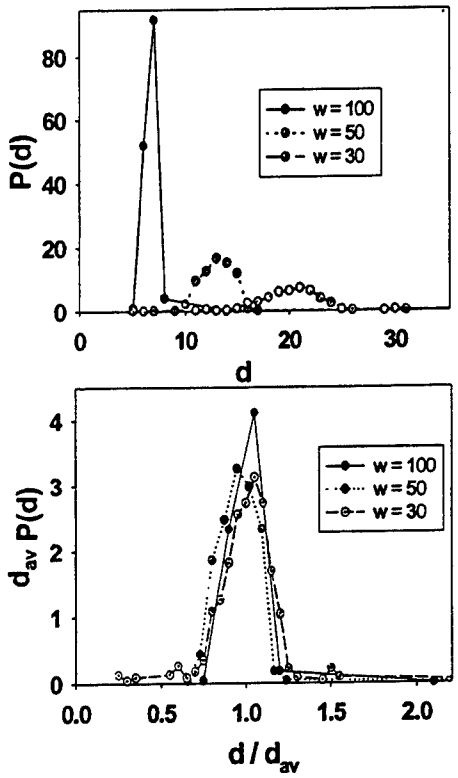
SESSION W2K
PLASTICITY III

Dislocation Patterning in Two Dimensions and Size Effects in Plasticity

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We carry out simulation studies of dislocation dynamics and patterning in two dimensions to identify fundamental mechanisms controlling the elastic-plastic response of crystalline solids at the mesoscale. In a simulation of screw dislocations under applied shear, we observe coalescence of slip bands and show that their spatial distribution has scaling behavior similar to that observed experimentally for geometrically necessary boundaries (GNB/s) in FCC metals.



Simulation studies of screw dislocations in 2-d. (a) Distribution of slip band spacing at three strain rates: (b) Scaling behavior is observed when the distribution is scaled by the characteristic length d_{av}, the average slip band spacing.

We also carry out simulations in geometries with imposed strain gradients with samples of varying size, and find evidence that mechanical properties depend systematically on sample size. We discuss the origin of these size effects and the emergence of a characteristic length scale in plastic response of crystalline solids.

Keywords: Dislocation patterning, slip bands, plasticity, size effects

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Investigation of the Low Plastic Strain Amplitude Cyclic Plasticity of Single Crystal Nickel

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Detailed results will be presented for reversed Tension-compression cycling of single crystal nickel, oriented for single slip at constant plastic strain amplitudes ranging between 50 microstrain and 4000 microstrain. Evaluation of cyclically saturated dislocation substructures using TEM and surface relief using optical microscopy of acetate replicas will be correlated with cyclically saturated response characteristics. Substructure evolution will be explored with interrupted tests at a plastic strain amplitude of and this will be used to infer connections between substructure evolution events and evolution of some response characteristics, including bulk Young's Modulus.

In addition to dislocation-based plasticity mechanisms, it will be shown that a significant component of inelastic strain at the lowest plastic strain amplitudes is due to reverse magnetostriction, arising from magnetic domain re-alignment in stress reversals.

Constitutive models will be presented for the lowest plastic strain amplitudes that link dislocation substructures to the slip system level response for the dislocation-based plasticity. These will be coupled to a model of the magnetostriction response that assumes magnetic domain rotation toward the crystallographic "easy direction" closest to the direction of maximum compressive elastic strain, in conjunction with spontaneous magnetostriction in single crystal nickel. Constitutive model parameters will be determined by fitting some experimental responses

assuming uniaxial stress. Assumed uniaxial model responses will be compared to experimental responses. Finite element models of the experiments will also be presented, where the lateral constraint of specimen gage sections is modeled to explore the validity (at these strain amplitudes) of the uniaxial assumption commonly used in extracting information from single crystal tests on single crystals oriented for single slip.

Kink Shear Sector Boundaries in Single Crystal Crack Tip Fields

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This study considers the deformation fields at the tip of a crack in ductile single crystals. The asymptotic deformation and stress fields at the tip of such cracks were first derived by Rice (1987, Mech. Mater., 6, 317-355) using continuum single crystals plasticity. The results showed that the deformation field consists of discrete angular sectors within which certain slip systems are active. Sector boundaries are discontinuities of stress and strain. He physically motivated the existence of these discontinuities by postulating the type of dislocation stuctures necessary to effect the discontinuity. One type of discontinuity, a glide shear discontinuity, invoked dislocation motion parallel to the discontinuity. The other type, a kink shear discontinuity, invoked dislocation motion on slip planes perpendicular to the discontinuity.

Glide shear discontinuities have been observed experimentally by several research groups. Only recently, though, has a kink shear discontinuity been observed (Kysar, J. W. and Briant, C. L., Acta Materialia, to appear) by measuring the rotation of the crystalline lattice in the near tip region. In order to explain the existence of a rotation discontinuity at a kink shear sector boundary, it was necessary to invoke a new type of disclocation structure that requires the motion of dislocations on slip planes that are oblique to the line of discontinuity.

In this study, Rice's continuum theory is used to analyze kink shear sector boundaries in light of the new dislocation structure. Among other things it is possible to derive the sign of the rotation discontinuity using the continuum theory. In addition, using concepts of dislocation theory, it is possible to derive approximate bounds on the magnitude of the rotation discontinuity. We will also discuss how critical insight into the mechanisms which determine constitutive plasticity relationships at the microscale can be gleaned from this type of study.

Discrete Dislocation Modeling of Edge Cracks in Single Crystals

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Monotonic and cyclic loading crack growth behavior of 90° edge cracks is studied using discrete dislocation dynamics. The study is motivated by the apparently *anomalous* fatigue behavior of mechanically short cracks. Plastic deformation is modeled through the motion of edge dislocations in an elastic solid with the lattice resistance to dislocation motion, dislocation nucleation, dislocation interaction with obstacles and dislocation annihilation being incorporated through a set of constitutive rules and the fracture properties specified through an irreversible cohesive relation. In accord with experimental data we find that the fatigue threshold $\Delta K_{\rm th}$ decreases with decreasing crack size below a critical crack length. Examination of the numerical results shows that the dislocation densities near the crack tip increase with decreasing crack length for the same applied remote stress intensity factor range $\Delta K_{\rm I}$. This acts to increase the stresses locally which results in crack growth at lower applied remote $\Delta K_{\rm I}$.

Modeling of the Plastic Deformation of Two-Phase Polycrystalline Materials

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An integration of the microstructure-based micro mechanics with the general phenomenological laws can play a significant role in creation of the materials with given properties. Much discussion has been concerned with the deformation of the single crystal including applications to the comprehensive texture analysis. It is well known that the main macroscopic effect of texture is the anisotropy of material properties, and in most metal forming operations,

where the plastic strains are dominant anisotropy can be substantial. It may depend on several factors such as the texture gradient and morphology of precipitates. In order to incorporate the influcence of precipitates into analysis a polycrystalline plasticity simulation is required.

So the main purpose of this paper is to develop a polycrystalline model which takes into account the influence of precipitates on the anisotropy within the well-established self-consistent approach and phenomenological laws. Some homogenization and localization problems of micro-mechanics of metals are considered. The macroscopic response of the non-linear materials with or without precipitates is obtained in terms of the local behavior of the constituents. On the other hand, the convenient set of equations is derived for the determination of the local tensors in terms of the given macroscopic velocity gradient.

A visco-plastic material with plastic precipitates is modeled as a two-phase composite. Rather than to consider the direct interaction among the grains belonging to the same or different phases the volume fraction simplification is adopted which leads to the interaction of a grain with a homogeneous equivalent medium. The particular case of a single-phase material follows directly from the genral formulation. To reduce the computer time the model allows for the phenomenologically determined tangent moduli of the precipitates and the base material. The computational procedure is fully described for the general case, and consists of repeated series of the macroscopic deformation increments. These increments are specified by a macroscopic velocity gradient and a time increment Δt. The orientation of the grains and the critical resolved shear stress are updated at $t + \Delta t$.

The model proposed can be effectively used for the analysis of texture development in metals with the mild heterogeneities; however, the influence of precipitates can be investigated. The model does not require sophisticated computer programming facilities. On the other hand, it is compatible with the different finite element routines.

Keywords: Polycrystalline model, Microstructure, Anisotropy, Precipitates

Effect of Grain Structure on Elastic-Plastic REsponse of Polycrystalline Aggregate

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During previous years a lot efforts were made to determine the mechanical properties of polycrystalline aggregates of different sizes. It was shown that classical continuum mechanics cannot accurately predict the differences between measured responses of specimen, which are different in size but geometrical similar (size effect).

A numerical approach, which models elastic-plastic behavior on mesoscopic level, is proposed to determine effect of polycrystalline grain structure on macroscopic response. The main idea is to divide continuum (e.g., polycrystalline aggregate) into a set of sub-continua (grains). Analysis of macroscopic element is divided into modeling the random grain structure (using Voronoi tessellation and random orientation of crystal lattice) and calculation of strain/stress field (using simple physical models). Mesoscopic response of monocrystal grains is modeled with anisotropic elasticity and crystal plasticity. Material parameters for pressure vessel steel 22 NiMoCr 3 7 with bainitic microstructure with b.c.c. crystals are used in analysis. Finite element method is used to obtain numerical solutions of strain and stress fields. The analysis is limited to 2D models.

Main purpose of this paper is to estimate minimum size of polycrystalline aggregate above which the macroscopic inhomogenity of grain structure of given material vanishes and is therefore not expected to cause significant size effects.

SESSION F3A
SEISMIC ANALYSIS

Strain State of the Crust of some Regions of the Central Asia

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The numerical model of coming to the surface of the mantle's non-uniformity's and their effects on the crust was proposed for analyzing the point of view of fixists and mobilists of the origin of the Pamir-Tjan-Shan orogens. The numerical models of Buchara - Khiva rift zone and Surhandarja megasinklinal. are constructed with the equations of convection of thermal and conducting fluids mathematically for estimating the potential resources of oil and gas. In every time step Stocks' equations for creep are solved by the methods of boundary integral equations for zone-homogenous bodies. The continuity of the rate deformation and the vector of strains it suggested or the condition of the contact with friction depending on whether there are breaking or not are extracted on the joint of zones with different geophysical properties. Singularities in integrals are calculated analytically to rise accuracy

of the calculations. The resultant matrix of the algebraic equations are regularized by Tikhonov's method. The approximation scheme that takes account of availability of the first partial derivatives in the differential operators is chosen for the equation of convection conductivity. The results show that it is difficult to explain from the point of verticalists the origin of orogens of Pamir-Tjan-Shan. Moreover, the calculations from the positions of techtonical plates does not only explain the existence or the double crust in this region but also confirms availability of such strains under which the formation of heavy eclogits is possible. The conditions of forming modern structures are revealed for Buchara-Khiva and Surhandarja regions and the approximately sizes of the regions containing potential carbon-hydrogen are estimated.

Keywords: Geodynamics, Boundary element method, Convection, Earth's crust.

Dynamic Design of Ground Dams under Non Stationary Seismic Effects

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An improved method of dynamic design of ground dams with account of non-linear models of soil are given in the paper. A complete closed system of differential equations is given; it is solved by the method of finite differences according to the scheme offered by Wilkins. The material of the dam ground is simulated by S.S. Grigorian's elastic-plastic equation with constant and variable strength characteristics of the ground. The problem to study a stress-strain state of ground dam is solved with account of elastic-plastic characteristics of the material under dynamic load along the foundation of the dam in the form of records of synthetic seismogram and real velocigram, recorded in the foundation of studied dam . Results of design are followed on dynamic behavior and stress-strain state of specific points of the dam, located in observed zones.

Stress-Strain State of Ground Dam under Seismic Loads

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Earthquake resistant design of the dams built in seismic regions is carried by two approaches: spectral method and the method of wave dynamics. Spectral method which is now widely used in practice does not consider real peculiarities of seismic action as a dynamic one and substitutes the latter by some conditional static load. The account of wave character of seismic action including irreversible deformations of structure displacement leads to design and building of economic and reliable hydrostructures in seismic zones.

The authors of this paper worked out the methods using the finite-differential methods of M.Wilkins' scheme and carried out the design of heterogeneous ground dam with account of wave processes occurring in the body of the dam on seismic action (according to records of real velosigrams). Numeric solutions of closed system of differential equations using different equations of state (elastic, elastoplastic and with account of rheological characteristics of ground) of dam material were obtained. Basing on results of the calculations dynamic behavior and stress-strain state of ground dam under seismic load in the form of record of real velosigram were studied. The zones of formation of plastic flows of ground leading to a loss of bearing capacity and stability of the dam were revealed and the stability of dam slopes under seismic action was assessed.

Research of the Ground Movement with the Help of Percussive Waves Created by Permeation of a Blunt Wedge

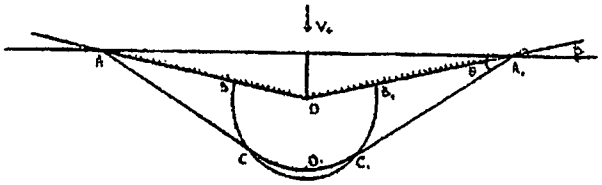
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The behaviour research of any grounds with the help of percussive waves occurred under the influence of short-term loadings is based on invention of simplified and schematized models of the ground. One of such models is based on early researches of academician H.A.Rahmatulin. In that model, pecularities of the ground environment are described by experimentally determinable functions $P = P(\Sigma)$; $\sigma_1 = \sigma(\Sigma)$, describing the volumetric compression and deformation of shift.

Here, these diagrams are used by review of permeation of a blunt wedge in the ground half-space with the constant speed $V_0 < a_0$ and the speed of points A and A_1 (crossing points of a wedge edge with free surface) $C_0 = V_0^* \mathrm{ctg}\beta > a_0$ (a_0 - speed of a sound in the quiet environment).

In this case one occurs a percussive wave that separates the area of the perturbed movement from the quiet environment (picture). In figure $BC(B_1\ C_1)$ - waves of unloading move to the right and to the left from the top of

a wedge with a speed of sound - a. And also they are arches of a circle with the centre in point $a_{\xi 0}$ $a_{\eta 0}$ located in the plane of new dimensionless coordinates $\xi = X/a_0 t$, $\eta = Y/a_0 t$ and have a radius $r = a/a_0$.. The site of a percussive wave of loading - (CC_1) will be some unknown in advance the curve, which is defined during the decision of a task.



The quotient derivative equations of elliptic type will be solved in the field of the wedge's top (BCC_1B_1). And here it is received a formula for the speed of a percussive wave (CC_1).

$$N = D/a_0 = \frac{2k_0\eta_0 - \eta_0^2 + \eta^2}{2\sqrt{\eta^2 tg^2\eta + \eta_0^2}} * tg\theta,\ k_0 = C_0/a_0$$

Calculations made with different permeation speeds into different kinds of ground have shown, that values of parameters of the ground during approach to the point O_1 fall and reach their minimum. On a cheek (BO, OB_1) the minimal value is reached at the top (O).

SESSION F2C
SOFT ACTUATORS AND SENSORS

Implementation of Strain Sensitive Skin S3

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This paper documents the development and implementation of a new full-field measurement technique for determining the in-plane mechanical strain-state on the surface of components. The method, developed at the University of Florida in conjunction with Visteon Corporation, is called Strain Sensitive Skin (S^3). S^3 involves applying a paint that contains a luminescent compound to the surface of a mechanical component using aerosol technology. When the paint layer is illuminated with a low wavelength light source, the coating emits light in the red wavelengths. Specific curing conditions induce a network of micro-cracks randomly dispersed in the brittle paint layer. The micro-cracks when viewed through a microscope take on the appearance of a dry lakebed. The microcrack network scatters the waveguided emission as a function of the strain of the underlying substrate, causing luminescent intensity change. When viewed from a modest distance, the discrete effect of each individual crack is not spatially resolved leading to an average measured response. S^3 provides information of the addition of the two principal strains, $\varepsilon_1 + \varepsilon_2$, or the center of the Mohrs circle. Calibration on uniaxial tension as well as torsion specimens has been used to verify and calibrate the response. To implement the paint, full-field images of the emission intensity are taken for the no load condition as well as for the loaded conditions. The ratio between the no load and loaded intensities at any location on the part represent the optical strain response. The optical strain response is determined on a full-field basis. Corrections for non-uniform lighting and object distortion are implemented to increase the accuracy of determining the full-field optical strain response. The method can be used to determine the state of strain on complex 3-D parts since the response is not strongly dependent on viewing angle. We have implemented the technique on 2-D open-hole tension specimens as well as 3-D mechanical components. This paper covers the theory, results from calibration tests and results from an application on a control arm for a motor vehicle. Full-field images of the strain distribution on the control arm will be presented and compared to finite element analysis. The experimental results can be used for FEA model validation and calibration.

The Optimal Configuration of Piezopolymer Actuators for Active Vibration Control of Cylindrical Shell. Application to Antifouling Process.

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Piezolectric materials offer potential applications for the sensing and actuating components in advanced smart structures. These materials are commonly available in the form of thin layers, which can be bonded to surfaces or embedded into flexible laminated composite structures. Their applications can be classified into two categories: controlling the shape of structures, and controlling the vibration characteristics of structures. One example of this second application is the antifouling process.

This paper studies the optimal configuration of piezoelectric polymer actuators for active vibration control of

a composite cylindrical shells. The optimal placement of the actuators to obtain the desired level of vibration for antifouling process is still a significant design problem.

Stiffness and Energy Density Determinations in Ionic Polymer Transducers

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Ionic polymers are commonly used in fuel cells, water electrolyzers and desalinization, chlorine generation, and other niche applications. A more recent development is the potential use of these materials as "smart" material transducers. Able to function as actuators and sensors, ionic polymers could one day replace many conventional transducer technologies. Currently, the performance characteristics and high cost of these devices has prevented them from experiencing widespread use. This presentation discusses novel approaches to overcome these obstacles.

The transduction mechanism in ionic polymers requires that uniform electrical contact be made with the surfaces of the membrane. This is accomplished by plating a conductive material onto the surfaces. Traditionally, this conductive electrode was made using gold or platinum in a lengthy and labor-intensive process. The current research focuses on using less costly metals and revising the metal deposition process. By using more economical metals like nickel and copper, the goal of this research is to bring ionic polymer actuator technology closer to real applications. Initial results showed that the use of non-noble metals would result in an electrode that was not stable upon actuation. More recently, it has been found that by alloying these less expensive metals with gold and platinum, a *stable* electrode with significantly lower loadings of noble metals is realized–see Figure 1.

Another interesting result of this research is that besides revealing the possibility of using less expensive metals as the electrode, it was also found that the electrodes could be made in very thin layer, thus reducing the density of the composite. This also had the effect of reducing the stiffness of the polymer-metal composite. As a result, the actuators made by this new method showed significantly less force output than the baseline material, but significantly more free displacement. Performance results for these new devices are reported, including energy densities and force/deflection curves. Equations and discussions are presented to demonstrate the relationship between the stiffness of the device and its force and deflection.

Keywords: smart material, ionic polymer, Nafion®, energy density

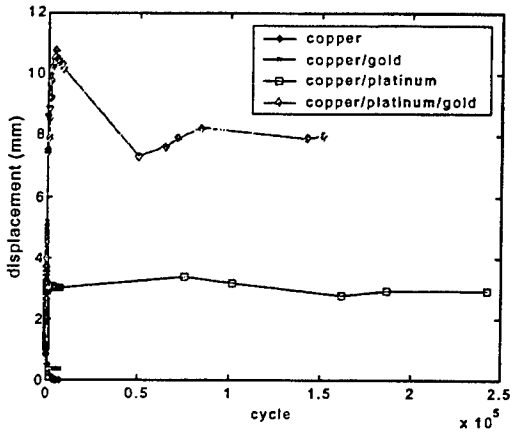


Figure 1. Peak-to-peak free deflection response to a 1.25 V, 1.0 Hz sine input. Sample size is 10mm × 35mm.

SESSION R3E
STRUCTURAL DYNAMICS I

Detection of Transient Mechanical Displacements in Aluminum Plates with Optical Fiber Sensors

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Experimental data have been collected using extrinsic Fabry-Perot interferometric optical fiber sensors, while mechanical displacements are excited in aluminum plates by means of pencil lead breaks. The data are compared with mechanical displacements predicted from modeling the plate response to a step force loading at a point using a dynamic finite element model.

The sensitivity of the sensors to out-of-plane and in-plane displacements are described for displacements on the order of Angstroms.

Experimental and Analytical Study of Flyrod Mechanics

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In the sport of flyfishing, the design and manufacture of graphite composite flyrods has become as much of a science as an art. The study of flyrod and flycasting mechanics is an ideal topic of study, both from a research perspective and from an educational one. To understand the relationship between the angler, the rod and the line during casting requires the solution of a multi-faceted mechanics problem. The deformations and rotations experienced by a rod during casting are extremely large, and their prediction requires solving a nonlinear dynamic structural analysis problem. This is further complicated by the fact that the rods are hollow and tapered. In addition, it is necessary to incorporate aerodynamic drag into the analysis of the line motion.

In the present study, static and dynamic experiments and simulations were performed. Several commercial flyrod blanks (i.e. rod sectios) were subjected to static tip loading applied at various angles, chosen to simulate rod loadings expected during casting and fish retrieval. A nonlinear finite element solution was used to correlate predicted response with experimental data. The blanks were sectioned and microscopically characterized to obtain dimensions and effective mechanical properties, accounting for the irregular distribution of fibers resulting from the method of fabrication.

After completing the static study, the project then moved into the dynamic realm. The motion of the flyrod, the line and the anglers arm were studied using high-speed video of actual casting maneuvers. These experiments provide the data and initial conditions required to compute an accurate simulation of flycasting. A nonlinear dynamic analysis code was then developed to accurately simulate the cast. The effects of the flyrod design parameters and their interaction with the line could then be studied.

Keywords: flyrod, nonlinear, dynamics, structures, composites

Sensitivity Analysis of Transmisibility of a Piecewise Linear Isolator for Steady State Vibration

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Vibration isolation with piecewise linear damping and stiffness are used in various industrial applications. Two examples include suspension systems and engine mounts with clearance and stoppers as geometric constraints. The piecewise linear system in these case represent hard nonlinear, which cannot be assumed small, and hence standard perturbation methods are unable to provide a complete analytical solution.

We have adopted the averaging method to analyze the nonlinear behaviour of piecewise isolators at resonance, and to provide a comprehensive analysis that is used to design the optimised vibration isolator of this type. We have also shown the results obtained by averaging method is in agreement with numerical simulation and experimental measurements.

Sensitivity analysis is conducted in order to find an optimal range for the system parameters in order to minimize transmissibility of the piecewise linear isolators while certain amount of clearance is inevitable.

Experimental Investigation of the Nonlinear Normal Modes of a Parametrically Excited Buckled Beam

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The nonlinear normal modes (NNM's) of discrete or spatially continuous systems exhibiting various sources of nonlinearities have been studied quite extensively with the principal focus on the general mathematical framework and the relevant techniques [1-3]. In contrast, relatively few experimental works have been carried out to clearly demonstrate the nonlinear spatio-temporal characteristics of these special motions.

In this paper, the NNM's excited by an external principal parametric resonance at frequency approximately twice that of the second mode of a hinged-hinged buckled beam, subjected to an end load, are investigated theoretically and experimentally. The method of multiple scales is applied directly to the integral-partial-differential equations of motion and associated boundary conditions to construct the NNM's. The beam deflections and the frequency-response curves are obtained. As theoretically known, the standing-wave characteristic of the linear modes of a self-adjoint system - as the one herein investigated - is shown to be destroyed by the nonlinearities. An experiment is conducted on a test beam.

The beam is hinged at both ends. One of the hinges is mounted on a sliding support actuated by a linear motor delivering the static buckling and parametric excitation forces. A high-speed camera is used to capture the overall motions of the parametrically excited buckled beam. The video is contrasted with an animation of the theoretically obtained NNM's. The experimental frequency-response curves and the time evolution of the deflections are in very good agreement with the theoretical predictions.

Keywords: Nonlinear normal mode, buckled beam, principal parametric resonance, experimental frequency-response curve.

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Modal Analysis of Cantilever Plates Undergoing Accelerated In-plane Motion

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Structures having a plate-like shape can be found in several engineering examples such as aircraft wing, rocket fins and spacecraft appendages like solar panels. These structures are often accelerated significantly during their normal operation. Such accelerated motion induces inertia force which often causes the change of system bending stiffness. The change of system bending stiffness results in the variation of modal characteristics which should be identified accurately for reliable designs of the mentioned structures. Earlier investigations on variations of modal characteristics started in the field of vibration of rotating blades. A large number of literature on this field is available and still being produced. In those studies, however, the structures are mostly idealized as rotating beams. Since some structures behave like plates rather than beams, a modeling method for plate is needed. Furthermore, the variations of modal characteristics due to translational motions were rarely studied. Recently, Yoo and Chung [1] introduced a dynamic modeling method for plates undergoing overall motion. The integrity of the modeling method was confirmed for the modal analysis of rotating plates. However, the modal characteristics of plates undergoing translational motion have not been studied so far. The purpose of the present work is to investigate the modal characteristics of cantilever plates undergoing accelerated in-plane motion. The equations of motion are derived and transformed into dimensionless forms in which dimensionless parameters are identified. The effects of the dimensionless parameters on the variations of natural frequencies and their associated mode shapes are investigated.

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SESSION R4E
STRUCTURAL DYNAMICS II

Static and Dynamic Response of Torsionally-Restrained Anisotropic Composite Thin-Walled Beams

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Static and vibration response of a thin-walled anisotropic composite beam with torsional restraint is

investigated using an exact solution methodology of a refined anisotropic composite thin-walled beam model. Comparisons are made between analytical results obtained within the restrained torsional model with results from its Saint-Venant model counterpart. The results suggest that the beam slenderness and thickness ratios, as well as the elastic anisotropy, considered in conjunction with the warping restraint have profound effects on the beam response characteristics. For anisotropic composite beams with large slenderness ratios, the exact solution methodology presented in this paper, provides more accurate results compared to those of the Saint-Venant model.

The proposed paper summarizes the analytical methodology for thin-walled anisotropic composite beams, a detailed discussion of results obtained from the proposed restrained twist model and the Saint-Venant one is provided, and pertinent conclusions are outlined.

Keywords: Thin-walled beams, anisotropy, composite materials, restrained torsion, Saint-Venant torsion.

Coupling of Rigid Motion and Large Deformation in Dynamics of Elastic Bodies.

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In the paper a general description od dynamics of bodies undergoing large displacements and finite strains is presented. Contrary to classical dynamical analysis of continua where local rotations are obviously taken into account, the present approach presume motion to be resolved into displacements due to deformation and dispacement due to global rigid body motion. Such an approach allows to describe and to analyse the mutual dependence between rigid motion and large deformation. This may be important in many applications like e.g. motion of flexible systems, control of structures, biomechanical systems etc. To circumstances differs the present paper from results known up to now in the literature: first - we demonstrate a simple derivation of the equation of motion based on Gibbs-Appell equations; second - using consequently the unified analytical mechanics description we calculate the generalized forces for continua and than its finite dimensional approximation in terms of strong nonlinearity of the system. The obtained system of equations shows the dynamical coupling of rigid motion and deformation and hence its visible interaction. The structure of these equations is suitable for numerical integration (by using e.g. the Runge-Kutta procedure or the Newmark method). Contact conditions of any kind and other constraints may be incorporate into the system without essential difficulties. The paper is organized as follows: we start with a general form of description of motion which include rigid as well as deformation induced displacements; then velocities and accelerations are calculated. Next the equations of motion by using the Gibbs-Appell formulation are derived. This system of equations has a suitable for a general discussion form. To solve this system, the finite dimensional approximation for dispacements due to deformation have been introduced. On this way an effective system of dynamical equations for the complex large displacement and large deformation stricture is presented. Planar motion of an elastic plate and slender beam resting on rough foundation is considered. Some final conclusions which concern perspectives of the presented formulation and results end the paper.

Keywords: rigid motion. large deformation, coupling.

Dynamic Stability of Circular Cylindrical Shells Subjected to Axial Loads

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The fundamental work on the subject of circular cylindrical shell stability is due to Von Karman and Tsien [1], which, in 1941, analysed the static stability and the postcritical behaviour of axially loaded shells. In this pioneeristic work was explained the role of the sub-critical bifurcation in the failure of the linear theories in predicting the actual buckling phenomenon observed in experiments.

Roth and Klosner, 1964, analysed the buckling of circular shells subjected to a suddenly applied load. They used the Nonlinear Donnell Shallow Shell theory. The presence of a contained fluid in the linear vibration of shells is well understood. Nevertheless, the literature regarding large amplitude nonlinear vibrations of shells with fluid structure interactions is not wide, se e.g. Kubenko and Koval'chuk 1998 an interesting review on the subject can be found. In the present work the dynamic stability and postscritical dynamics of a circular cylindrical shell with periodic and static axial loads is analysed using the Nonlinear Donnell's shallow shell theory; the ef-

fect of a contained fluid is considered. The transversal flexural displacement is expanded using linear vibration modes, the expansion is suitably truncated in order to ensure the convergence; companion modes and axisymmetric modes are included. The dynamical system obtained through a Galerkin procedure is analysed with numerical techniques, namely: a software for the continuation and bifurcation of solutions of ordinary differential equations and direct integrations.

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On Transverse Vibrations' Equation of Annular Plates of Convex Parabolic Thickness Variation

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An approach for solving the governing partial differential equation of the transverse vibration of annular plates is to transform it by the method of multiple scales to two simpler equations which basically represent the two levels of approximation and which can be analytically solved. A small dimensionless parameter was introduced in the governing equation as a bookkeeping device of the space-dependent, second-order partial differential operator. The method of multiple scales was then directly applied to the partial differential equation considering an asymptotic expansion of the solution. Both levels of approximations were described by the space-dependent fourth-order partial differential operator, which is expressed in terms of Laplace operator in polar coordinate, and the transverse displacement acceleration term. Separating variables, the homogeneous equation of the first level of approximation allowed solutions assumed to be time harmonic and 2pm angular periodic, m natural, and it reduced to a fourth-order differential equation of a radial-dependent function. The case of annular plates of convex parabolic thickness variation led to a fourth-order differential equation which was factored into a pair of second-order differential commuting operators. The differential equations of these second-order differential operators were transformed to hypergeometric equations and consequently the radial-dependent function of the general solution of the first level of approximation was expressed in terms of hypergeometric functions. Determining the eigenvalues and the eigenfunctions of the first level of approximation problem for certain boundary conditions, the natural frequencies and the mode shapes of the annular plate can be found as next level of approximation by solving the equation of the second level of approximation.

Impact of a Pressurized Thin Spherical Shell with a Flat Rigid Surface

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The impact of a pressurized thin spherical shell with a flat rigid surface was studied using both analytical and experimental methods. The equations of motion for the shell during impact were developed by treating the shell as a pressurized, thin, spherical, inextensible membrane and the impact between the shell membrane and the flat rigid surface as plastic. Large deformations were taken into account. Two non-linear equations of motion for the position of the center of the sphere were derived: one for the deformation, and one for the restitution. The equations were integrated numerically and yielded the displacement of the center of the sphere as a function of time. The velocity, acceleration, contact diameter, internal pressure, and restoring force were calculated as a function of time. The coefficient of restitution was also calculated. Surprisingly large deformations and contact forces were predicted. The impact of a pressurized thin spherical shell with a flat rigid surface was recorded using experimental video techniques. In addition, a second technique was used to measure the maximum contact diameter and determine the maximum displacement, internal pressure, and contact force. Surprisingly large deformations and contact forces were observed. The experimental results were compared with the analytical results.

Effect of Randomness in Material Properties on Forced Response of Laminated Composite Plates

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For the study of dynamic response of structures made of fibre reinforced composites, it is customary to assume that the structure has precisely defined system properties. However, system properties can at best be determined within a certain range due to the large number of parameters associated with its manufacturing and fabrication processes and inability to control them precisely. Therefore for reliability of the design, it is essential that the response should be predicted accurately. The aim of the present work is to suggest an approach for computing the mean and the variance of response of composite laminates with random system properties subjected to deterministic excitation.

Higher-order shear deformation theory is employed to model the plate behavior. Rotary inertia effects have also been accounted for in the development of the governing equations. First-order perturbation technique has been employed to handle the randomness in system properties. The equation of motion can be obtained either by a classical method or by a numerical method. The system equations can be expressed as:

$$\mathbf{M}\ddot{\mathbf{X}}(t) + \mathbf{K}\,\mathbf{X}(t) = \mathbf{F}(t); \tag{1}$$

where M and K are n×n) system inertia and stiffness matrices, respectively. F(t) is the excitation vector and X(t) is the response vector.

Equation (1) can be written in state-space form

$$\dot{\mathbf{Z}} = \mathbf{A}\,\mathbf{Z} + \mathbf{B}\,\mathbf{U}; \tag{2}$$

where Z, (2n×1), is the response vector, A, (2n×2n), is the stiffness matrix, B, (2n×2n), is the inertia matrix and U, (2n×1), is the time dependent load vector. Without any loss of generality the random variable may be split up as the sum of the mean variable and a zero mean random part.

If the random variations are small compared to the mean part, as is the case in most engineering applications, one can write: $\mathbf{Z} = \bar{\mathbf{Z}} + \varepsilon\mathbf{Z}^r$; $\mathbf{A} = \bar{\mathbf{A}} + \varepsilon\mathbf{A}^r$; where ε is small, over bar denotes mean and superscript r denotes the zero mean random part of the variables. On substitution of the above in equation (1) and collecting terms up to first order, we obtain

$$\begin{aligned} &\text{Zeroth order: } \dot{\bar{\mathbf{Z}}} = \bar{\mathbf{A}}\bar{\mathbf{Z}} + +\mathbf{BU}; \\ &\text{First-order: } \dot{\mathbf{Z}}^r = \bar{\mathbf{A}}\mathbf{Z}^r + \mathbf{A}^r\bar{\mathbf{Z}} \end{aligned} \tag{3}$$

Mean response is obtained from the first of equation (3) and covariance of response is obtained by further processing of the second equation (3). Using Taylor's series expansion and retaining term up to first order, the second equation (3) can be rewritten as

$$\dot{\mathbf{Z}}^r = \bar{\mathbf{A}}\mathbf{Z}^r + \mathbf{C}^r; \text{ with } \mathbf{C}^r = \textstyle\sum_{l=1}^{m} (\partial\mathbf{A}/\partial b_l)_{b_l=\bar{b}_l} b_l^r \bar{\mathbf{Z}} \tag{4}$$

where b_l^s $(l = 1, 2, \ldots m.)$ are the system parameters which are modeled as random variable (RVs).

Assuming initial condition $\mathbf{Z}(t_0) = \mathbf{0}$, the solution of equation (4) can be used to find expression for covariance of the dynamic response and are given as

$$\mathbf{K}_{zz}(t_1, t_2) = \textstyle\int_{t_0}^{t_1}\int_{t_0}^{t_2} \mathbf{S}\boldsymbol{\Lambda}_1\mathbf{P}\mathbf{K}_{cc}(\tau_1, \tau_2)\mathbf{P}\mathbf{P}\boldsymbol{\Lambda}_2\mathbf{S}\mathbf{S} d\tau_1 d\tau_2 \tag{5}$$

where S is the modal matrix of A and

$$\boldsymbol{\Lambda}_1 = \begin{bmatrix} e^{\bar{\lambda}_1(t_1-\tau_1)} & \mathbf{0} \\ \mathbf{0} & e^{\bar{\lambda}_n(t_1-\tau_1)} \end{bmatrix};$$

$$\boldsymbol{\Lambda}_2 = \begin{bmatrix} e^{\bar{\lambda}_i(t_2-\tau_2)} & [0] \\ [0] & e^{\bar{\lambda}_n(t_2-\tau_2)} \end{bmatrix};$$

$$\mathbf{P} = \mathbf{S}^{-1},\ \mathbf{SS} = \mathbf{S}^{*T};$$

$$\mathbf{PP} = \mathbf{P}^{*T}\,\mathbf{K}_{cc}(t_1, t_2) = < \mathbf{C}^r(\tau_1)\mathbf{C}^r(\tau_2)^{*T} >$$

Numerical results are presented for simply supported symmetric cross-ply plates with random material properties and deterministic loading. These have been validated with results from Monte Carlo simulation (MCS).

The panel carries a distributed transverse loading

$$f(x, y, t) = \begin{cases} q_0 \sin(\pi x/a)\sin(\pi y/b)\sin(\pi t/t_1), & 0 \le t \le t_1 \\ 0, \quad \text{otherwise} \end{cases}$$

The mean and standard deviation (SD) of transverse center displacement have been computed for graphite-epoxy plates having stacking sequence [0°/90°/90°/0°]. It is observed that the mean response initially increases and reaches a maximum value and then decreases with increase in time in the forced vibration zone. The dispersion in response is most affected with scatter in E_{11} and least affected with scatter in the Poisson's ratio ν_{12}. The sensitivity of response to scatter in E_{22}, G_{12}, G_{13} and G_{23} is of the same order of magnitude.

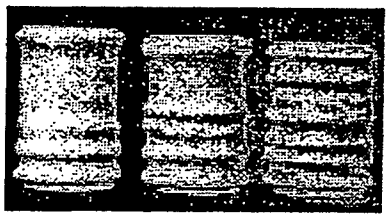
Keywords: Composite laminates; Random, Dynamic response; Standard deviation.

Experimental Investigation and Computer Simulation on Elasto-Plastic Dynamic Buckling Behavior of Liquid-Filled Cylindrical Shells under Axial Impact

Zhang Shanyuan, Lei Jianping, Cheng Guoqiang and Lu Guoyun

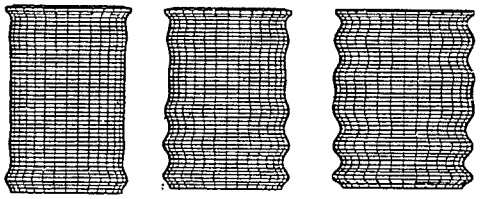
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An experimental investigation on the axial impact buckling of thin metallic cylindrical shells fully filled with water is reported. The impact tests are carried out by DHR-9401 drop hammer rig. The whole process of dynamic buckling is simulated using LS-DYNA computer code. The buckling modes of liquid-filled cylindrical shell under some impact velocities are shown in Fig. 1. Fig. 2 shows the buckling modes of several typical times chosen from animation display given by simulation. Fig. 3 and Fig. 4 show the time-history curves of impact force and internal pressure from simulation and test respectively. From the time-history curves we can see that the whole impact process can be divided into three stages: the dynamic loading with violent oscillation, smooth dynamic post-buckling and rapid elastic recovering. The consistency between experimental observation and numerical simulation is quite satisfactory. During post-buckling the liquid inside shell supports most of axial force so that the crashworthiness of whole structure is raised and imperfect sensitivity of shell is obviously reduced. The investigations indicate that quite high internal hydrodynamic pressure occurs inside shell during impact process. Under the combination action of the high internal pressure and axial compression the thin-walled shells take place easily plastic buckling and buckling modes take on regular and axisymmetric wrinkles. This property can be utilized in some forming technology without mould.



(1)v= 3.43m/s (2) v=3.96m/s (3)v=4.43m/s

Fig. 1 The buckling modes of shells under different impact velocities



t=2.6997ms t=4.9965ms t=13.0000ms

Fig. 2 Buckling modes at different time step
□V = 4.43m/s□

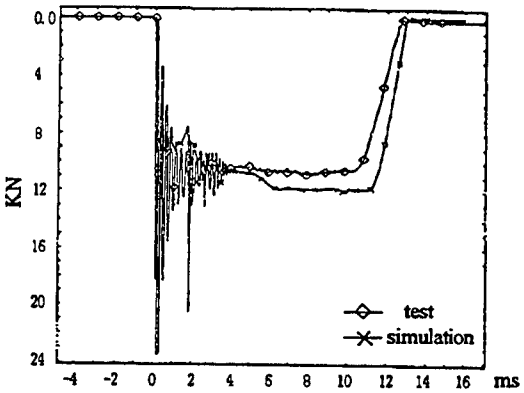


Fig. 3 The time-history curves of impact loading
V = 4.43m/s

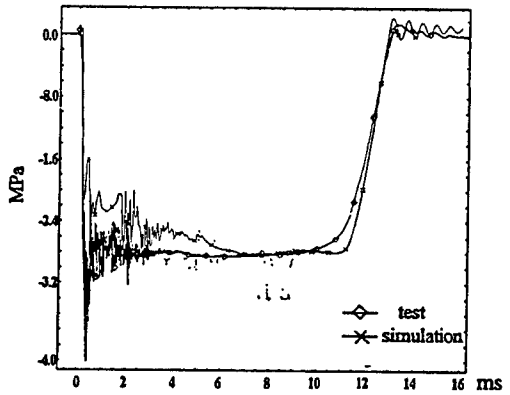


Fig. 4 The time-history curves of internal pressure
V = 4.43m/s

Keywords: liquid-filled cylindrical shell, impact buckling, experiment, simulation

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SESSION T2J
STRUCTURES I

Mechanics of Folded Media

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Crumple a sheet of paper [1]. This is what we will call a folded medium. The classical structural analysis presents serious difficulties in solving this problem.

If we are interested only in global variables as the geometric characterization, total stored energy and material ductility, is it possible to establish a "global law" that would correlate some appropriate variables leading to the characterization of the final shape?

Consider a very thin spherical shell, initially with a radius R that is forced to colapse into a kind of crust bounded by to spherical surfaces R0 and $R0 + h$. The final configuration is composed by small tiles connected together through the edges forming a complex polyhedron. The original shell keeps folded within the "spherical crust" without any external or internal restrain.

If we just give up following the classical approach, it is necessary to define new variables that are more appropriate to this class of folded structures:

1. Packing Capacity: the ratio between the surface of the original spherical shell with radius equal to R and the surface of the support with radius equal to $R0$.
2. Slenderness Ratio: The shell thickness "t" divided by the shell original radius "R".
3. Packing Plastic Work Density: The ratio between the the dissipated plastic work in the folding process and a reference work, that can be interpreted as the dissipated work for the limit case when R tends to $R0$ and t tends to h.

Previous work suggested that mass conservation requires that the packing capacity $P^* = S/S0$ varies with the slenderness ratio $r^* = t/R$ according to the power law:

$$P^* = e(r^*)^{(2-D^*)} \text{ or}$$
$$\log(P^*) = \log(e) + (2 - D^*)\log(r^*)$$

Where D^* is the fractal dimension associated to the folded configuration. The parameter "e" has to be more closely investigated. A plausible hypothesis is to assume that this parameter is a function of the plastic work density.

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Smooth Approximations of Tension Field Deformations of Various Membranes

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It is known that nonlinear elastic membranes are incapable of supporting compression. Physically, they are seen folding in response to such an edge load. Incorporating this observation into a theory of large deformations of elastic surfaces resulted in the so-called Tension Field Theory, which offered a set of characteristics a physically realizable deformation must satisfy. A. C. Pipkin [1] established equivalence between tension field deformations and minimizers of the relaxed energy functionals for the membrane. This approach has proven difficult to apply because of the challenges in calculating the quasiconvexification of the membrane energy density function.

Another approach to approximating tension field deformations is based upon the physical observation that highly elastic membranes will exhibit bending stiffness during the folding process, thereby smoothing creases. M. G. Hilgers and A. C. Pipkin [2] developed a model of elastic sheets with bending stiffness under the assumption that the strain energy density function of the sheet depends on first and second order derivatives of the deformation. Furthermore, they proposed several examples of appropriate strain energy densities for these sheets. Most of these decompose into a membrane energy term plus a bending energy term, which is dependent upon a bending stiffness parameter.

Recently, Hilgers [3] has shown that sheets with small bending stiffness have energy minimizing deformations that are uniformly close to the tension field solution for the corresponding membrane. In this talk, Hilgers will review the aforementioned theories and offer examples of these result as applied to various known membrane models.

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Large Deformations of Nearly Spherical Inflated Membranes

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As is well understood, an initially spherical membrane composed of a homogeneous, isotropic material will remain spherical upon inflation by an internal pressure. It is also well known that homogeneous, isotropic membranes that are not initially spherical become more spherical as the internal pressure is increased. However, upon initial inflation, the minor principal stress of certain initially non-spherical membranes will be compressive, rendering the solution unstable. For example, as shown by Timoshenko and Woinowsky-Krieger, an axisymmetric ellipsoidal membrane that has a major axis length greater than square root of two times the minor axis length will develop a compressive circumferential stress when initially inflated. Although compressive stresses may occur upon initial inflation, as the pressure increases and the elastic membrane deforms, these compressive stresses should eventually become tensile. The amount of pressure required to remove all compressive stress in the membrane depends on the membrane stiffness and initial geometry. This was demonstrated numerically for axisymmetric ellipsoidal membranes by the author and others in a 1998 paper in the Journal of Biomechanics.

In this work, the large deformations of nearly spherical, axisymmetric, inflated membranes are studied using approximate analytical methods. In particular, perturbation methods are used to determine approximate solutions for nearly spherical membranes from the known solutions of the inflated spherical membrane. High order perturbations are readily obtained as the perturbed solutions are governed by inhomogeneous Legendre's equations. Solutions are compared to those obtained numerically. Convergence is rapid for membranes with meridian curvatures that do not deviate greatly from constant.

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[2] Serina, E., et al, "A Structural Model of the Forced Compression of the Fingertip Pulp," *Journal of Biomechanics*, 1998, vol. 31, no. 7, pp. 639-646.

Uniform Stabilization of a One-dimensional Hybrid Thermo-elastic Structure

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In this talk we consider the question of uniform stabilization of a 1-D thermo-elastic structure consisting of a thermo-elastic beam which is hinged at on end with a rigid body attached to its free end. The model takes account of large deflections and rotational inertia effects in the beam. The property of uniform stabilization of the energy associated with the model is asserted with the aid of an appropriate Lyapunov functional. Critical use is made of a multiplier of an operator theoretic nature, which is the negative "square root" of the biharmonic operator pair acting in the problem. An explicit decay rate of the energy is obtained.

Dynamic Compression of Cross-linked & Linear PVC Cores

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Closed-cell PVC foam cores are often used in structural applications for packaging and impact protection. The sandwich structure is one particular application that is finding increased use of these cores. The damage tolerance of a sandwich composite is largely influenced by the energy absorption capabilities of the core. Unlike a honeycomb core, a damage tolerant foam core is capable of diverting the shock wave in the panel direction, absorbing the energy through its its cellular structure. Many cellular foam cores are fabricated with various degrees of cross-linking. Since the structure of the polymer chain in cellular foam cores also has a significant effect on the mechanical properties, it is important to understand how the impact properties may be altered when using foams that have been lightly or heavily cross-linked.

The focus of this study is to investigate the response of cross-linked and linear foam cores to impact loading and their effects on the sandwich composite. Two types of PVC foam cores, H130 and HD130, are considered in this study. Both cores are of the same density. Each core has been subjected to various strain rates using a modified

Split Hopkinson Pressure Bar apparatus. In this modified apparatus, polycarbonates bars are used as the incident and transmission bars. The energy absorption capabilities of the both PVC cores are compared.

Since temperature as well as strain rate affects the impact properties of polymers, the vulnerability of foam cores to impact loading at various temperatures is also examined. High strain rate testing have been performed at room and elevated temperatures. The stress strain behavior and the failure analysis under various rates of strain and environmental conditions will be presented in this paper.

SESSION W2J
STRUCTURES II

Reconstruction of Elastic Constants of Laminated Shells using a Combined Inverse Technique

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In the application of laminated cylindrical structures to aerospace, nuclear and automobile industries, property evaluations of laminated cylindrical shell are of very importance. In this paper, this inverse problem of reconstruction of elastic constants is formulated as a parameter identification problem in which a set of parameters corresponding to the elastic constants can be found by minimizing error functions formulated using the measured displacement response and the one computed by a forward solver based on projected candidates of parameters. An analytical-numerical method is employed as the forward solver to calculate the dynamic displacement response on the outer surface of the laminated cylindrical for given material property. A combined method is used as the inverse operator to determine the elastic constants of the cylinder. In this method, genetic algorithm is first used to select a set of better solutions close to the optima; then the nonlinear least squares method is applied using these better solutions as the initial guesses. Finally, the identification results can be determined from the solutions of nonlinear least squares method by comparing their corresponding error function values. Actual material characterizations of a laminated cylindrical shell demonstrate the higher efficiency of the present method.

Comparison of the Two Formulations of w-u-v and w-F in Nonlinear Plate Analysis

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In a moderately large deflection plate theory of von Karman and Chu-Herrmann, one may consider plate equations of the transverse and in-plane displacements, w-u-v formulation, or the transverse displacement and Airy stress function, w-F formulation. Although the two plate formulations are completely equivalent in theory, they are not in practice. This is because the displacements and Airy function are approximated by a finite degree-of-freedom representation by whatever the means used for computation, i.e., the finite-difference, finite-element or Galerkin representation. Under the Galerkin procedure, we examine if the modal equations of two plate formulations preserve the Hamiltonian property, as demanded by plate motion in the conservative limit of no damping and forcing. In the w-F formulation, modal equations are Hamiltonian for the first four symmetric plate modes. On the other hand, the corresponding four modal equations of w-u-v formulation do not exhibit the Hamiltonian property, when a finite number of sine terms are included in the in-plane displacement expansions.

Adherence of an Axisymmetric Flat Punch onto a Clamped Circular Plate and its Application to Mechanical Characterization of Thin-walled Bio-capsules

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A clamped circular film is adhered to a rigid cylindrical punch. An external force pulls the punch away causing delamination at the punch-plate interface. The deflections of the film are discussed for a wide range of film thickness and stiffness, detailing the continuous transition from a plate under bending to a membrane under stretching. An equilibrium theory of delamination mechanics is derived based on an energy balance. A complete separation at the punch-film interface, or the "pull-off" event, is predicted when the contact circle shrinks to approximately 0.18 of the film diameter. The theory provides a theoretical framework to elastic deformation of a bio-capsule due to indentation of an atomic force microscope (AFM) tip. The spherical cap surface is approximately considered as

an infinite plane and the Beltrami-Laplace operator $\Delta_B w$ is approximated by the Laplace operator on a plane (with w the elastic deformation or normal displacement). Constitutive relation governing the applied load and vertical displacement of the AFM tip is shown to be a function of the turgor pressure within the capsule, the flexural rigidity and extentional modulus of the capsule wall. Mixed deformation modes of bending and stretching occur in the capsule wall.

Keywords: Atomic force microscope, bio-capsule, thin film adhesion, delamination

On the Importance of Classical Plate Theory for Getting Accurate Results for Thick Plates

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Classical plate theory (CPT) is an extremely important theory. The purpose of the paper is to highlight the added importance of CPT for the thick plate problems wherin shear deformation effects are important. In the light of a recent work on a new refined plate theory [1], the paper discusses the use of CPT to obtain accurate results in such problems. Such use of CPT can be made in situations wherin formulation is required to be variationally consistent. But, it is shown that the process of obtaining accurate results becomes quite simple, if variational consistency is not insisted upon.

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A New Approach of Differential Quadrature Element Method for Analyses of Euler Beams

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Recent literature shows that the differential quadrature method (DQM) has the advantage of producing highly accurate solutions with minimal computational effort. However, this method can only be applied to structural elements without discontinuity in geometry, boundary conditions, material properties and loading. Recent research effort has been directed to use an element approach based on the DQM for a wider application.

In this article, a new approach of the differential quadruatre element method (DQEM) is developed for analyzing Euler beam problems. By using the method of domain decomposition, an Euler beam with discontinuous properties can be dealt with by using elements, which are represented as homogeneous uniform beam. By introducing the modified relationships and a new formulation process, the representative algebraic equations will be furnished with consideration of boundary conditions in each element. The global equations of the entire beam are assembled from the element equations with consideration of compatibility and continuity conditions. Computational scheme of this approach is easily implemented. Static and dynamic analyses of Euler beams having discontinuities in geometry and loading are performed. Results obtained by the present approach are shown to have high accuracy and good convergence. This new approach of DQEM can be extended for a wide range of applications.

Structural Response of an Ancient Wooden Construction to Dynamic Loadings

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Wooden construction was a typical structure in the ancient time, especially in China. Nowadays, the oldest wooden tower in the world is still standing in the northwest of China as shown in figure 1, which was built up almost one thousand years ago. It is a marvel that such an old wooden can still be open to tourists now.

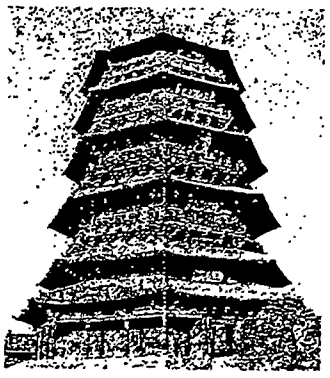


Fig. 1: The oldest wooden tower

By means of finite element computation, a structure analysis revealed that the building was flexible, and a symmetric octagonal cross-section and pyramid-looking structure have set up a stable support for the whole building. Mortise and tenon joints, which linked layers and

branches in the construction, played a key role as transmitters of forces, which enabled strong forces being dispersed over all the building. A mortise and tenon joint was individual studied under a special finite element model. The simulation result showed realistic responses of the mortise and tenon joint to the loadings as showed in figure 2. With firm but gentle, it was no doubt that the tower was a typical example of coupling hardness with softness, which enabled the soft conquer the hard over the years.

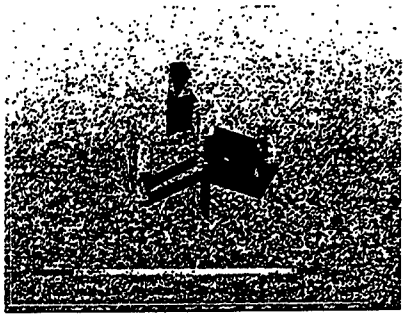


Fig. 2: Stress distribution on a mortise and tenon joint

However, being long beaten by winds and various loadings, the tower was damaged seriously now, especially on the second floor and the third floor. It is obviously inclined to one side on the whole. Both modes analysis and responses simulation of the structure to dynamic loadings showed that, it was the elements on the second floor and the third floor that bore the heavy burden and took on larger deformation under the loadings. Figure 3 showed a deformation shape of the tower after being loaded by a seismic shock for 2 seconds.

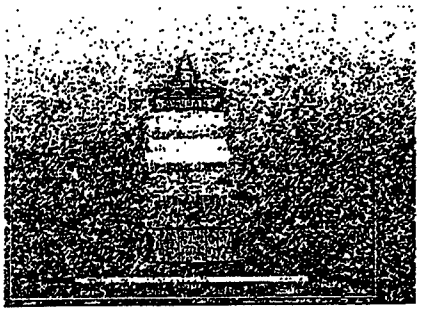


Fig. 3: Dislocation distribution on the building

Phenomena and damage features simulated from the structure analysis and dynamic response by the finite element method are consistent with the real situationand experimental data of the tower very well. The investigation here is useful for understanding mechanism of how the ancient wooden construction could bear so long, and why it was damaged as looked. It may helpful for finding a reasonable way to repair and reinforce such an ancient building without additional damages.

Keywords: wooden construction, mortise and tenon joint, structural response, dynamic loading.

SESSION R2J
STRUCTURES III

Validation of 3D Modelling of a Steel Portal Structure using a Modified Genetic Algorithm

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The present paper has three objectives. Firstly, prove that the developed optimisation algorithm can be successfully incorporated in optimization problems of steel structures. Secondly, minimize the difference between the results obtained from a finite element model and others obtained from experiment. Thirdly, obtain values for various variables, simulating the model, that give the best fit with the measured results, i.e. parameter identification.

The aim of the model validation is to develop a three-dimensional computer clad model that behaves under the imposed base movement in a similar way to the physical one. To achieve this, a single set of parameters giving acceptable results for all five base movement modes is required. There are a large number of unknown parameters for the clad model and it is impossible to find out their values by trial and error. Therefore, an optimization technique based on a modified genetic algorithm (GA) is developed and linked to a finite element package. The cladding panels are simulated as shell elements having orthotropic properties. The fasteners are modelled as springs having only longitudinal stiffness in three directions. In the formulation of the optimization problem, the objective function is the differences between the structural behaviour i.e. computed using the finite element model and the real structure i.e measured experimentaly. The design variables, i.e. the model parameters were classified into two parts. The first contains parameters describing the rotational stiffnesses of various connections of the finite element model of the bare frame. The second consists of parameters representing the panel thickness, the orthotropic properties of the cladding and the stiffness of the fasteners.

Keywords: Genetic Algorithm, Model Validation, Parameter Identification, Structural Optimization, Finite Element Analysis.

Composite Joints of Airplane Structures

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In most cases structure joints are responsible for strength, integrity and safety of the structure. A variety of possible and optimal designs is presented. A new, alternative solution of structures joints, based on composite (with glass, kevlar and carbon component) connections is presented as well as results of strength tests. Some of results have been obtained during research project financed by State Committee for Scientific Research and when designing new acrobatic airplane DEKO-9 Magic (www.kaiser-flugzeugbau.de). This idea is protected by Polish patent: UP RP P 173 997.

RC T Cross Sections Bending Design According to EC2 Standard Implementing Analytical Solutions

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The uniaxial bending analysis of reinforced concrete T cross sections is based on the assumption of Bernoulli's-hypothesis. If the neutral axis lies within the web, bending analysis deviates essentially from the analysis of a rectangular cross section due to a discrete change in the width of the web section caused by the flanges.

The paper discusses a detailed analysis of a reinforced concrete T cross section with a neutral axis within the web implementing the bi-linear design stress-strain relationship for the concrete wher the margin between the linear distributions of stresses and the constant value of stresses lies at the strain 1.35% in compression. The paper covers all three possibilities that result from the value of the maximal strain in concrete that appears in the more strongly compressed edge of the compressive zone, and the position of the fibre with strain 1.35% in compression.

If the maximum strain in the concrete is smaller than 1.35%, the stresses in the concrete are assumed to have only a linear distribution, which represents the first case.

If the compressive stresses in the top compressed edge exceed the value of 1.35%, the stress-strain relation is linear for the strains below 1.35%, and the stress is constant for strains over 1.35%. As the margin between the two mathematical descriptions is 1.35% this is the motive to distinguish two further cases according to the position of the fibre with the strain equal to 1.35%: either within the flange or within the web.

For all three cases mentioned, the paper presents the development of the analytical expressions for all the coefficients that are required for reinforcement computation. As all the expressions are given in closed analytical form they replace all charts and diagrams and also represent a very suitable form for computer programs.

Reliability Analysis Applied to Pipelines under Axial Tension, Bending and External Pressure Loads

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The increasing interest in oil exploitation in deep waters has demanded new techniques to better understand the collapse mechanism of pipelines associated with structural analysis. Reliability techniques represent a tool able to investigate target reliability levels by checking the performance of the system against structure collapse.

The collapse strength of pipelines can be strongly influenced by initial geometrical imperfections. Laboratory tests have been conducted using small scale steel models of pipelines with diameter to thickness ratios typical for deepwater applications to determine the collapse under combined axial tension and external pressure loads. Full measurements of the specimens outer surfaces have been performed to obtain the initial imperfection distributions and sectional ovalities. Specially designed apparatus for applying tension loads was employed inside a hyperbaric chamber to simulate the tension pressure load combination.

Analytical formula has been adjusted to the experimental results to obtain the ultimate strength limit equation. Uncertainties due to material, geometry and applied loads have been determined from the experimental data. Sensitivity studies of the variables involved have been performed using a reliability computer program based on Monte Carlo Simulation. The ultimate strength equation

has been used to generate a design curve with adequate reliability level.

A Semi-Analytical Method for Analysis of Floor Slabs in Tall Building Structures

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The out-plane stiffness of floor slabs in tall buildings plays an important role in controlling the top drift of the building. In general, up to 15% of reduction in the top drift of a tall building can be achieved if taking the contribution of out-plane stiffness of floor slabs into account. In the analysis of a tall building, however, number of the simultaneous equations will greatly be increased if all the floor slabs are included into the finite element model. Particularly, it is time consuming to solve these equations when the floor slabs are in irregular shapes. The commonly employed methods to reduce the unknown variables are the static condensation method and the finite strip method. The static condensation method requires a large amount of work for matrix inverse, while the finite strip method is proved to be more effective to handle some regular and uniform plates, but it is not convenient to deal with the plates with an irregular shape, multi-connective-domain or discontinuous material property.

This paper presents a semi-analytical method of analysis for the floor slabs in tall buildings with consideration of the out-plane stiffness. By using this method, the number of simultaneous equations in the finite element model of the building, in which all the floor slabs have been included, will not be increased. In this method, the floor slabs are first divided into several strips. Fig. 1 shows that the two sides of the strip are not necessary to be parallel and there can be a vacuum, material discontinuity or beam elements within the strip.

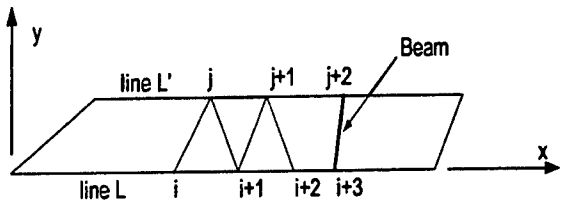


Fig. 1 Typical strip of a floor slab

The strip itself can then be discreted as what can be done using the finite element method (FEM). Displacements of the sides of the strip (see Fig. 1 lines L and L'), which can be described by some specific functions with a few parameters, have the same displacement models as those of FEM It indicates that the relationship among these parameters (generalised displacements) and the FEM displacements of the plate and/or beam elements within the strip can be determined. Based on this relationship, the FEM simultaneous equations for the floor slabs and beams can conveniently be converted to the equations for generalised displacements. The unknown variables are then reduced significantly.

Keywords: semi-analytical method, plate element, floor slabs, tall buildings

The Analysis of the Intense Condition Condition of a Construction of Station "Yunus Rajabiy" of the Tashkent Underground

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The analysis is made with the purpose of determination of bearing ability of a construction of station.

For determination of bearing ability it is necessary to determine internal efforts (flexings moment (M), transversal (Q) and normal (N) forces) in elements of a construction.

For determination of internal efforts (M, Q, N) is used the program: "Account of the 3-rd vaulted station were in an elastic medium".

Main parameters of the program

For account of the 3-rd vaulted station the interface Excel is used. The module of account is named ≪tonnel_36.xls≫ with fitted macross. Account is made by the finite elements method, using plane four angular (plane strain analyses) and beams elements.

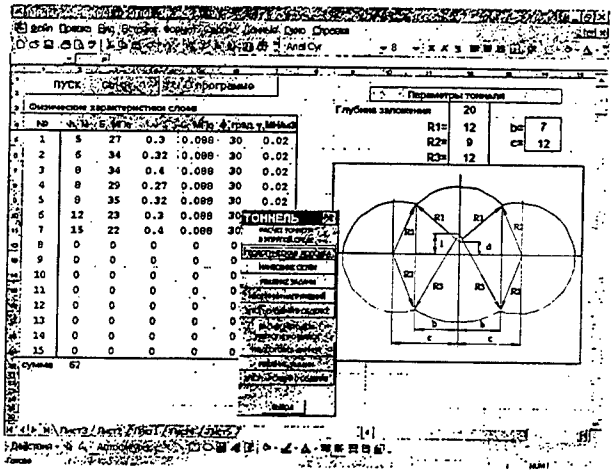
After start of the program on a screen appears 3-rd sheet of the document, on which of we may change parameters of a tunnel and physical characteristics of a geological column. With the help of interface Excel are entered:

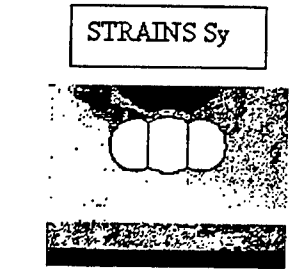
- Depth of a location of station
- Radiuses of station tunnels (R2)
- Radius of vaults of station (R1)
- Radius of a sole of station (R3)
- Distances from an axes of a station tunnel up to an axes of station (C)
- Distance from an axes of station up to an axes station column.

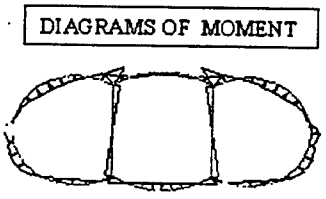
In the table of physical characteristics of stratums are entered the characteristics of a geological column (represented under the base of geological surveys):

- Depth of a stratum (h, m)
- (E, Mpa)
- (ν)
- Volumetric weight, MN/M3

For getting settlement datas in an elastic medium it is necessary to press a key ≪START≫ in the upper left angle of open page. In an result on a screen will appear the settlement submenu with items:







SESSION F3J
STRUCTURES IV

A General Nonlinear Theory for Sandwich Shells with Transversely Compressibile Core

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Structural sandwich panels are important elements in lightweight construction, where plates and shells with high bending stiffness and low specific weight are required. The classical structural sandwich panel is a layered medium consisting of two high-density face sheets, which are adhesively bonded to a low-density core. The buckling and postbuckling behavior of sandwich plates and shells is essentially different from the stability behavior of standard laminates and monolayer panels due to the different features relevant to the face sheets and the core. In this sense, the face sheets are modeled within the framework of the Kirchhoff-Love hypothesis wheras for the weak-type core, the assumption of transverse compressibility is adopted.

In the present contribution, a comprehensive geometrically nonlinear theory for flat and doubly curved sandwich shells is derived. The structural model accounts for finite strains and initial geometric imperfections, as well as for dynamic effects. The nonlinear equations of motion and the corresponding boundary conditions are derived by means of Hamilton's variational principle. As a result of its comprehensive formulation, all interactive features are incorporated in a natural manner, and their effects are thoroughly investigated.

The model is applied to a buckling and postbuckling analysis of orthotropic elastic sandwich panels. Both flat and curved shells are considered. An analytical solution is obtained by means of an extended Galerkin scheme. Both the overall buckling and the local face wrinkling stability modes are adressed. In addition, coupling effects between both types of stability are investigated.

Keywords: Sandwich structures, Geometrical nonlinearity, Composite shells, Stability

Importance of Geometric Nonlinearity on the Vibration of a Shell Under Pressure

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It has been realized in the past that geometric nonlinearity is important in order to account for the effects of pressure on the vibration of a shell. Several approximations have been made by researchers in order to simplify the equations of motion. In this work, we explore the accuracy of these approximations by considering an inflated toroidal shell with free boundary conditions. Using the line-of-curvature coordinates and the exact geometric nonlinearities in the in-plane strains, equations of motion are derived. The nonlinearity is considered only with the prestress terms, and the governing equations of motion about the pressurized equilibrium state are linear. After that, the equations are rearranged by utilizing the static equations and the Gauss-Codazzi conditions. These equations have been derived earlier by Budiansky using tensor notation (Budiansky, 1968). Thereafter, we approximate the equations to get the derivations of Sanders (1963), Soedel (1986), and Plaut et al. (2000). In order to investigate the accuracy of these approximate equations, we solve the free-vibration problem of the inflated torus using Galerkin's method and Fourier series. We compare the natural frequencies based on these four theories. It is shown that the approximations lead to nonzero natural frequencies corresponding to the rigid-body modes.

1. Budiansky, B., 1968, "Notes on Nonlinear Shell Theory," *Journal of Applied Mechanics*, Vol. 35, pp. 393-401.
2. Sanders, J. L., 1963, "Nonlinear Theories for Thin Shells," *Quarterly of Applied Mathematics*, Vol. 21, pp. 21-36.
3. Soedel, W., 1986, Vibrations of Shells and Plates, Marcel Dekker, New York.
4. Plaut, R. H., Goh, J. K. S., Kigudde, M., and Hammerand, D. C., 2000, "Shell Analysis of an Inflatable Arch Subjected to Snow and Wind Loading," *International Journal of Solids and Structures*, Vol. 37, pp. 4275-4288.

Modelling a Bistable Composite Structure

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In 1981, Hyer described the bistability of certain unsymmetric composite laminated structures. These structures were formed initially flat, but when cooled from an elevated curing temperature, thermal contraction combined with extensional-curvature coupling led them to take a cylindrical profile about one of two different axes; the resulting structure could be switched between these two bistable positions.

This talk will describe a new type of bistable structure where the bistability is deliberately engendered by forming the structure in a cylindrical shape; the structure can then be used, e.g. for a deployable mast that can be compactly coiled. These structures are made from particular antisymmetric composite laminates; in this case it is necessary for the layup to be antisymmetric to eliminate curvature-twist coupling. A simple model that captures the key behaviour of these structures will be described, and will be shown to give identical results to applying the Dano and Hyer model for the deformation behaviour of unsymmetic laminates to an initially curved structure.

Virtual Load and Substructure Method in Repetitive Structures Analysis by Discrete Fourier Transform

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In this paper, the static equilibrium state of finite repetitive lattices is represented by a functional governing equation written in terms of the physical stiffness operator with a matrix-function kernel. The operator acts as a discrete convolution sum over the kernel and displacement functions, and is written independent of boundary conditions to represent the structural properties only. The boundary conditions are taken into account at a subsequent stage of the analysis through the virtual load and substructure technique, which is used to formally close the structure and emulate the cyclic symmetry. Discrete Fourier transform

has been utilised to solve the boundary value problem with the governing equations for both beam- and plate-like lattices. The displacement solutions are sought as vector functions of discrete spatial parameters, to represent response of the lattice to in-domain loads and general boundary conditions. These solutions have been written as discrete convolution sums over the Green's and load functions. The Green's function does not depend on the beam or plate boundary conditions either, since it is obtained for the modified closed structure to describe the basic response behaviour of the last. The virtual boundary loads are included into the final solutions to eliminate the effect of the additiona l virtual substructure, required for the cyclic symmetry emulation. The equivalence of static responses of the modified and original lattices is achieved, when the modified structure solution satisfies the original boundary conditions.

Calculation and Analysis of Support Force for Large-scale Rotary kiln with Multi-support

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Abstract Kilns are the key equipment in the production of metallurgy, cement and material of fire-fast. It is a very important task for those plants to maintain equipments. And it is the key method to advance the economic benefit of the above plants to ensure the kilns work safely and efficiently, which is very difficult to treat with. The following is the reasons.

- It is the statically indeterminate system with over load, large torque and multi-support. The kiln is general very weighty to about a thousand tons, which has 4 9 groups of shelf support. It is impossible to solve the equations by using general statically indeterminate method.
- When operating the equipment, owing to asymmetric thermal expansion and abrasion, the practical center of rotation is not in line of that of the multi-support.
- The change of the operating axes of kilns will affect the distribution of support force. The support bending torque and the stress of the shell will in crease three times when the center line change.
- It is very difficult to measure the support force of the kiln directly.

There are some researches on measuring the operating axes of kiln, which is helpful to obtain the support force. In this paper, the general model and matrix, which are used to solve the variable-stiffness beam upon complex load for kiln, are established Based on the research on the distortion of variable-stiffness beam. The relation between the support force and warp is derived. The resultant force of kiln in vertical and horizontal direction is calculated. Firstly, the reference frame is established in vertical plane. The head of kiln is coordinate origin, an ideal rotary axes is x direction, the vertical direction of section of kiln shell is y axes, and the horizontal direction is z axes. In the vertical plane of the kiln, another coordinate is established In two ends, there is reactive couple in this statically indeterminate beam model. The coordinate origin of $x-y$ system is the left end support of the beam. The bending stiffness of variable-stiffness beam is divided into s segments with the same stiffness in the direction of x, which will produce $s-1$ variable-stiffness sections. For k segment with the same stiffness, the coordinates of its two ends sections are x_{k-1} and x_k respectively. Its bending stiffness is EI_k. The load of beam can be converted into several concentrated couple, concentrated forces and uniformly distributed load. The load of the beam is grouped and numbered according to the same stiffness. Accordingly, the liner formulas for calculating the support force of the support wheels fixing on the rotate kiln are obtained. For segment s with n spans in the statically indeterminate beam model, the variable vector for solving is defined as $\mathbf{X} = [\mathrm{y}_0, \theta_0, \mathbf{M}_0, \mathbf{R}_0, \mathbf{R}_1, \mathbf{R}_2, \ldots, \mathbf{R}_{n-1}, \mathbf{R}_n, \mathbf{M}_n, \theta_n, \mathrm{y}_n]'$ Obviously, there are $n+7$ variables and $n+7$ equations in the vector $\mathbf{X}$. When defined $\mathbf{y} = [\mathrm{y}_0, \mathrm{y}_1, \ldots, \mathrm{y}_n]'$ as the support warp calculating the support force; $\mathbf{k}$ is stiffness matrix of support system, which imply the immanent response characters of statically indeterminate structure. The calculating and applying example are given. And some useful analysis conclusions can be obtained.

(1) The load and the axes structure are not simplified in the deriving; the support form at the axes ends is not limited. So the method is a general calculating one for multi-support load beam.

(2) The matrix has nothing to do with initial level and load and it imply the immanent response characters of statically indeterminate structure.

(3) The support force can be calculated conveniently by the linear relation of support force from support wheel and support warp in vertical and horizontal.

(4) The support force distribution of support wheel is affected large by horizontal displacement, less by vertical. When vertical support force is positive, load of wheel also will become negative due to horizontal warp.

Keywords: multi-support; variable-stiffness beam; rotary kiln; calculation of the support force; linear formula

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A Comparitive Study of FE Model Order Reduction Schemes for 2D Linear Transient Elastodynamics

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Over the years, in the field of Computational Mechanics, the accurate representation of full order elastodynamic characteristics by solving a lower order system has been appreciated as one of the most interesting area of research. This has potential utilities in many large-scale industrial applications such as vibration and noise transmission. In the proposed paper, various FE model order reduction techniques such as Improved Reduced System (IRS), Dynamic Condensation (DC) technique and System Equivalent Reduction and Expansion Process (SEREP) for 2D linear transient elastodynamics are first studied. Comparative results are presented for accurate analysis of a thick cantilever plane-stress model subjected to in-plane and transverse excitations at low and high frequency bands. A computational strategy to extract the accurate response against high frequency narrow band excitation is implemented within the framework of SEREP and results are compared with the full-scale system. This is the most challenging problem as far as model order reduction schemes are concerned as the position of the central frequency lies at the arbitrary point on frequency axis in the Power Spectral Density (PSD) distribution. This has particular application in structural acoustics and diagnostics simulations using guided wave technique.

Towards application in structural diagnostics, it is essential that the damage parameters are estimated accurately while dealing with a highly reduced order model. Considering LEFM in 2D metallic and laminated composite structures, the effect of model order reduction on J-integral is focused in the this paper. A two dimensional cantilever structure with Mode-I type edge crack is studied for the dynamic response against high cycle fatigue loading. Also preservation of the global dynamical characterstics of the system is shown as observed correlation of the displacements, velocity and stress histories with those of the full systems.

SESSION W2O
THEORY AND MODELING IN FLUIDS

Towards a Split Lagrangian-Eulerian Model for Autorotation Phenomena

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The subject of autorotation is barely mentioned in textbooks and considered more a curiosity than a serious topic, but autorotation gained interest in several unrelated areas (flight dynamics of aircraft, aero-ballistics, biology meteorology and sports). The diversity of these application areas and the difficulty (experimental and theoretical) in obtaining qualitative data are the reasons for the lack of a comprehensive treatment that explains autorotation satisfactorily (Lugt H. J., 1983). We introduce here a new model to predict the evolution of free-moving bodies based on the body interaction with its vortex-wake. We proposed to split the analysis into two parts each dealing with a separate region of the flow: an Eulerian analysis in the close surroundings of the body (what we call the micro-model) and a Lagrangian free-vortex-lattice scheme that models the behavior of the wake (the macro-model). For the Eulerian analysis we propose a new approach for studying flows around bodies with no separation: the Constant-Curl Laplacian Equation, it owns the simplicity and linearity of potential analysis but includes rotational effects induced by the rotational displacement of the body. It assumes that rotation is constant inside each time step so complex curved trajectories are approximated by a sequence of circular tracks. The idea is based on a kinematic scheme that states the nullity of the velocity field Laplacian, imposing simultaneously conditions of incompressibility and constant curl for velocity. We use 9-node isoparametric finite elements, interpolating velocities and imposing the incompressibility and curl-constancy conditions by a combined penalty method. Results match experimental data for aerodynamic forces and wake constitution on wind-turbine blades.

Keywords: Vortex-model; Finite element method; Moving bodies; Autorotation

Enhancement of Heat Transfer in Oscillating Flows

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It has been reported [1] that for Helmholtz pulse combustors, a heat transfer of the order two to five times higher than expected can be found. From experiments [2], where the temperature profile in the tail pipe of a pulse combustor has been measured, there is no indication why the heat transfer should be enhanced. Interaction between the oscillating velocity and temperature fields might be the explanation and/or perhaps that the classical constitutive relations usually set up is incomplete or insufficient.

First, the heat transfer of an oscillating flow between two parallel plates will be examined from first principles by simply analytically solving the classical governing equations. The analytical solutions obtained for the velocity and temperature fields then give the heat transfer. For pulse combustors the calculated and experimental results are in good agreement 3]. Generally, the calculated heat transfer at the plates over one cycle is found to depend on the frequency of the oscillations and the phase difference between the pressure and temperature oscillations. That means, for certain intervals of and enhanced heating (and cooling) processes can be found in oscillating flows. The magnitude of the heat transfer will depend on the amplitude of the oscillating fields.

The next step will be to examine, using the analytically found velocity and temperature fields, the consequences of introducing more general constitutive relations. The magnitude of thermo-mechanical generators can now be estimated and compared.

[1] See e.g. Dec,J.E., Keller,J.O. and Arpaci,V.S., (1992) Int. J. Heat Mass Transfer 35:2311-2325.

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Exact Solutions for the Unsteady Unsteady Plane Couette Flow of a Dipolar Fluid

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In 1967, Bleustein and Green [2] presented the theory of dipolar fluids, the simplest example of a class of non-Newtonian fluids known as multipolar fluids. In this work, the unsteady Couette flow of an incompressible dipolar fluid between two infinite parallel plates is studied, the flow being initiated by the sudden acceleration from rest of the top plate to a constant velocity $V_1 (\neq 0)$. Exact solutions, which are valid for arbitrary values of the dipolar constants $d(\geq 0)$ and $l(> 0)$, are obtained by solving the IBVP

$$u_t - \nu u_{yy} - d^2 u_{yyt} + \nu l^2 u_{yyyy} = 0, \quad (y,t) \in (0,h) \times (0,\infty), \tag{1}$$

$$u(0,t) = 0, \;\; u(h,t) = V_1 H(t), \;\; \mu l^2 u_{yy}(0,t) = \mathcal{M}_0, \quad \mu l^2 u_{yy}(h,t) = \mathcal{M}_1, \quad t > 0, \tag{2}$$

$$u(y,0) = 0, \qquad 0 < y > h, \tag{3}$$

where $\mathbf{v} = (u(y,t), 0, 0)$ is the velocity vector, $H(\cdot)$ is the Heaviside unit step function, h is the distance between the plates, ν is the kinematic viscosity, μ is the shear viscosity, and the constants $\mathcal{M}_0$ and $\mathcal{M}_1$ denote the values taken by the dipolar stress component Σ_{yyx} (or traction) at the lower and upper plates, respectively, using the Laplace transform. In considering special/limiting cases of the dipolar constants, exact solutions are also determined for Rivlin–Ericksen fluids, fluids with couple stresses, and viscous Newtonian fluids. In addition, the effects of start/stop plate motion are considered. Most significantly, it is shown that the velocity fields of fluid's with nonvanishing d all suffer the same jump discontinuity on start-up, a transient back flow condition is possible when $l > d$, and for special values of the material parameters the flow instantly attains steady-state.

Keywords: dipolar fluid, instant steady-state, jump discontinuity, Laplace transform

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The Model of Accelerately Deforming Fluid

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Newtons model of viscous flueid well describes the motion of structureless fluids and is defined by the only rheological parameter of a dynamic viscosity. In real fluids there take place such a physical processes as rebuilding of above-molucular structures, molar transfers, subbuilding of abmixture to the motion of fluid. To consider such processes it is necessary to build a model determined by rheological parsmeter characterizing mentioned above processes in real flows of fluids a new approach in modelling of internal processes of transfer of physical substances of simultaneous participation in this process of different level of structural units is developed in the paper.

On the basis of author's hypothesis, modelling the process of molar transfer of the quantity of motion there was abtained an equation expressing the proportionality of stresses of spatial heterogeneity of the field of acceleration, where the coefficient of proportionality is a rheological parameter with dimension of linear density. A concept of accelerated deformation of fluid and an equation defermining this value are introduced.

A closed system of differential equations describing the motion of fluids with elastic, viscous and inertial characteristics of deformation is offered. The possibility to obtain from a given model in this or that approximation the multitude of partial models is shown. The interaction between limit tangent stresses to and newly introduced rheological parameter me is stated. A mechanical element of accelerately deforming medium is introduced; when combined with Hook and Newton mechanical elements, different reological models of elastic-viscous-inertly deforming media were obtained; the possibility of classification of media was shown. The media are classified by homo-thermal, exothermal and endothermal classes depending on relation of the time of relaxation to the time of retardation.

Keywords: Non-Newtonian fluids, molar transfer, retardation, relaxation.

Spectral Filtering Formalism and its Application for Multi-Resonant Multi-Phase Water Waves

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A new formalism of spectral filtering for description of modulation processes is proposed. The method allows one to solve a hard classical problem of multi-phase modulations in dispersive systems. Here, deep water waves are considered. Spectral filtering for deep water waves results in a system of equations that describe modulations of carrier wave and its harmonics. As a result, the method unifies and extends a few well-known expansion methods: description in terms of discrete modes, approach of single-mode modulation, and one-dimensional three-wave interaction technique in optics. In the context of the water waves, the equations given by the method may be considered as an alternative to the well-known integral Zakharov equation. The formalism may find applications in a broad range of physical situations with multi-phase dynamics.

Wake/Vortex Breakdown in Supersonic Flows

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The paper is concerned with the interaction of the shock wave with the viscous wake downstream of a solid body in a supersonic flow. Two approaches were used to study the process of the interaction. The first approach is analytical, it relies on the asymptotic analysis of the Navier-Stokes equations at large values of the Reynolds number. It is assumed that the shock impinges the wake (planar or axisymmetric) finite distance downstream of the trailing edge of the body. The analysis of the wake/shock interaction process shows that the fluid deceleration inside the wake is predominantly inviscid phenomenon, such that the wake breakdown may be easily predicted using the Bernoulli's equation. It governes the flow inside the core of the wake, while for the flow outside the wake the Ackeret formula (or its axisymmetrical counterpart) may be used. The corresponding "inviscid-inviscid" interaction

integro-differential equation have been studied numerically. It was found that on the final stage of the interaction process (leading to the flow reversal near the axis of symmetry of the wake) the viscosity becomes important. Interestenly enough, the solution in this new viscous region could be found in an analytical form.

The second approach is based on the conventional triple-deck description. It may be used when shock impinges on the wake within the conventional trailing edge triple-deck region. The results of the calculations show the incipience of the separation at the shock location, and reveal hysteresis behaviour of the flow as the shock is moved downstream, giving rise to three solution branches. The critical shock strength seen on the upper branch corresponds well to that predicted by the Bernoulli's equation in the case of an inviscid interaction as seen where the shock impinges downstream of the conventional triple-deck region.

Keywords: Viscous-Inviscid Interaction, Vortex Breakdown.

SESSION M2P
TURBULENCE

Construction of a Subgrid Model for Fluid and MHD Turbulence Based on EDQNM Closure Theory

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Direct numerical simulations of turbulence at high Reynolds numbers are not possible due to limitations of supercomputers. Large-eddy simulations (LES), which resolve the three-dimensional, time-dependent large scales of the flow, while modeling the more universal smaller scales, have been very successful in fluid turbulence calculations.

Using the kinetic energy transfer obtained from the eddy-damped quasi-normal Markovian (EDQNM) model, the asymptotic eddy viscosity and backscatter terms are computed as a function of k/k_c (where k_c is the cutoff wavenumber) and time. The behavior of these terms is studied using several assumed forms of the kinetic energy spectrum and a spectrum from an EDQNM calculation, as well as different filters. The eddy viscosity and backscatter are further decomposed into a sum of contributions corresponding to the Reynolds and cross stresses, and studied as a function of energy spectra and choice of filters. The implications of these results for subgrid-scale modeling in spectral large-eddy simulations of incompressible, isotropic turbulence are discussed.

There has been very little effort to develop subgrid models for LES of high Reynolds number MHD turbulence. A subgrid model based on the EDQNM closure will be constructed here, which contains models for both the mechanical and magnetic eddy damping and backscatter. The properties of the eddy damping and backscatter terms will be investigated for several filters, and the contributions from the cross and Reynolds stresses will be discussed. The analysis is carried out both in terms of the velocity and magnetic fields, as well as in terms of the Elsasser variables. The spectra are obtained from direct numerical simulations and assumed power law forms. This model is expected to be used in future LES of high Reynolds and magnetic Reynolds number MHD turbulence.

Keywords: LES, closure, viscosity, backscatter

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Turbulence Intensity Distribution for Flow Along a Streamwise External Corner

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The streamwise development of turbulent boundary layer over an external corner (chine) is influenced by secondary flow driven three-dimensionalilty. In practice this kind of flow occurs on ship's hull, wingtip of an aircraft and long transport vehicles like train, truck, bus etc. Direct effect of this secondary flow is to increase the drag force. Here secondary flow, which is known as Prandtl's second kind, is induced by inequality of Reynolds stresses around the corner. This flow is expected to exhibit symmetry about the corner bisector. Moinuddin *et al.* (14AFMC, 2001 and 9ACFM, 2002) has established the symmetry of this flow based upon mean flow measurements. Normal wire measurements for the streamwise turbulence intensity $< u'2 >$ profiles, measured at about Re_θ 5700 and 4.7 m from the model leading edge, will be presented. These represent total 19 profiles measured over the horizontal surface (denoted as h), vertical surface (denoted as v) and in the turning region. Comparisions are made for $< u'2 >$ profiles at equal spanwise

distance, from the corner, on both surfaces. The profiles agree quite well having nominal deviation depending on spanwise and normal distance from the corner as evident from Figure 1. Isointensity contours also depict symmetrical turbulence distribution. It is also revealed that far from the corner turbulence profile agrees well with the standard two-dimensional turbulence profile. The measurements provide the general behavior expected from this kind of flow as reported by Xu & Pollard (Phys. Fluids, Nov,2001) for their large eddy simulation of flow in an annular square duct.

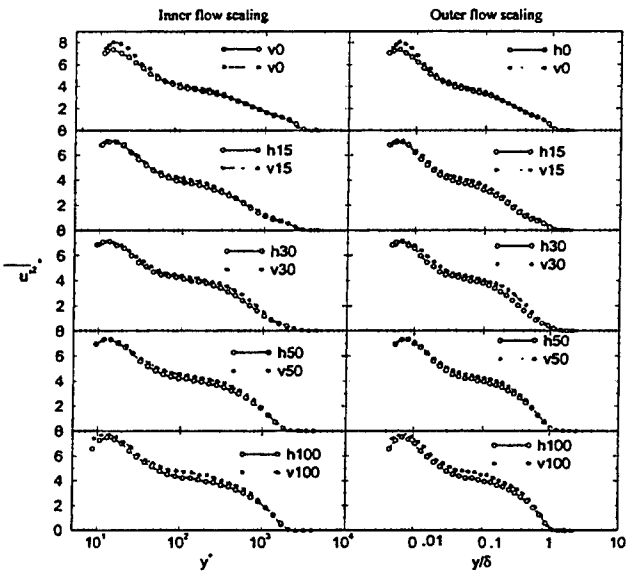
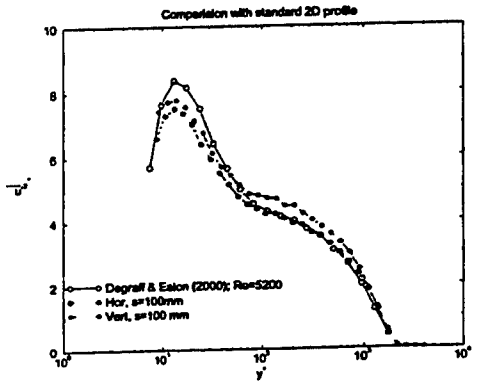


Figure 1: Comparison of Streamwise turbulence intensity profiles at equal spanwise distance from the corner.



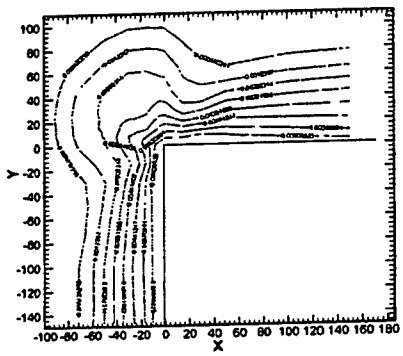


Figure 2: Top figure shows the comparison with Degraff & Eaton (JFM,422,2000)'s LDV data(s denotes spanwise distance from the corner). Bottom figure shows isointensity contours (distances are in mm).

Self-Sustaining Mechanism of Organized Structures in Near-Wall Quasi-2D Turbulence

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A direct numerical simulation of quasi-2D forced turbulence in channel flow was performed in order to verify the newly proposed hypothesis (Nikitin and Chernyshenko, [1]) according to which near-wall coherent structures result from an instability caused by anisotropy of normal Reynolds stresses. The theory utilizes the fact that within viscous and buffer layers the difference $q = < v'^2 - w'^2 >$ is nonzero (w', v' and z, y are the wall-normal and spanwise velocity fluctuations and directions respectively) and states that $-\partial q/\partial z$ acts similar to a buoyancy force normal to the wall. It was found from visualization of DNS results that the number of low-speed streaks (or quasi-streamwise vortices) that form in a fixed spanwise periodic length agrees well with results of linear stability analysis of the cross-flow plane governing equations utilizing $\frac{\partial q}{\partial z}$ vs z profile. Based on our findings we propose that the loop of the regeneration mechanism of near-wall turbulence can look like chaotic motion $\rightarrow$ longitudinal vortices $\rightarrow$ streaks $\rightarrow$ their instability $\rightarrow$ nonlinearity $\rightarrow$ chaotic motion.

We used the pseudo-spectral channel flow code of Sandham and Howard [2], in which Fourier and Chebyschev methods are used for spatial discretization. The calculations were performed in a computational box of size $L_x = 0.5$, $L_y = 2\pi$ and $L_z = 2.0$ on a grid having 4*512*320 nodal points at a $Re = 360$ based on mean pressure gradient. The initial random velcoity field had no organized structures and was divergence-free and independent of streamwise direction x. Body forces in y-z plane were used to generate cross-flow motion. These

body forces had random amplitude in time, a sinusoidal spatial variation of fixed wavenumber in spanwise direction and a peaked near-wall amplitude in wall-normal direction. In this study we discovered that near the wall the resulting large-scale structures produce streaks similar to those observed in 3D near-wall turbulence. On the whole our findings give circumstantial evidence in favor of the theory [1].

Keywords: Self-sustenance, 2D near-wall turbulence, Anisotropy, organized structures

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Numerical Study of Stratified Oil-water Two-phase Turbulent Flow in a Horizontal Tube

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Stratified oil-water two-phase turbulent flow in a horizontal tube (ID=55.75mm) was numerically simulated using a volume of fluid (VOF) model. The oil is a petroleum distillate with density of 790 kg/m^3 and dynamic viscosity of 1.6 cP at 25°C. Water cut is in the range of 10 $\sim$ 86%. The maximum Reynolds numbers of oil and water reach 55000 and 110000 respectively.

In the VOF model, a single momentum equation is solved throughout the domain while a volume fraction equation is solved to track the interface between phases. The RNG k$-\epsilon$ model combined with a near-wall low-Re turbulence model is applied to each phase, and a continuum surface force (CSF) model is applied for the calculation of surface tension. A piecewise-linear interpolation scheme is used for interface calculation. The simulation was performed in a time-dependent way for the sake of numerical stableness and then the final solution which corresponding to steady-state flow was analyzed.

Present numerical results were compared to data of G. Elseth et al.'s (2000). As shown in Fig. 1, the present model shows more successful in predicting the axial velocity profile than G. Elseth et al.'s ascribing to our more delicate modeling of turbulence and surface tension; and the predicted water fraction profile also agrees with experimental results very well. As shown in Fig. 2, the predicted slip ratio is reasonably in accord with experimental data, while the predicted pressure loss achieves good agreement with experimental results when water cut is within 0.2 $\sim$ 0.8 and exhibits prominent deviation when water cut exceeds 0.8.

Extensive calculations were carried out for the cases of various phase fractions and flowrates. Based on the numerical results, flow field and interface characteristics were described as well as correlations for pressure loss and sectional phase fraction were presented.

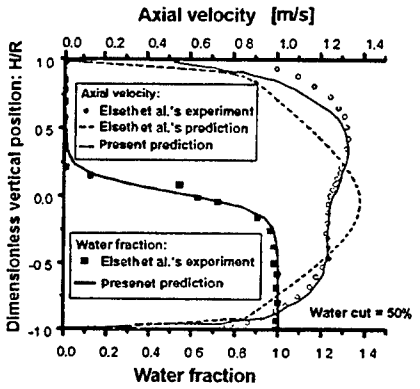


Fig 1. Predicted and measured profiles of axial velocity and local water fraction

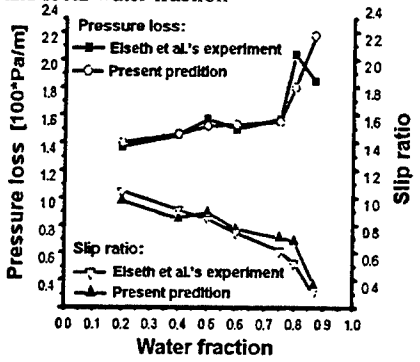


Fig 2. Predicted and measured pressure loss and slip radio

Keywords: Stratified two-phase flow, Turbulence, Numerical simulation, VOF model

Supported by the National Natural Science Foundation of China (59995460-2).

SESSION T4D
TURBULENT FLOWS & INSTABILITIES

Turbulent Transport Downstream from a Step Change in the Heat Flux from the Wall of a Channel

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Numerical experiments using a Direct Numerical Simulation (DNS) of turbulent channel flow, combined with Lagrangian Scalar Tracking (LST) of trajectories of thermal markers in the flow field (Papavassiliou & Hanratty, *Int. J. Heat Mass Tansfer*, 1997), are conducted. The probability density function that describes the behavior of an instantaneous heat source at the wall of the channel is used to create the mean temperature in the case of a step change in the heat flux from one wall, and in the case of heat transport from both walls. The method is applied for a wide range of Prandtl number fluids ($0.01 < Pr < 50000$). The Reynolds number of the flow, based on viscous wall parameters, is 150.

Results from the DNS/LST method are compared to previous data available for different Pr fluids. The heat transfer coefficient downstream from the step change in wall heat flux is also calculated for different Pr. The distance at which the thermal layer is fully developed seems to be larger than previously thought, for the case of low Pr.

The influence of Pr on transport properties is examined next. The heat transfer coefficient is conventionally given in the form of a correlation for the Nusselt number. Regarding Pr dependence, there is a controversy among investigators that argue for a heat transfer coefficient, h, that goes as $h\ Pr^{(-3/4)}$, and those that argue for $h\ Pr^{(-2/3)}$. This argument originates from the asymptotic behavior of the eddy diffusivity, Ec, very close to the wall. If $Ec\ y^3$ as $y- > 0$ then $h\ Pr^{(-2/3)}$ but if $Ec\ y^4$ as $y- > 0$, then $h\ Pr^{(-3/4)}$. To further complicate the issue, there is experimental evidence that the exponent is neither of the above (Shaw & Hanratty, *AIChEJ.* , 1977). We will show that DNS with LST can be used to provide answers to these questions.

Keywords: Turbulent transport, DNS, Lagrangian methods.

Interaction Between a Trailing Vortex and External Turbulence

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Trailing vortex has been investigated for many years both from the practical interest to improve the efficiency of the safe operation of airplanes and from the theoretical interest to understand motions of swirling fluids. Here, it is important to study the interaction between the vortex and external turbulence.

We consider the Lamb-Oseen vortex and Batchelor's trailing vortex and investigate their instabilities in ambient turbulence using direct numerical simulation. As an external field, numerically produced turbulence by the Fourier-spectral method is used which R_λ is about 120.

Both of the ordered vortex and worms can be extracted by the low pressure swirling vortex method[1]. As in [2], we can observe spiral structures (deformed worms) around the Lamb-Oseen vortex. We find that the columnar vortex, which itself expands slightly, winds up the worms. They enhance energy dissipation considerably.

Using the two-point energy-spectrum tensors, we can capture such phenomena as the 'Blocking Effect' (fluid particles cannot invade the core of the ordered vortex) and the excitation of bending and axisymmetric vortex waves. As Miyazaki et al.[3] predicted, the axisymmetric (Blocking Effect) components grow time-dependency as t^2. They have outstanding magnitude at $k_z \simeq 0.5$. In contrast, axisymmetric vorticity correlations, represent the wrapped worm structures, are large at $k_z \simeq 10.5$.

In addition, we study the instability of Batchelor's trailing vortex. At the early stage of the numerical computations, the growth rate of the unstable modes agree with those of the linear analysis[4]. When the secondary instability is excited, the ordered vortex collapses and many fine scale vortices appear abruptly.

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[3] Miyazaki, T. et al.: J. Fluid Mech. 402 (2000) 349.
[4] Mayer, E.W. et al.: J. Fluid Mech. 245 (1992) 91.

Continuous Three-Component Velocity Measurements in a Near-Wall Cross-Stream Plane in Channel Flow

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We have previously applied time-resolved PIV to measure near-wall cross-stream velocities in a smooth-bed open channel flow at $Re_\tau = u_\tau h/\nu = 300$ (flow depth $h = 10.0$ cm; width 50 cm). Applying Taylor's hypothesis to time series of streamwise vorticity, reference [1] provided the first direct experimental evidence for the staggered arrangement of streamwise vortices (gSVh) educed from DNS data by Stretch[2]. Ref. [3] presents spatio-temporal correlations that reveal the typical orientation of vortex cores, and demonstrate a strong tendency for

straining regions to lie above, or to the sides of, vortex cores. The present communication reports the first time-resolved *stereo* PIV measurements in the cross-stream plane of a turbulent channel flow, and investigates the relationship of streamwise vortices with slow-speed streaks and with regions of high $-uv$.

Method. Conditions are as above, but flow depth is now 8.00 cm. The measured region is 5.0 cm wide * 4.5 cm high. 1K*1K images are recorded at 30 f.p.s. Twin Nd-YAG lasers are run at 15 Hz with a 5 ms delay, and illuminate a 3 mm thick cross-stream sheet. Scheimpflug cameras view the sheet from upstream and downstream through liquid prisms at 30^o to the stream direction. This nonstandard scheme exploits the higher intensity of forward-scattered light to both cameras, and yields image distortion which is symmetric for the two cameras.

Results. Three dimensional spatio-temporal plots of streamwise vorticity often reveal low-speed regions snaking under staggered counter-rotating SV, and regions of high $-uv$ to the sides of SV, exactly as inferred by Stretch. We will report on spatio-temporal correlations related to such aspects of near-wall structure. Although the most likely outcome is simply to confirm knowledge already obtained by DNS, we plan in subsequent work to extend our program to higher Reynolds number and to rough boundaries.

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Investigation of the Instantaneous Dynamics of the Large-Scale Structures In The Impinging Jet

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Didden and Ho [J. Fluid Mech., 160, 235-256, 1985] examined the development of the large-scale structures in an acoustically excited impinging jet with a nozzle to plate spacing of 4 diameters using measurements of the velocity field conditioned on the fluctuating wall pressure. They showed that there was an unsteady separation of the large scale ring vortices approximately 1.5 diameters from the jet centreline. Gao and Ewing [Proc. of the 48th CASI conf., 2001] and Hall and Ewing [Proc. of the CSME Forum, 2002] later examined the evolution of the large-scale structures in an impinging jet exiting a fully developed pipe using measurements of the two-point, two-time correlation of the fluctuating wall pressure in both the radial and azimuthally directions. They showed that this technique could be used to examine the development of the vortex ring structures in the impinging jet. They also found that the importance of the vortex ring structures in the evolution of the radial wall jet decreased as the nozzle-to-plate spacing was increase beyond 2 diameters and that the evolution of the ring structure before and after the separation point were correlated even though they traveled at different convection velocities. The objective this investigation is to extend the work of Hall and Ewing by investigating the dynamics of the large-scale structures in the field. This will be accomplished by simultaneously measuring the fluctuating wall pressure at the 112 points taps on the impingement plate. The resulting field will be filtered using proper orthogonal decomposition and wavelet techniques to extract the dynamics of the large-scale structures for a range of nozzle to plate spacings.

Thermal Effect on Crossflow Instability in Supersonic Boundary Layers

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There has been renewed interest in supersonic laminar flow aircraft in recent years due to the DARPA Quiet Supersonic Platform (QSP) project. This paper is intended to study feasibility of thermal control on supersonic swept-wing boundary layers. Viscosity is a strong function of temperature; it follows that wall cooling directly affects the stability characteristics of viscous-mode instability waves. Thermal effect on Tollmien-Schlicting (TS) wave, the first-mode and higher-mode disturbances in compressible boundary layers is well understood owing to the work by Mack[1]. On the other hand, little is done for crossflow instability wave.

We use the NASA Langley LASTRAC[2] code to study the thermal effect on supersonic boundary layers. For a Mach 2 flat plate boundary layer at typical flight conditions, it was found that by decreasing the wall tempera-

ture from adiabatic to $T_w/T_{ad} = 0.97$ (about $20°F$ reduction in wall temperature), transition Reynolds number (based on a boundary-layer length scale and measured at an N factor of 10) changes from 4940 to a value of about 6450, a 70% reduction. It was found that wall cooling also stabilizes supersonic crossflow instability waves. Stability results for the same Mach 2 flow over a 70° swept wing show that by lowering the wall temperature to $T_w/T_{ad} = 0.75$, which amounts to about $160°F$ reduction in wall temperature, transition location based on $N = 15$ for traveling crossflow moves from $x/c = 0.24$ to 0.43, an increase of about 80% in x/c. Our results indicate that wall cooling has a stabilizing influence on both stationary and traveling crossflow instability waves for a supersonic swept wing boundary layer at a typical flight condition. The results suggest that for the same free-stream condition, the reduction in T_w/T_{ad} required to maintain laminar flow is larger for crossflow instability than that in the first-mode case.

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Nonlinear Instability of a Liquid Compound Jet

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In their experiments Hertz and Hermanrud [1] visualized the flow of a compound (two-layer) jet consisting of a liquid core (primary jet) and coaxilal (secondary) layer of another immiscible liquid. It is demonstrated that similar to the classical one-layer jet (see e.g. Rayleigh [2]) the compound jet is unstable as well and its final disintegration form is controlled by the properties of the both liquids (phases). The present paper deals with the nonlinear instability of an axisymmetric compound jet, assuming both phases are incompressible and nonviscous. The equations of motion of the core and secondary layer are written in 1D approximation (generalized Lee model [3]). In these equations the effects of the surface tensions of both the inner and outer interfaces are taken into account, while the gravity effects are neglected. A numerical method is proposed for calculating the evolution in time of the disturbed interface radiuses and axial velocities of the core and layer. The initial form of the spatially periodical disturbances is taken from the linear instability analysis of the jet. Three different disintegration regimes are found namely (i) breaking of the core, (ii) simultaneous breaking of the core and secondary layer, (iii) disintegration by meeting of the interfaces. The First and Second regimes are controlled by the ratio of the surface tensions, while the Third regime depends on the density ratio. The experimental observations that the jet disintegration gives rise of both main and satellite drops are confirmed numerically. Moreover it is shown that the satellites for the First regime are formed from the core liquid only and are entrained by the layer flow the latter remaining continuous. In the Second regime compound satellite drops appear consisting of a core and concentric layer from the liquids of the jet core and surrounding layer respectively.

Keywords: capillary instability, interfacial hydrodynamics, computational hydrodynamics.

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SESSION F2J
VIBRATION ANALYSIS

Elasto-Plastic Modelling of Shaking Table Tests

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The seismic response of structures resulting from earthquakes is strongly influenced by the phenomenon of dynamic soil-structure interaction. In order to investigate this phenomenon, scaled model tests, as well as numerical analyses, should be performed. The scaled model tests allow the direct understanding of the behaviour of a scaled structure, even if they are affected by scale effects. On

the other hand they are necessary to calibrate the numerical analyses. The validated numerical analyses can be used for the prediction of the dynamic behaviour of full scale structures. The present paper deals with the numerical simulation of some shaking table tests performed at the University of Bristol. The model studied consists of a Leighton Buzzard sand deposit pluviated into a laminar box (4.8x1.0x1.0 m) with flexible end walls. A concrete block (0.4x0.95x0.4 m) is embedded 0.1m into the sand and carries a centred surcharge of 30 kN. The whole model rests on a shaking table (3.0x3.0 m). A sine-dwell displacement time-history, characterised by a frequency of 5 Hz and a variable maximum acceleration between 0.16g and 0.35g, is applied to the shaking table. Numerical analyses have been performed to simulate the experimental tests using the commercial code ADINA (Automatic Dynamic Incremental Non-linear Analysis), with a mesh which takes into account the flexibility of the laminar box end walls, as well as the Mohr-Coulomb contact interface between the sand and the concrete block. A Drucker-Pruger constitutive model with elliptical cap is considered for the sand, while an isotropic, linear elastic constitutive model is considered for the concrete block.

The results are reported in terms of accelerations and displacements, and in terms of stress and strain distributions inside the sand and the concrete block. Good agreement is obtained between the experimental and numerical results, emphasising the potential of numerical analysis to reproduce the seismic behaviour of structures. Study of stress paths within the sand provides clues for areas where improvement of the constitutive model may be desirable.



Figure 1. Strain distribution due to a sine-dwell input of 0.16 g.

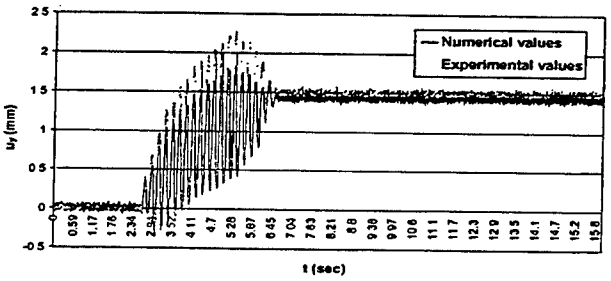


Figure 2. Concrete block horizontal displacements.

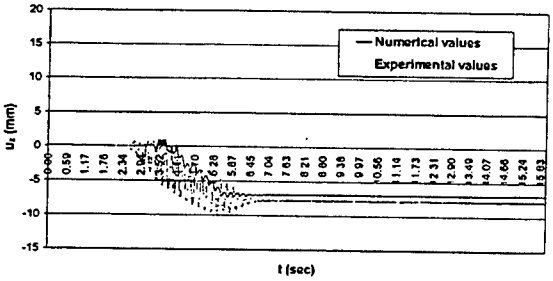


Figure 3. Concrete block vertical displacements.

On Interactions Between Parametric and Self-Excited Vibrations in The System with Ideal and Non-ideal Energy Source

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In engineering practice we can distinguish systems which oscillations are caused by different reasons. Well known are: self-excited systems in which, roughly speaking, a constant input produces periodic output, parametrically excited systems, characterized by periodically changing in time parameters and systems excited by external force. All these systems were comprehensively analyzed in literature separately. However, we can find some papers devoted interaction between different kinds of vibration, for example: self and external excited vibrations [1], self and parametric excited vibrations [2], [3], as well as between self parametric and external excited vibrations [4]. When a forcing function is independent of the system it acts on, then the function is called ideal. Then, the excitation may be formally expressed as a pure function of time. If in a certain model its ideal source is replaced by a Non-ideal source, the excitation can be put in the form $F(f)$, where f is a function, which depends on the response of the system. Therefore, a Non-ideal source can not be expressed as a pure function of time but rather as an equation that relates the source to the system of equations that describes the model [5]. Hence, Non-ideal models always have one additional degree of freedom as compared with similar ideal. Recently, a review of this kind of problems was done in [6]. In the classical book devoted to Non-ideal systems [6], the energy source is mod-

eled by the stationary characteristic of the motor (classical Kononenko approach). To obtain dynamical model, which is closer to the realistic system, it is necessary to consider also an additional equation called the electrical equation of the motor. It can be important, particularly for systems with complicated (e.g. chaotic) dynamics. The main goal of this paper is to analyze influence of ideal and Non-ideal energy source on the parametrically and self-excited system and present it's new dynamic phenomena.

Keywords: Ideal and Non-ideal and parametric and self-excitation vibrations.

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Vibrational Mechanics - a New Effective Approach in Nonlinear Dynamics

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The presentation is devoted to the general approach to the solution of the problems on the effect of vibration on non-linear mechanical systems. This approach consists in the following. In many cases the motion which appears under the action of vibration in non-linear systems can be presented as a sum of slow motion and fast oscillations (not necessarily small). The question arises, if it is possible to pass from the initial differential equations of the motion of the system to the equations containing only a slow component, which is of special interest. At certain, sufficiently common conditions, such a transfer is actually possible. The resultant equations contain along with ordinary slow forces some additional slow forces called vibrational forces. The presence of these additional forces explains the special effects connected with the action of vibration. They are as follows: the change of the character of the equilibrium and stationary movements of the system, the appearance of the new and disappearance of the previous equilibrium positions and motions, seeming changes of rheological properties of the bodies, and even seeming changes of the main laws of mechanics.

The equations of slow motions are substantially simpler than the initial ones. They do not contain excessive information that is not necessary for finding slow motions. These equations can be autonomous when initial system is not autonomous, and they can be potential when initial system is essentially non-conservative. These equations can be "smooth" at "not smooth" and even discontinuous initial system. And finally they can have considerably smaller dimension. The presentation contains a review of main results obtained within the frame of this approach. A special attention is given to new results, both in the development of the theory and in expansion of the scope of this approach applicability, and in the solution of application problems. For example, the problem of creating new dynamic materials, the problems of synchronization theory, the studying of the systems with dry friction and shocks. Some unsolved problems are also discussed.

Keywords: vibration, non-linear systems, separation of motions

The Bend, Vibration and Stability of Three-layer Anizotropically Right-angled Plates

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The article interest that basic equations and boundary conditions of three-layer anizotropically right-angled plates with absolutely rigid transverse connections and elastically pliable ortotropic fillers without and with regard for the influence of interacting elastic foundations result in basic equations of three-layer ortotropically and isotropically right-angled plates with absolutely rigid transverse connections and elastic pliable isotropical

fillers. A number of problems of bending and vibration of three-layer anizotropically right-angled plates with and without regard for the influence of the pliable foundation are solved. A number of problems of vibration of three-layer anizotropically right-angled plates with and without regard for the influence of the interacting elastic foundation are solved. Influence on strength, hardness, stability and vibrations of three-layer plates are analized for the following factors: boundary conditions, elastic foundation, anizotropic parameters. Numerical results and tables of comparison of frequency meanings and critical forces with and without regard for the factor of constructive anisotropy are given. It is shown that non-consideration of the anizotropic factor and the influence of pliability of the foundation result in considerable underestimation of frequency meaning and critical loads and so it is necessary to calculate three-layer plates for vibration and stability with regard for anizotropical properties of materials with regard for anizotropical properties of materials by interaction with elastic environment for pliability. The algorithm and program for FORTRAN for calculation on strength, stability and vibration of three-layer anizotropically right-angled plates have been worked out.

Keywords: bend, vibration, stability, anizotropically, plates.

SESSION R2P
VIBRATION AND CONTROL

On a Control Technique to a Simple Machine Foundation with Limited Power Supply by Using Internal Resonance and Saturation Phenomenon

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In this paper, a theoretical implementation of a control method by using internal resonance and saturation phenomenon is presented.

An engineering application is presented namely a Non-ideal portal frame foundation of an unbalanced rotating machine (see Figure 1). In the Non-Ideal problems we need to take into account the interactions between the Structure and its energy source (with limited power supply- See Kononenko [3]).

One of the more important aspects of this particular control technique is defining the parameters such that the system exhibits modal coupling effects. For this control strategy, a 2:1 internal resonance condition is utilized. Further, quadratic nonlinearities are considered in the system of equations. The regulating control acts on the excitation source, in particular, on the angular velocity of the rotor that corresponds to a shift in the characteristic of the DC motor. The nonlinear vibration control acts on the first and second mode of vibrations of a portal frame that corresponds the dynamic coupling between the Non-ideal portal frame and the controllers through the nonlinear feedback control laws and the torque applied to the Non-ideal portal frame coordinates.

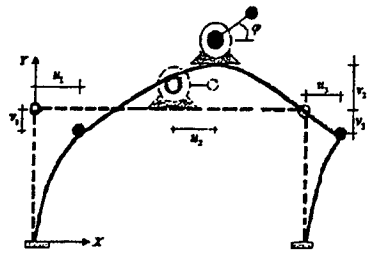


Figure 1: The Non-Ideal Portal Frame (Excited by a DC Motor- with Limited Power Supply)

Keywords: Saturation, Internal resonance, Control, Portal Frame.

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Vibration Forces in Physical Systems

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In each vibrating system there are inertial forces. If there are any free elements these forces can shift them

to new positions or move them in continuous way. We can observe such properties in nonlinear systems. Vibromotors, micromotors and vibration transport they are also the examples when these forces decide of the behavior of the system. New materials such as special alloys, combination of silicon with piezoresistive layer, and new magnetic materials give large possibility to build very small and effective vibromotors that can be used in robotics and microrobotics.

If we can define the vibration forces as a function of the system parameters (e.g. amplitude and frequency of vibration) then the system can be divided into subsystems. Each subsystem can be analysed separately with the dynamic reactions between them. It makes the nonlinearly problem a little easier.

Some other properties of mechanical system can be also explained if we consider these forces. The unbalanced rotor generates vibrations that produce a torque. It brakes the rotor and if the driven torque is too small it is impossible to overcome the resonance range of the rotor. It is known as effect of a non-ideal source of power. Sometimes there is a jump of the speed of the rotor.

Vibration forces can also be used for dynamic balancing of the rotors. When distribution of the rotor mass changes during its rotation or for each start then the traditional method of balancing can not be used. The author works in this domain. There will be given relations describing these forces and the positions of the equilibrium of the balls. It will be shown that these positions can be dynamically stable or unstable depends on the rotor speed.

The author proposed a new dynamic eliminator of vibration. There are also free elements and because of the action of vibration forces they move with the proper velocity and shift angle with respect to the excitation. They produce a force, which can be opposite to the excitation or can be in phase with the excitation. Depends on it they can eliminate the vibrations of the object or increase them.

For the vibromotors we would like to define the torque and the velocity of the rotor. Another examples where the vibroforces play important role:

- Vibration transport, vibration mixing, and vibration segregation,
- Vibration drive of piles,
- Synchronization of mechanical systems (external and internal),
- Dynamic stability of the positions that are statically unstable and vices verse,
- New position of equilibrium,
- Vibratory finishing in abrasive medium,

If we do not take into consideration the vibration forces then some data obtained from the experiment can be interpreted in false way. It is especially important for this experiment where the friction force is measured.

Some of the strange behavior of the mechanical systems can be explained in simple way if the vibration forces are known. Author will give some examples.

Keywords: vibrations, vibration forces, synchronization, automatic balancing

Large Amplitude Free Vibration Study of Square Clamped Plate through a Static Analysis

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Studies on free vibration problems of rectangular plates have a very old history. Different researchers have addressed the problem employing different methods. However, the majority of the work is on small amplitude vibration with specific boundary conditions and aspect ratios only. Recently, different researchers studied the non-linear vibration problem with some specific boundary conditions. Studies are primarily focused on free vibration and work on forced vibration seems to be scanty. Quite a few different techniques have been used to obtain the natural frequencies and mode shapes. Under this context, the need is felt for development of a general-purpose method to identify the frequencies and mode shapes of plate under large amplitude vibration for any kind of boundary condition. In the present paper, a new methodology, based on variational principle, is employed to solve the problem. The necessary higher order constitutive functions are formed by following Gram-Schmidt orthogonalisation procedure, thus making the solution space complete. The solution of the dynamic problem is obtained through the solution of static deflection field. The static deflection field required in the present analysis is obtained for the plate under uniform transverse loading. The static problem is solved by employing an iterative method with an appropriate relaxation technique. The present paper documents the large amplitude frequency parameters of the clamped plate for the first six vibration modes. The documented results are furnished through backbone curves in dimensionless amplitude-frequency plane. The vibration mode shapes for all the cases are also presented corresponding to the minimum and maximum amplitudes of vibration.

Keywords: large amplitude deflection, non-linear vibration analysis, static deflection field, relaxation technique

Fundamental Vibration of Rotating Pre-twisted Conical Shells

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Blades are often found in the aerospace, turbomachinery and others, such as aerial propellers and turbofans, it is very important for safety and life of machinery to determinate their dynamic characteristics accurately as they rotate at high speed, however it is a hard work and impossible to obtain an exact dynamic solutions because of complicated geometric configuration such as twist, curvature, non-uniform cross section and thickness, which is the reason that researchers devoted their efforts to the problem. Beam is as the simplest model of blades which was often used in study on the dynamics of blades in past and is also used in engineering now under considering non-linear vibration, shear deformation, non-uniform cross section, pre-twist, coupled vibration and concentrated mass. Plate and shell are more approximate models of blades, but there was a few related work done, such as rotating twisted plates and tapered plates by FEM and the Rayleigh-Ritz method, shells with camber and twist on shallow shell theory by Ritz method and twisted cylindrical thin panels on general shell theory by the Rayleigh-Ritz method.

The main purpose in here is to extend our researches on twisted shells and do some essential work on the vibrations of the shells subjected axial forces. Based on the study of non-rotating pre-twisted conical shells, a nonlinear strain-displacement relationship on general shell theory is considered, a numerical method for free vibration of rotating pre-twisted conical shells is presented by the energy method, where the effect of rotation is considered as initial deformations and initial stress resultants, and the steady initial quantities are obtained by the principle of virtual work for deformation, then an energy equilibrium equation of vibration under the initial conditions is given by the principle of virtual work, and an eigenfrequency equation is formulated by the Rayleigh-Ritz method. The effects of parameters in the system, such as an angular velocity and a radius of a rotating disc, a setting angle, twist, curvature and a tapered ratio of cross section, on the fundamental vibration frequency are investigated.

Keywords: Nonlinear strain-displacement relationship; Rotating pre-twisted conical shell; Principle of virtual work; Rayleigh-Ritz method

Synchronous Eliminator of Vibrations in 3-D

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The author gave the propositions of the automatic dynamic eliminator of vibrations in which the phenomena of synchronization was used. The results of research for the object with one degree of freedom was publish in [1] and the results for the object moving in the plane in [2,3]. There are free elements as balls, rollers or pendulums and they rotate with respect to the object. For some ranges of frequencies they can generate the forces that are opposite to excitation and in this way they can eliminate the vibrations of the object. But in other ranges of the frequency they can increase the vibrations.

The paper will present the principle of the method,

- equations of the motion,
- the discussion of the possibility of elimination of vibrations in 3-D,
- the computer simulation of the system behavior,
- the planes in which the dynamic eliminators should be located,
- the stability of the system,
- efficiency of this method of elimination of vibrations.

Keywords: vibrations, elimination of vibrations, synchronization

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SESSION W2L
WAVE MOTION I

Nonlinear Normal Waves in Free Crystal Lamina of Cubical Systems

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The results of numerically - analytical analysis of spectral boundary problems of higher harmonic of one- two- and tree-partial monochromatic running and edges standing normal waves, and also higher combinative harmonics of interacting normal waves in cubic crystal laminas - waveguides of three-dimensional geometry are presented. The solutions of these problems for single-crystal waveguides of a cubical system are constructed in an analytic form with draft on funds of computer support of analytical transformations. Are investigated and are generalized of regularity in properties of second harmonics of monochromatic normal waves and combinative harmonics of normal SH and P-SV waves along directions of an elastic symmetry of a crystal lamina and tree-partial normal waves with arbitrary propagation direction in lamina. For second harmonics in the waveguide from a cubic crystal of germanium with free flat edges and with fixed flat edges are investigated the amplitude - frequency dependence and distribution on depth of a lamina of flows of power in running normal waves. Are investigated of qualitative and quantitative regularity of three-phonon interaction of second harmonics of normal waves, which one belong to different modes of a dispersion spectrum. Are investigated the effects of localization of second harmonics of nonlinear monochromatic normal waves in short-wave diapason.

Modeling Kissing Bonds for Ultrasonic leaky Lamb wave NDT

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The bond region in composites is found to develop - either while in service or during fabrication- vacous pores leading to what are known as kissing bonds. This region can be thought of as an area of physical contact without mechanical adherence. Very often these kissing bonds escape detection in NDT. In the present work an attempt is made to develop an analytical model to facilitate detection of kissing bonds by ultrasonic leaky Lamb waves.

In experimental studies,a kissing bond is generally simulated by an internal crack parallel to the plate surface which splits the plate into two. The present analytical model treats the thin region of contact as a linear elastic material with voids(LEMV).These vacous pores simulate the cracked bond region. The LEMV is characterised by the presence of four wave velocity parameters. Two of them are made to coincide with the velocities of the adherend and the other two velocities are obtained using a cracked elastic solid model. This model composite is taken to be insonified in water. The early leaky Lamb modes in the plate are seen to be influenced by the presence of kissing bonds. The model is expected to serve as a good first approximation in identifying kissing bonds in NDT.

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Stability of Solitary Waves in Compacting Media

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This paper studies any compacting media that could include liquidfection, petrolium reservoir investigation, compaction of magma chambers, and formation of igneous rocks. The McKenzie equations (1984) are modified to explicitly reflect the buoyancy effect in modeling the compaction problems. Several classes of multidimensional solitary-wave solutions of these equations are derived and investigated. General nature of the solutions is discussed, followed by finding the solutions numerically. Stability analysis of these solutions is then carried out, and the prefered solutions are determined.

Keywords: Comapction, Solitary waves, Magma dynamics, Stability analysis

Stress Wave Propagation in Functionally Graded Materials using Continuously Graded Finite Elements

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Numerous applications exist for advanced materials in areas such as lightweight armors, aerospace and high temperature applications. These advanced materials can be designed using functionally graded materials (FGM) wherein synthetic materials are graded for specific engineering applications. These materials have mechanical properties that are functions of position, thus generating a continuously non-homogeneous material.

There has been a significant amount of research recently in the modeling of such materials. However, these are mostly analytical solutions to static fracture and 1D wave propagation problems. In addition, the form of material non-homogeneity in these solutions is always a simple function of position, such as an exponential or linear function. In order to improve upon these solutions and to develop a method for more general problems, one needs to resort to the finite element method (FEM).

A conventional FEM model uses elements wherein each element assumes a single uniform set of properties. To model FGM using such elements, the material property functions must be discretized on the same size scale as the element mesh. This piecewise approximation gives good accuracy for global energy calculations. However, the local element stresses and displacements are approximated. In certain applications such as stress wave propagation studies, these local values may be of critical importance.

Hence, we have developed and implemented a graded, 2D finite element with continuous material properties to model stress wave propagation in materials with graded elastic properties. The stress wave results obtained from this model are compared with those obtained from an existing analytical model and a conventional FEM model for a simple problem, thus verifying the formulation.

Keywords: Functionally graded materials, stress wave propagation, graded finite elements

A Theoretical Model for the Detection of Surface-breaking Cracks with Laser-generated Ultrasound

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A theoretical model for a novel non-destructive technique for the detection of small surface-breaking cracks using laser-generated ultrasound ? the Scanning Laser Source (SLS) technique ? is presented. This technique [1] does not monitor the interaction of a well-established ultrasonic surface wave with a flaw, but rather monitors the changes in the generated ultrasonic signal as the laser source passes over a defect. Changes in amplitude and frequency of the generated ultrasound, which result from the changed constraints under which the ultrasound is generated over uniform versus defective surface areas, are observed. The inspection process can greatly benefit from a quantitative model and a corresponding simulation tool. The cracked test specimen is modeled as an isotropic, homogeneous, linearly elastic half-space with a two-dimensional surface-breaking crack, which is perpendicular both to the direction of scanning and the free surface of the half-space. The ultrasonic response of the half-space to a pulsed laser line source operating in the thermoelastic regime is decomposed, by virtue of linear superposition, into the incident and the scattered fields, which can be obtained consecutively. The incident field is generated by the line laser heat source in the uncr acked half-space. The corresponding thermoelastic problem is solved semi-analytically. Since the laser source is swept across the test specimen, and therefore passes over the flaw, an accurate description of the field both far and near the source is required. While the far field can be well approximated from equivalent elastic sources, the thermal effects from the generation process are needed for the near field and therefore have to be taken into account in the formulation [2]. The scattered field in the cracked half-space is obtained by a direct frequency domain boundary element method (BEM).

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Elastic Plate Waves in High Porosity Materials

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Porous materials exist in a variety of forms, including wood, foams and other materials for structural and chemical applications. The existence of excessively large inclusions or holes can result in stress concentrations or loss of structural integrity. One of the most familiar of these situations is a knot in wood. Fluid filled porous materials will propagate both slow and fast longitudinal waves under some important practical conditions. In previous work highly porous materials with a wave velocity significantly higher than water have been considered [1]. However, in many other porous structures, the velocity of the wave in the solid material differs only slightly from the velocity of the wave in the fluid.

This work considers the use of plate waves propagated to detect defects. The work is based on the fluid-filled cylindrical cavity as treated by Mow and Workman [2]. A closely related problem, the scattering by a spherical inhomogeneity in a fluid-saturated porous media has also been investigated by Berryman,[3]. The objective of this work is to investigate the scattering by a cylindrical inhomogeneity in a fluid-saturated porous media. The velocity of the longitudinal wave in the bulk material is close to that of water. Experimental issues are addressed and the results are shown for simple configurations. The effect of the visco-elasticity of the material is also considered from the perspective of the sensitivity of the wave velocities and dispersion to frequency of the wave.

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[2] C.C. Mow and J.W. Workman, J. Appl. Mech., 33, 793-799 (1966).

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SESSION R2L
WAVE MOTION II

Pressure and Particle Velocity Fields Generated by an Underwater Explosion

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A model for a moderately deep underwater explosion bubble has recently been developed that integrates the initial shockwave phase and the subsequent oscillation phase of the motion [1]. A hyperacoustic volume-acceleration model for the shockwave phase employs an empirical pressure-profile expression for the far field to determine bubble radius as a function of time, thereby providing initial conditions for the subsequent oscillation phase. The model for the oscillation phase produces bubble-response equations that incorporate first-order wave effects in both the external liquid and the internal gas. Here, we formulate and evaluate a radiation model that is consistent with the bubble model.

The far-field pressure profile produced by the bubble during the *shockwave phase* is given by the empirical formula

$$P(r,t) = P_c(\frac{a_c}{r})^{1+A(t)}\{C_P \exp[-C_1(\frac{a_c}{r})^{B(t)}\frac{v_c}{a_c}t] + (1-C_P)[1+C_2(\frac{a_c}{r})^{B(t)}\frac{v_c}{a_c}t]^{-4/5}\}, \quad (1)$$

where $A(t) = A_0/[1 + C_A(v_c t/a_c)^5]$, $B(t) = B_0/[1 + C_B(v_c t/a_c)^5]$, and P_c, a_c, v_c, C_P, C_1, C_2, A_0, B_0, C_A and C_B are constants. This field emanates from a stationery monopole that is initially hyperacoustic, but becomes acoustic later. The relation between far-field radial velocity and pressure is the acoustic one $u(r,t) = (\rho c)^{-1}P(r,t) + (\rho r)^{-1}\breve{P}(r,t)$, where $\breve{P}$ is the integral of P.

The acoustic-radiation model for the *oscillation phase* incorporates a translating source and dipole [2]. The velocity-potential field thus produced is given by

$$\phi(r,\theta,t) = -\frac{q}{R}(1+\frac{\dot{u}}{c}\cos\Theta) - \frac{\mu}{R^2}[(1+3\frac{\dot{u}}{c}\cos\Theta)\cos\Theta - \frac{\dot{u}}{c}] - \frac{\dot{\mu}}{Rc}\cos\Theta \quad (2)$$

where R and Θ are implicit functions of r, θ, and t. The source and dipole strengths (q, μ), as well as the translation velocity ($\dot{u}$), are determined from the radius and translation histories produced by the bubble model. The pressure and radial-velocity fields associated with this velocity-potential field are determined from the usual acoustic relations.

In the presentation, pressure fields produced by (1) and (2) are compared with experimental data. Agreement is good.

Keywords: transient acoustics, bubble dynamics, underwater shock, asymptotic expansions

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[2] Leppington, F.G., and Levine, H., 1987, The sound field of a pulsating sphere in unsteady rectilinear motion, *Proc. R. Soc. Lond. A*, Vol. 412, pp. 199-221.

Impact Fracture in Destructive Disassembly of Joining Elements: Analysis and Experiment

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Application of impact for separating joining elements such as screws and bolts has been adopted as a cost-effective method for destructive disassembly in recycling process. Disassembly, the process of physically separating parts in a product includes parts separation through unfastening and also the destructive disassembly through cutting and sawing etc. In several disassembly line situations, it may be advantageous to destroy the fastener element such as the screw to achieve economic viability of the process. Disassembly environment is complex due to the wide range of fastener geometry and variation in fastener damage during use.

The objective of this research is to analyze the impact disassembly process by studying the characteristics of elastic waves caused by impact. We model the elastic waves in one-dimensional bar which transfers the impact energy to a protruded bolt head mounted in an infinite elastic medium or structure. Based on the developed equations for the elastic waves, we propose a method that would improve the efficiency of the process for fracturing a bolt head. This paper presents results from the experimental investigation on the developed equations and method. The results can be used in developing new destructive disassembly device for removing bolt or screw fasteners. This research has potential for advancing demanufacturing technology resulting in an increase of disassembly efficiency and a reduction of recycling cost.

Keywords: destructive disassembly, elastic waves, impact fracture, recycle

Investigation on SHPB Technique for Soft Materials Testing

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Because of low strength and low impedance of soft materials, the dynamic stress equilibrium is hard to reach in the specimen during split Hopkinson pressure bars (SHPB) experiments when testing soft materials. The phenomena of non-equilibrium states of stress in the specimen were investigated numerically and experimentally in this study.

To monitor the dynamic stress equilibrium in soft material specimen during the testing, quartz-crystal force transducers were installed on the specimen-contacting faces of an aluminum SHPB to directly record the axial force histories on the two ends of the specimen. Detail information about the stress state in the specimen was obtained by means of numerical simulation using a finite element code.

A silicone rubber was tested. The investigation showed that, reducing thickness of the specimen was a way to improve the non-equilibrium problem. The force histories on two sides of the specimen were shown in figure 1, where length to radius ratio of the specimen was 0.24. To furthermore ensure the dynamic stress equilibrium and thus a homogeneous deformation at a constant strain rate during the whole dynamic process, loading pulse profile must be carefully shaped. A pulse shaping technique was designed to modify conventional SHPB aiming at remedying the non-equilibrium problem in this study. Figure 2 showed a better result of the two faces force histories when using a pulse shaping technique in the experiment. The specimen had the same length to radius ratio as the former one.

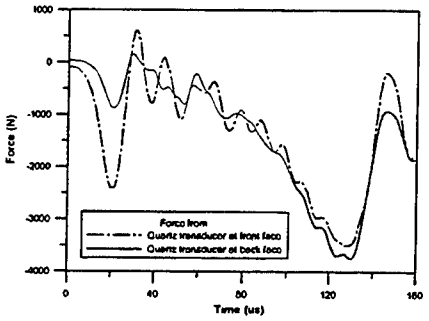


Fig. 1: Two-faces force histories without pulse shaping

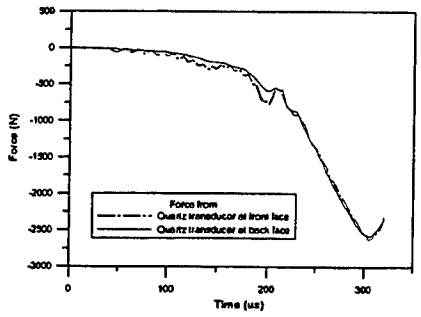


Fig. 2: Two-faces force histories with pulse shaping

However, numerical simulations results showed that, because the thickness of specimen was reduced badly, 2-D stress state in the specimens became serious as shown in figure 3, especially when the length to radius ratio was too small as we used in the experiments. The large the ratio, the better the 1-D state. To facilitate the basic principals of SHPB technique, an ongoing work for a reasonable design of soft material specimen's dimension is still required.

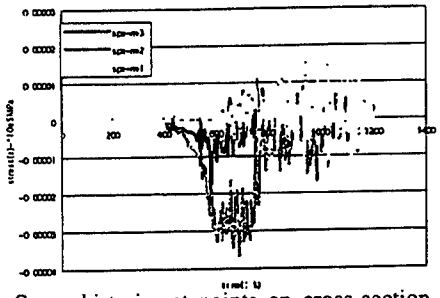


Fig. 3: Stress histories at points on cross-section in the specimen

Keywords: soft material, SHPB technique, pulse shaping, stress equilibrium.

Inverse Scattering and Lattice Motion Due to Generalized Nonlinear Interaction

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Whereas continuum descriptions of nonlinear waves (e.g. Korteweg de Vries, Boussinesq and sine-Gordon equations) have been borne out by natural phenomena such as canal waves, the same is not true for the microscopic, discrete lattice models. Experiments by Bridgman in the 1930's and Enikolopyan in the 1980's suggest peculiar lattice motions responsible for direct conversion of lattice potential energy into translational kinetic energy rather than thermal motion. Soliton or soliton-like waves have been observed in small crystalline samples, propagating supersonically through the lattices. These solitary waves show very little interaction with background lattice motions. Not only does a state of non-equilibrium exist, but the waves exhibit definite non- ergodic behavior. In order to explore the differences between dissipative acoustic waves that exhibit ergodic behavior and non-(or slightly) dissipative waves, we apply the inverse scattering theory to the equations of motion (with potential v) on discete lattices:

$$\begin{cases} \dot{Q}_n = P_n, \\ \dot{P}_n = v'(Q_{n+1} - Q_n) - v'(Q_n - Q_{n-1}). \end{cases}$$

The first step is to show that these types of waves are not limited to the Toda potentials, as it is highly unlikely that real crystal lattices obey the Toda potential exactly.

Wave and Crack Propagation of Elasticoplastic Solid (Mountain Bodies) by Influence of Explosion and by Accounting Rheologic Properties

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Powerful explosion of spherical body very rapidly extracts a large contraction pressure. Explosion pressure acts to the body as contraction stress. As a result it appears a large stress, which is larger than allowable stress, and it is propagated to all sides of the body by the same velocity. Therefore the solid momentarily is contracted. As a result particles of body are moving to radial directions.

The body is divided into three parts. The first part is a destroying part. Second one is a plastic part (plastic zone). The next part is an elastic part of the body (elastic zone). If the strain $\sigma_R(t,r) = \chi_1(r,t)P_{\text{det}} > [\sigma^c_{st}]$, then one can observed the destroying part of the body, where t is a time, P_{det} - is pressure on a surface charge, σ^c_{st} - is allowable limited pressure of stability.

One can observed the cracks of the body in the plastic zone. In generally form of the cracks may be very complicated. But, we suppose that the cracks have radial form (spherical form).

After some time the contraction and stretching stress decreased. So, $\sigma_R(t,r) = \chi_1(r,t)P_{\text{det}} < [\sigma^c_{st}]$ and we have $\sigma_\varphi(t) = \chi_2(t)P_{\text{det}} < [\sigma^r_{st}]$ in discontinuity of the body.

The plastic zone is extended by influence of the decreasing functions $\chi_1(t), \chi_2(t)$. If the conditions $\sigma_R(t) < [\sigma^c_{st}]$, $\sigma_\varphi(t) < [\sigma^r_{st}]$ are hold then destruction process is stopped. Moreover, the explosion gases come to cracks of the body. As a result pressure and temperature of the body are decreasing in the first part of the body. If $\sigma_R(t) = \chi_2(t)P_{\text{det}} < [\sigma^c_{pp}]$, then the plastic zone get over to elastic zone.

Influence of explosion to the body by accounting rheologic properties is long process. Solution of such problems is based on V.Volterra equation for integral operators:

$$E^*(t) = E_{pr}[1 - \beta_1 \, \mathfrak{z}^*_\alpha \, (-\beta)]f,$$
$$\nu^*(t) = \nu_{pr}[1 + \beta_2 \, \mathfrak{z}^*_\alpha \, (-\beta]f,$$

Where $\mathfrak{z}^*_\alpha \, (-\beta)$ is Rabotnov's integral operator.

The low of extending of radial and stress of tangent direction $\sigma_\varphi(t) - \sigma_R(t) = [\sigma^c_{st}]$ is established by using elastic condition due to Treska-Sen-Venan.

The dynamic problem for wave propagation from impulse is reduced to solution ofdifferential equation in

movements $u(r,t)$:

$$\frac{1}{R}[\lambda(t)+G(t)]\left(\frac{\partial^2 u}{\partial R^2}-\frac{1}{R}\frac{\partial u}{\partial R}\right) + G(T)\left(\frac{\partial^2 u}{\partial R^2}+\frac{1}{R}\frac{\partial u}{\partial R}\right) - G(t)\frac{u}{R^2}-\gamma_{pr}(R-R_0)=\frac{\partial^2 u}{\partial t^2}.$$

RESULTS:

1. We establish the low for propagation of cracks and also the low for propagation of blast wave by using rheologic properties of mountain bodies depending on a time and distance.
2. It is obtained dependence of the potential energy of the body deformation on charge energy. Also dependence of the volume of destroyed zone on force of explosion.

Keywords: explosion, crack, rheology, blast wave.

SESSION F2L
WAVE MOTION III

The Effect of Material Heterogeneity on High Amplitude Wave Propagation in Layered Material Systems

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Although, wave propagation studies in heterogeneous material systems have received considerable attention in the past few decades, it is still poorly understood. This lack of understanding stems from a lack of understanding of the interactions of a number of geometric, material and loading parameters usually in a nonlinear fashion. It has however been recognized, based on available experimental data that composite systems display markedly different behavior from that of monolithic metallic systems. As a practical means to study high amplitude wave interaction with materials, we choose high velocity plate impact test as the model boundary value problem. As the velocity of impact is increased, the wave interaction time decreases from a few seconds in the case of quasi-static loading, to a few milliseconds for low velocity loadings to a few microseconds for the high velocity impact cases. If the loading rate is high so that the wavelength is comparable to the heterogeneity size, then the internal reflections/transmissions occurring at various length levels play a significant role to the whole impact response. A multilayered system can be a practical configuration to study the inherent material heterogeneity effects, vis-à-vis interfaces on the wave characteristics. A configuration with alternating materials provides a simple but effective test bed to analyze the effect of scattering/reflection/transmission processes during a high velocity impact event. In this paper, some critical geometric and material parameters in layered heterogeneous materials that affect the shock behavior have been identified. We focus on two different aspects, material through modification of the model from elastic to elastic-plastic and geometric by altering the periodicity in the arrangement. The results show that plasticity effects dominate the wave characteristics in the intermediate pressure region where yielding strength is not negligible. For periodicity in the layered structure, disorders in the arrangement of layers and pre-damaged layers affect the whole response, which can be put into practical use in the design of armors and anti-armors.

Keywords: Layered heterogeneous materials, material heterogeneity, wave propagation, plate impact

Complex Representation in Nonlinear Dynamics and Localized Elastic Waves

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We present the general approach to complex representation of equations of motion in Nonlinear Dynamics. On the basis of this representation a modified version of multiple scale expansions is used. As a result we obtain in principal nonlinear approximation the continuous and discrete nonlinear complex equations admitting further analytical consideration of localized elastics waves. The following concrete systems are discussed.

1. The system of oscillators coupled by weightless elastic beam.
2. The chain of oscillators with alternating inertial or elastic characteristics and coupled by elastic string.
3. Plane zigzag oscillatory chain with nonlinear characteristics.
4. The system of weakly coupled nonlinear oscillatory chains.

In all cases the complex representation is used for description of short wavelength dynamics and in certain ones - long wavelength dynamics too.

The resulting equations of motion in principal approximation of multiple-scale procedure are the equations similar to Nonlinear Shroedinger Equation (NSE) or discrete NSE-like systems of equations.

Depending on the signs of coefficients in these equations, which are determined by type of nonlinearity and characteristic space scale, they admit bright or dark solitons in continuum case and discrete breathers in discrete one.

Keywords: Elastic Waves, Nonlinear Dynamics, Complex Representation, Localization.

The author are grateful to RFBR (Grant No 01-03-33122) for support of the research.

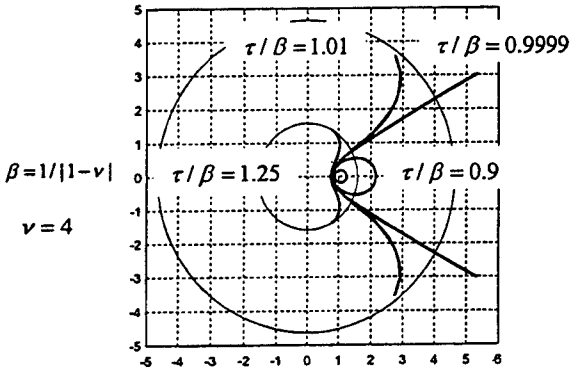
A Green Function for Radially Inhomogeneous Elastic Medium With an Impulsive SH-wave Source

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Wave propagation in inhomogeneous elastic media is one of the classical elastodynamic problems. However, a technique for ultrasonic material evaluation for functionally graded materials (FGMs) needs more accurate information about the wave propagation in inhomogeneous media. This revives the study of elastic waves in the inhomogeneous solid.

The present paper considers a transient SH-wave in a radially inhomogeneous elastic solid. Shear modulus and density are functions of radial distance and thus SH-wave velocity is also varying with the power of radial distance, i.e. $c = c_0(r/a)^\nu$, where c_0 is SH-wave velocity at a source point a. Applying the standard integral transform technique, an exact Green function for an impulsive point (line) source has been obtained for arbitrary number of the power ν. In addition to the regular direct wave from the source, one circular wave centered at the coordinate orig has been found. When $\nu < 1$, the circular wave em from the coordinate origin. However, when $\nu < 1$, ve comes from the infinity and approaches to the or A finite jump occurs on this circular wave front, nevertheless the direct wave has the inverse square root singularity. Typical wave front shapes are shown in the following figure, where thick and thin curves are the direct and circular waves, respectively.



It should be noticed that the direct wave from the source disturbed a region, $|\theta| < \beta\pi$.

Keywords: Green function, SH-wave, Impulse, Inhomogeneity, Elastic solid.

Mechanisms Which Use Travelling Deformation Waves

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Investigations of locomotions of some living creatures (caterpillars, earthworms) have led us to the creation of different wave mechanisms, which use the travelling deformation waves on the elastic bodies as a driving element. Figures 1, 2, 3 present the continuous (1) and stepping (2, 3) mechanisms, which use the flexible belt, and the travelling transverse waves are generated by rollers mounted at the end of driving arms. The driven element 2 (fig.3) and the driven element 3 (fig.1, 2) , which contacts the belt, is rotated with decreased angle velocity. In step mechanisms (Fig.2 and 3) the driven element moves in discrete mode. Figures 4, 5, 6 present continuous reducers, which use longitudinal travelling waves on elastic bodies 1 (in fig. 4, 6) and on elastic body 5 (fig.5). The rollers generate the travelling waves on the elastic body, which contacts the driven element (2 in fig. 4 and 3 in fig. 5 and 6). Fig. 4 presents linear reducer, fig. 5,6 present continuous reducer for rotating motion. In the report will be described in detail the wave mechanisms and our investigations of wave locomotion of some creatures. Some computer animations and photos will be demonstrated. Mathematical expressions to calculate main kinematic parameters will be presented.

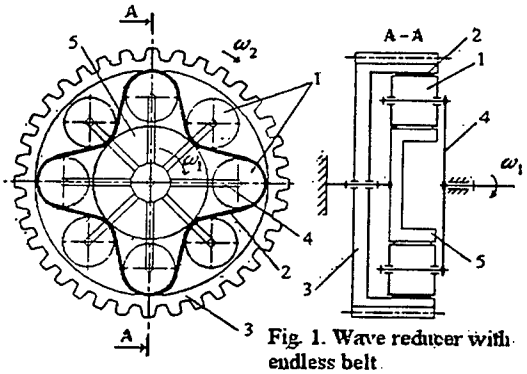


Fig. 1. Wave reducer with endless belt

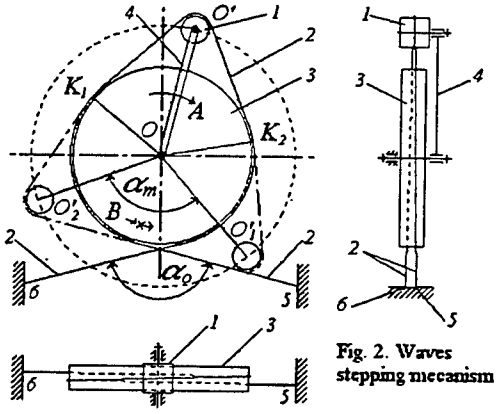


Fig. 2. Waves stepping mecanism

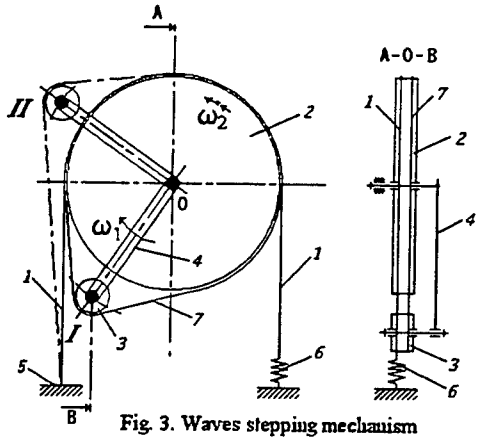


Fig. 3. Waves stepping mechanism

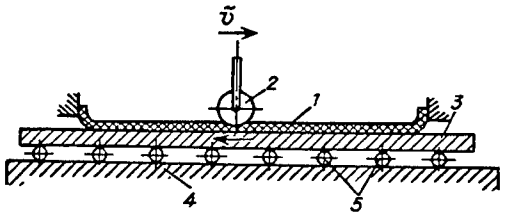


Fig. 4. Wave linear reducer

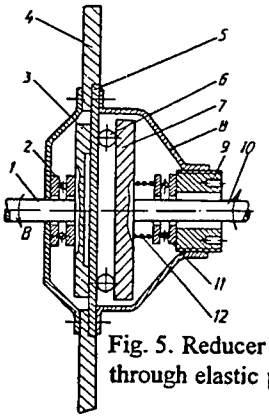


Fig. 5. Reducer with transmition through elastic partition

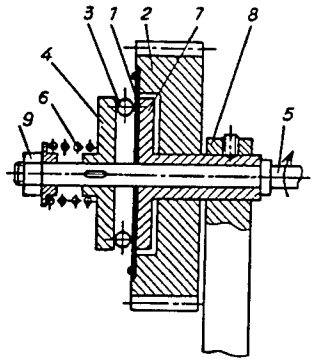


Fig. 6. Reducer on elastic layer

Nonlinear Electroelastic Waves in Fluid-filled Porous Media

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The equations of the motion of an electrically charged porous fluid-filled medium are derived in nonlinear space treatment. Using the method of evolutionary equation and the method of the nonlinear Shrodinger equation the soliton solution of first equation and the solution of wave beams of the second one are obtained taking into account linear and nonlinear dissipation. The soliton and modulation waves stability conditions are examined.

SESSION F4L
WAVE MOTION IV

Destruction and Shock-wave Processes in Isotropic and Anisotropic Materials under Dynamic Loads

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This paper presents a results of a numerical simulation and experimental investigations of anizotropic composite materials and rolled steel destruction under impact and puls load, received by the author for last three years. Anisotropic materials recieved lately wide application in different areas of engineering. This is closely connected with experimental investigations intensification new material models perfection and algorythms creation. Perfection of computer facilities and simulation methods allows substantialy to reduce and to complement physical investigation methods with numerical experiments , including analizis of constructions elements destruction character. To present time the effective methods to evaluate anizotropic materials behaviour under static loads were designed, but the methods of comparable efficiency for these materials being under high velocity dynamic load do not exist. In a given paper in scope of continual approach, in supposition of quazihomogenity anisotropic material and linear connection between the components of strain rates tenzor and and increments of stresses the transversal-isotropic materials and the orthotropic materials behavior under various types of dynamic loadings: normal impact, oblique impact, pulse influence is investigated. For describe a material destruction, the invariant criterion, based on phenomenological approach to destruction is used, taking account of hydrostatic pressuer. Numerical simulation is carried out by finit elements method. The impact loading of plate from anisotropic materials was carried out with steel strikers of different size. The range of interaction rates up 400 to 3000m/sec is investigated. The anisotropy degree is varied up 10 to 0.1. The comparative analysis of behaviour isotropic and anisotropic materials is carried out. Influence of orientation of properties of an anisotropic material on destruction and on shock-wave processes is investigated.

[1] This material is based upon work supported by the Russian Foundation for Basic Research under Grant No. 00-01-00552 and work supported by the ERO of the US Army under Contract No. N68171-00-M-5806.

Wave Propagation in Cylindric Body that Includes an Internal Holder

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The process of propagation of stress waves in elastic rod with moving external uncompressible holder is considered in the paper. On the border of the contact a condition of dry friction is taken. Such structures are mainly used in technique and machine-building (such as shaft-plug, two-layered in radius rod systems, etc.) In the case of immobile external holder many authors obtained an analytical solutions in one-dimensional statement. Here discussed problems are solved numerically in two-dimensional axis symmetric statement. The process of wave propagation was studied by numeric experiments. It was stated that in the case of motion of external holder opposite to the action of dynamic load on the butl-end of the cylinder? Wave parameters (stresses, particle velocity, etc.) are damping with time and distance similar to known results obtained for one-dimensional design. In the case of coincidence of the motion of external holder with the direction of stress waves we may observe an opposite character of changes of wave parameters. Here stresses and particle velocities of the cylinder increase depending on the velocity of motion of external holder. Design formulae to determine time and points of maximum increase of stresses in cylinder were obtained. A joint (combined) motion of the cylinder with external media was revealed when stresses and velocities reach their maximum values. In the cases of coincidence of the length of the holder with the cylinder, an analytical solutions of this problem were obtained in one-dimensional statement. The expression of energy "arrival" from the holder to the cylinder was also obtained. It depends on mechanical and geometrical characteristics of the cylinder, on the coefficient of friction and parameters of acting load. The opportunities for application of obtained results for rod structures are discussed in conclusion.

Keywords: stress-strain state, wave propagation, friction, contacts of problems

Interaction of Plane Waves in Elastic Medium with Extensive Cylindrical Obstacles

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The effect of plane expansion wave propagating in elastic medium with angle to longitudinal axis of cylindrical obstacles (cavity, pipeline, inclusion) is considered in the paper. Three-dimension dynamic problem is solved in Cartesian coordinates. It became possible due to new representation of formulas of the general solutions of the dynamical Lame's equations, expressed through polyharmonic and the polywave operators, are received by recurrence-operator method [1]. The full sets of particular solution for various classes of analytical function (polynomial, transcendental, various special analytical functions and orthogonal polynoms, etc.) can be obtained easily from the these general solutions. Particular solutions expressed through generalized circular function, are used in the this task. The new formulae of differentiation of generalized circular functions on Cartesian coordinates [2] and representation their functions through on Cartesian coordinates, circular and Cartesian cross-section of obstacles allows considered.

In cases of interaction of elastic medium with cylindrical inclusion, contact conditions satisfied by separately method solving boundary problems for the cavity and inclusion. Such approach allows to sufficiently decrease the order of the system of algebraic equations, obtained at forming of boundary conditions.

In case of plane problem (when the plane of incident wave is parallel to the axis of cylindrical obstacles) well-known solution of the this problem is obtained.

Keywords: obstacles, circular function, general solution polyharmonic and polywave operators, recurrence-operator method.

Dynamic Interaction of Deformable Rod Structures with an Elastic Medium by Coulomb Dry Friction Law

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Seismic Stability of Underground Structures Department, Institute of Mechanics and Seismic Stability of Structure of Uzbek Academy of Sciences, Tashkent, Uzbekistan. The research of deformabilty both ground mediums and engineering structures was carried out for action of intensive dynamic loads. It was considered a subsonic flow around the structures. The wave equations of motion are derived. The field of displacements for an elastic medium is determined, using axisymmetric Lame equations. The interaction conditions of structure and medium are defined using Coulomb dry friction law. On the base of the early obtained outcomes of researches about a subsonic flow around the cylindrical constructions by longitudinal waves [1], the analytical formulas for an evaluation of displacements, strains and stresses behind front of a reflected wave with a conic mobile surface were derived. These formulas allow to analyze the stress-strain state both elastic construction and deformable medium at an action of intensive short-term loads. The relationships of desired values from the physical parameters of interacting mediums are obtained. The outcomes can be used for an assessment of underground pipelines seismic vulnerability within the framework of the NATO scientific project SfP 971923 fulfilled in the city of Tashkent. Keywords: dynamic interaction, Coulomb dry friction law

[1] M.Sh.Mamatkulova The subsonic flow around cylindrical construction interacting with media by Coulomb dry friction law. Uzb. Journ. Problem of Mech. No 3. 1999.(in Russian)

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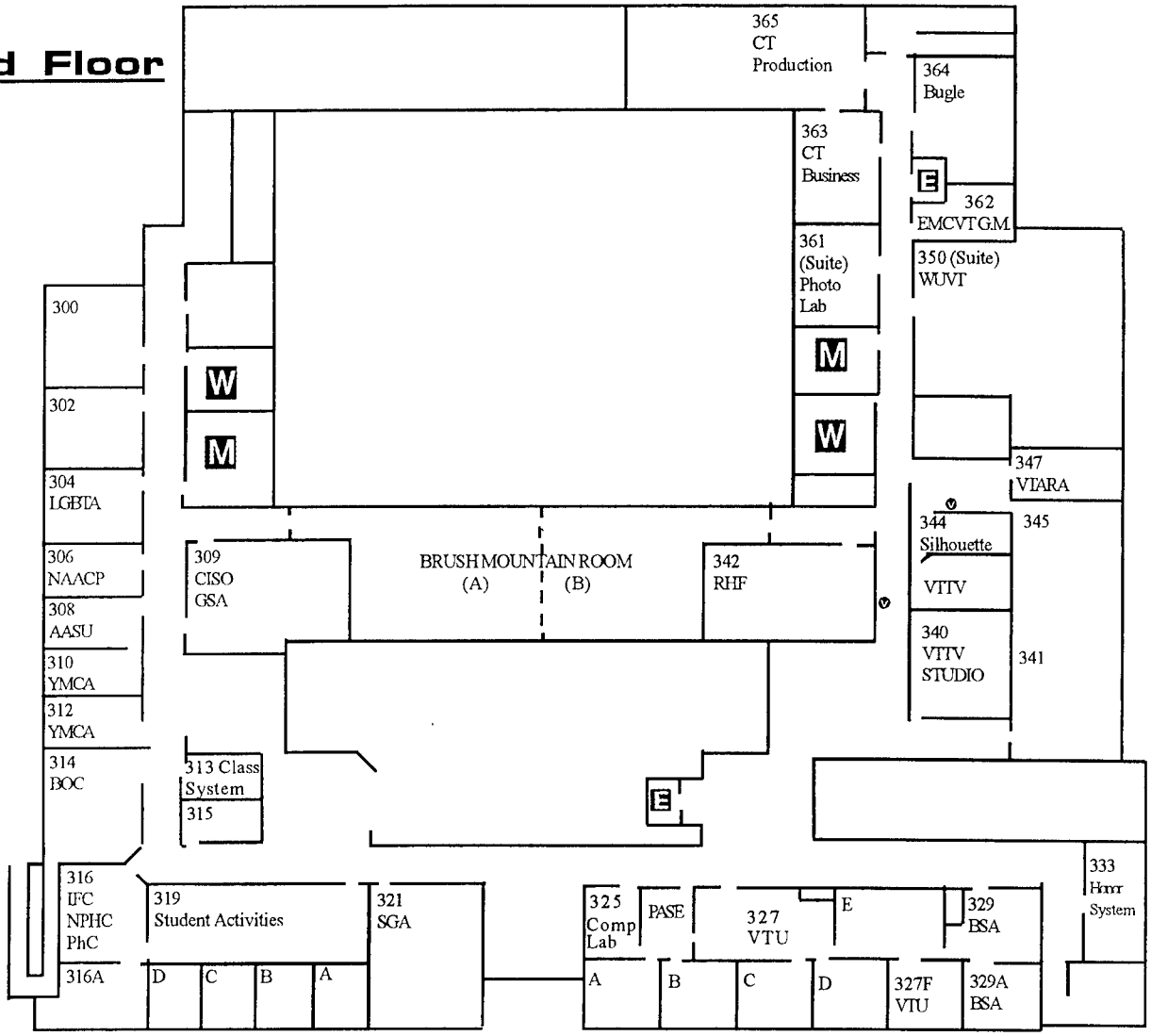
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Squires Student Center

Third Floor



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