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PROCEEDINGS OF THE TWELFTH ANNUAL MECHANICS OF
COMPOSITES REVIEW

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Deborah C. Mueller

Mechanics and Surface Interactions Branch
Nonmetallic Materials Division

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January 1988

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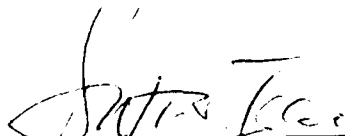
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This report contains summaries of the presentations of the <u>Twelfth Annual Mechanics of Composites Review</u> sponsored by the Materials Laboratory. Each paper was prepared by its presenter and is published here unedited. In addition to the presenter's summaries, a listing of both the inhouse and contractual activities of each participating organization is included.					
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FOREWORD

This report contains the abstracts and viewgraphs of the presentations at the Twelfth Annual Mechanics of Composites Review sponsored by the Materials Laboratory. Each was prepared by its presenter and is published here unedited. In addition, a listing of both the in-house and contractual activities of each participating organization is included.

The Mechanics of Composites Review is designed to present programs covering activities throughout the United States Air Force, Navy, NASA, Army and FAA. Programs not covered in the present review are candidates for presentation at future Mechanics of Composites Reviews. The presentations cover both in-house and contractual programs under the sponsorship of the participating organizations.

Since this is a review of on-going programs, much of the information in this report has not been published as yet and is subject to change; but timely dissemination of the rapidly expanding technology of advanced composites is deemed highly desirable. Works in the area of Mechanics of Composites have long been typified by disciplined approaches. It is hoped that such a high standard of rigor is reflected in the majority, if not all, of the presentations in this report.

Feedback and open critique of the presentations and the review itself are most welcome as suggestions and recommendations from all participants will be considered in the planning of future reviews.



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We wish to express our appreciation to the authors for their contributions; to the focal points within the organizations for their efforts in supplying the program listings; and to Sally Lindsay, the Conference Secretary, for managing registration.

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AIR FORCE INTERESTS IN COMPOSITES RESEARCH

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Bolling Air Force Base DC 20332-6448

ABSTRACT

The Air Force has long recognized the potential that composite structural materials have in aerospace applications. Accordingly, the Air Force has supported and continues to support research in composites conducted at Universities, Industry, and Government Laboratories. Our understanding of composites, although still in an evolving state, and a number of successful applications have demonstrated the gains possible when various materials are carefully combined at the microstructural level to yield the desired mechanical properties. This observation has revolutionized the approach of "designing" new structural materials and opened up seemingly endless possibilities.

As we move into an era of hypersonic flight, space-based operations, etc., we will have to take advantage of the potential presented by this process of "engineering" the microstructure in order to meet the extraordinary performance and reliability demands which will be placed on future structural materials and systems. The resulting multi-phase materials are expected to be highly anisotropic and inhomogeneous. $\rightarrow 6.14.73 \rightarrow$

As an example of the engineering process of composites from the constituent materials like continuous parallel fibers and a highly compliant matrix, the traditional micromechanics can be combined with macromechanics to achieve a level of design not possible with the conventional homogeneous material. With an integrated micro-macromechanics analysis or Mic-Mac, the contribution of each constituent to the stiffness and strength of a laminated structure can now be quantitatively stated. As composites enter into heavily loaded applications, thick laminates must be used. The finite thickness requires higher order theory than the classical laminated plate theory. The stiffness and strength associated with the thickness direction must be properly modeled. This is done by the emerging activity of minimechanics. The transverse shear coefficient and the interlaminar failure criterion can now be engineered following the same method of micromechanics. Thus we can now have an integrated micro-mini-macromechanics, or Mic-Mini-Mac.

But these application oriented solutions do not deal with many critical issues of mechanics and materials research. Nonlinearity, time-dependent phenomena are not addressed. The interface between phases is assumed to remain continuous. In fact, each constituent also remains continuous. Thus the basic research thrust in the mechanics of multi-phase materials will be directed toward identifying, mathematically modeling, and experimentally observing the actual mechanisms governing their behavior subjected to a wide spectrum of mechanical, thermal, chemical, and electromagnetic loading. This understanding is critical for accurately estimating useful service life, establishing inspection/maintenance procedures and schedules, and calculating life-cycle costs.

Specifically, we are interested in the constitutive modeling of multi-phase materials, to include the interactions associated with the material microstructure, and the onset and evolution of damage as a time-dependent process. The unprecedented levels of reliability demanded of these future systems will also require a fundamental understanding of the response of structural materials to very high temperatures and severe temperature gradients and to high energy bombardment. Research issues include transient dynamic thermo-mechanical modeling, damage and failure development, life prediction and associated diagnostic techniques.

To focus attention to these issues we have successfully presented to the senior Air Force research management a new research initiative, entitled "Mesomechanics: The Microstructure-Mechanics Connection." The term "mesomechanics" is intended to describe an area of research which bridges the microstructure-property relationship of materials with non-continuum mechanics. It expresses our belief that real progress in this endeavor can only come about by fostering a closer collaboration between the material science and the engineering mechanics communities. Quite contrary to the traditional approaches which seek to develop constitutive models from phenomenological observations of materials behavior, mesomechanics seeks to apply mechanics principles to the microstructural constituents of multi-phase materials, thus placing the microstructure-properties relationship on a quantitative basis.

The traditional continuum mechanics approach establishes a set of mathematical relations which link the intrinsic stresses with deformation, i.e., strains. These relations are assumed uniformly valid for material elements of arbitrary volume, implying that particle interaction is local, or at an arbitrarily infinitesimal range. This assumption permits us to apply the concept of limit of differential calculus throughout the interior and on the boundary of the material body. It also allows deriving material response relationships with sufficient generality without inquiring into material microstructure and micromechanics of deformation.

In multi-phase materials, such as fiber composites, the limiting scale is of the order of the fiber diameter or layer thickness. Whatever the limiting scale, care must be taken to either account directly for the individual microstructure and micromechanics, or to retain their important effects in a phenomenological description. Thus, the developed approaches associated with the traditional continuum assumption may no longer be applicable.

The development of non-continuum mechanics approaches must overcome a number of significant obstacles. Progress in two areas appears as a necessary prerequisite to progress. First, the material microstructure must be described mathematically--the complex shapes, orientation, and distribution of phases. This will serve as the common language used by mechanicians and materials scientists alike. Second, the kinematics of microstructural evolution must be linked with mechanics. This seems at this time to be the most difficult task. Most of the work in relating the evolution of microstructures to thermodynamic forces has been in the field of metallurgy. Mechanistically linking the differential changes in the microstructure with mechanical force would require considerably better understanding of the evolving load-microstructure interaction mechanisms.

The difficulties inherent in this new effort cannot be overstated. It is clear that it will be necessary for the mechanician and the materials scientist to join efforts and perform as a team. Repeated and refined correlations between physical understanding and mathematical description for the phenomena under consideration. This will be a major challenge to both communities.

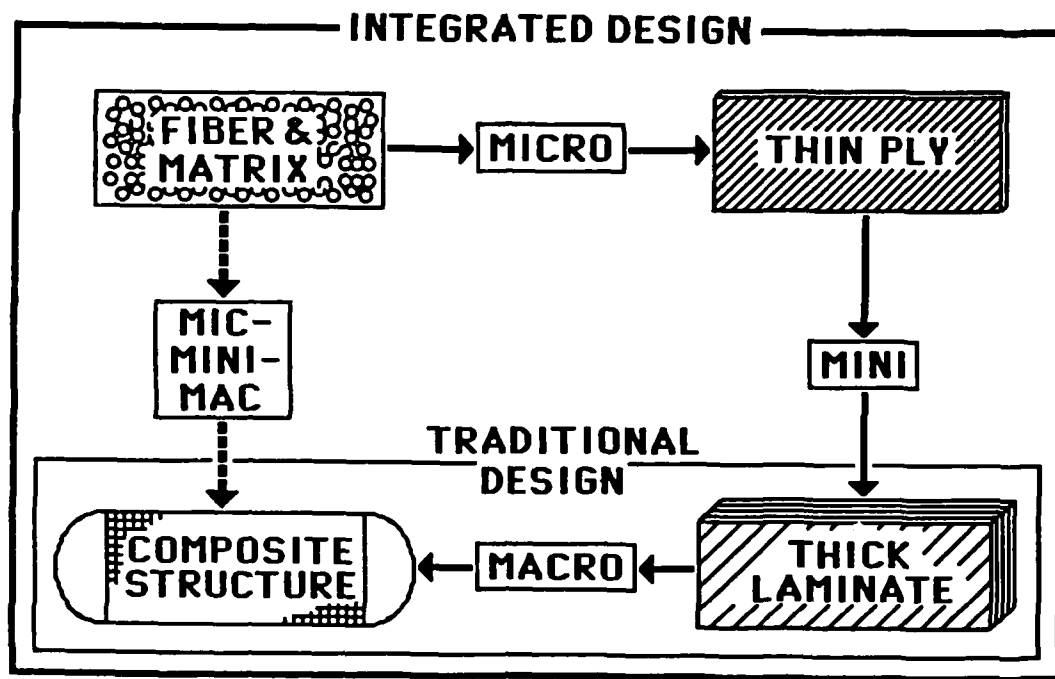


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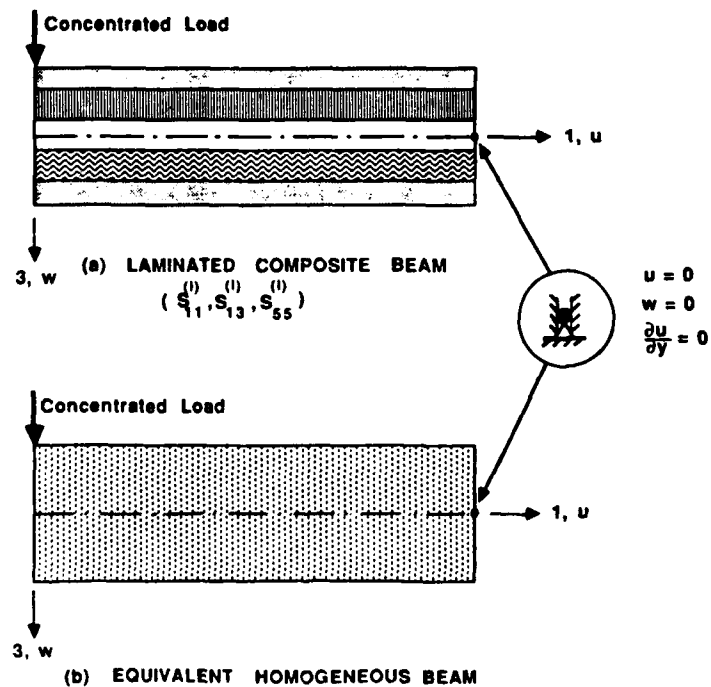
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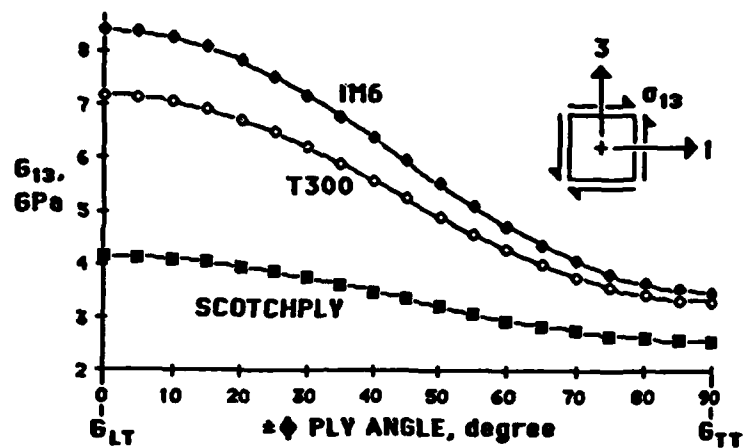
**AIR FORCE INTERESTS IN COMPOSITES RESEARCH
12th ANNUAL MECHANICS OF COMPOSITES REVIEW
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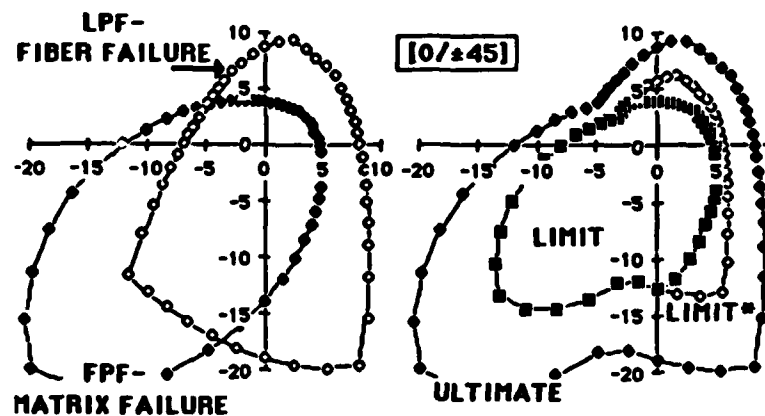
MINIMECHANICS FOR TRANSV SHEAR



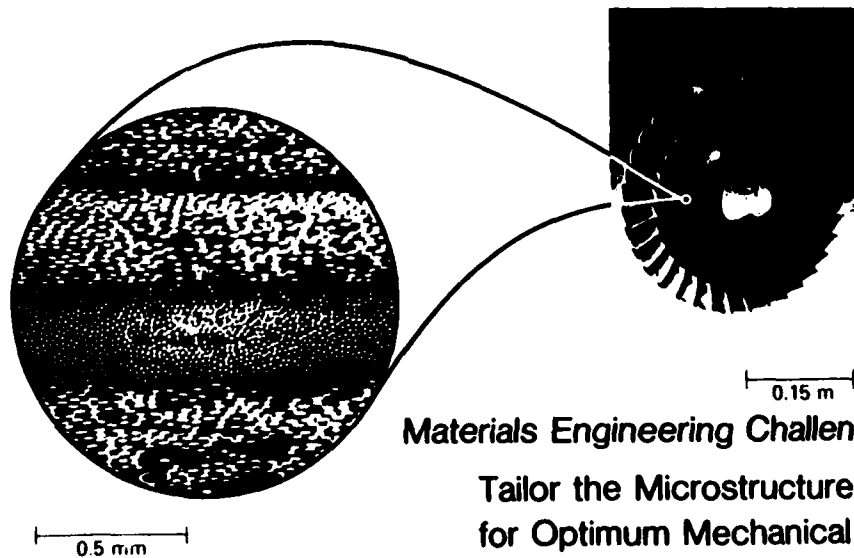
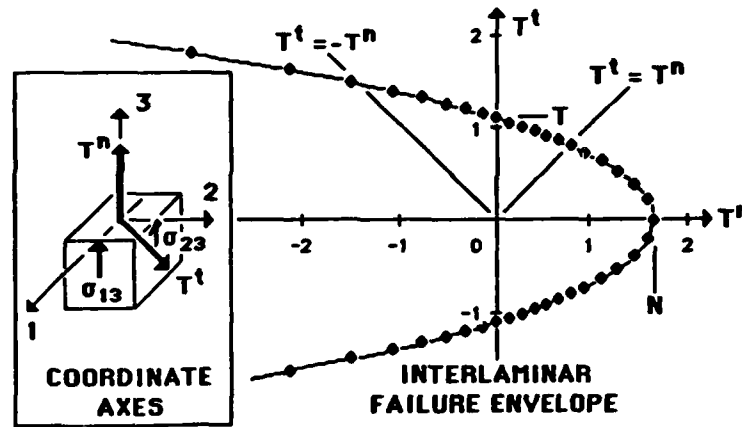
TRANSVERSE SHEAR STIFFNESS



STRENGTH ENVELOPE OF LAMINATES



SURFACE TRACTION FAILURE ENV



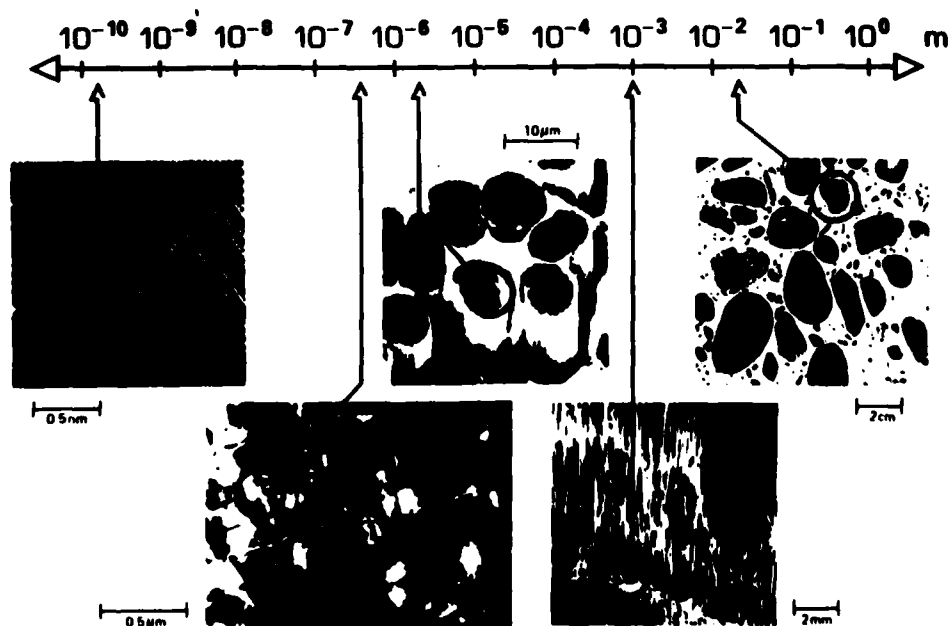
Materials Engineering Challenge:
Tailor the Microstructure
for Optimum Mechanical
Properties

FY 88
 MESOMECHANICS
 MICROSTRUCTURE IN LIVING MATERIAL



- Structural Features Exist On Range of Dimensional Scales
- Question: On Which Dimensional Scale Is the Property-Limiting Feature?

FY 88
 MESOMECHANICS
 MICROSTRUCTURAL DETAIL



← **FY 89** **MESOMECHANICS** →

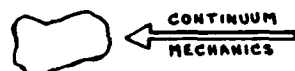
OBJECTIVES

Describe the constitutive behavior of families of heterogeneous materials at the appropriate scale and with sufficient detail as to enable predictions of the evolution of damage in each material and expected mechanical behavior at each state of damage.

Establish the correspondence between microstructural features and macrostructural behavior to enable "engineering" of the microstructure for optimum properties.

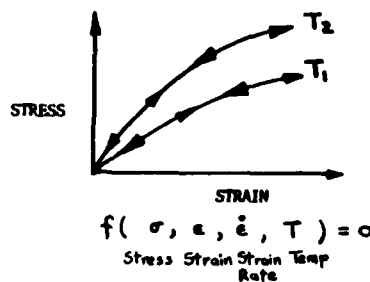
← **FY 89** **MESOMECHANICS** →
REALISTIC CONSTITUTIVE DESCRIPTION

● **CURRENT APPROACH**

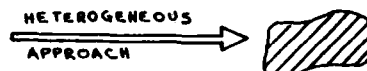


CONTINUUM
MECHANICS

- FAILURE CRITERIA DAMAGE-INDEPENDENT
- DISCREPANCIES AS TO FAILURE INITIATION
- UNABLE TO PREDICT MULTIPLE-FAILURE MODES
- CANNOT PREDICT INTERACTIONS AMONG DAMAGE MICROMECHANISMS

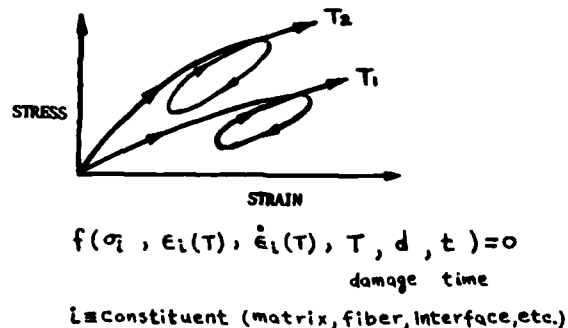


● **GOAL**



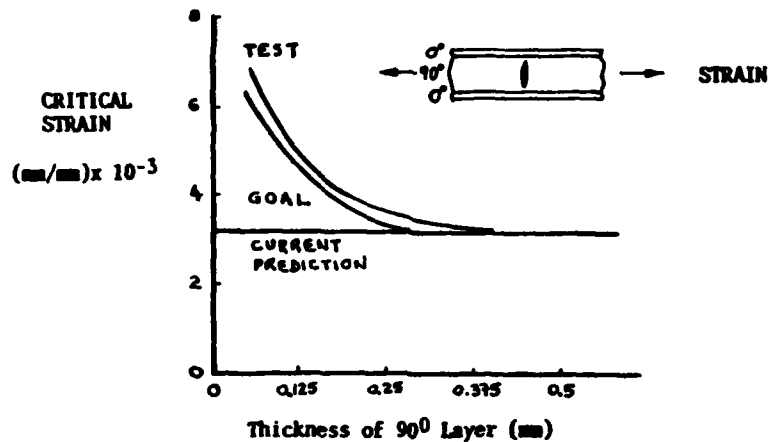
HETEROGENEOUS
APPROACH

- DAMAGE EVOLUTION INCLUDED IN CONSTITUTIVE DESCRIPTION
- FAILURE CRITERIA BASED ON DAMAGE STATE
- DELINEATE MODES OF DAMAGE AND MICROMECHANISM INTERACTION EFFECTS



MESOMECHANICS
 CONSTITUENT MATERIALS MECHANICS
 THE CHALLENGE

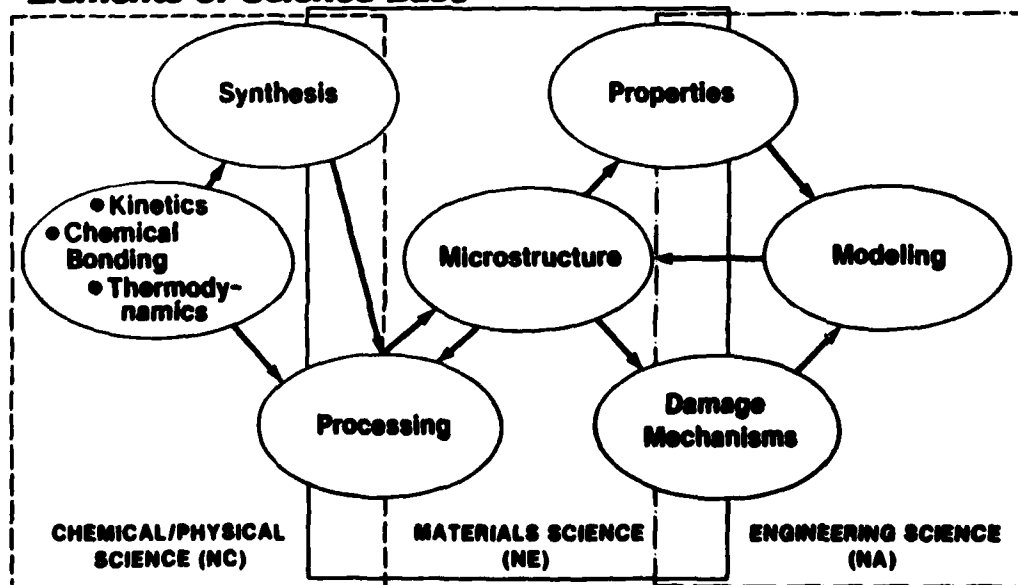
CRACK INITIATION IN LAMINATE COMPOSITES A FUNCTION OF THICKNESS!



CANNOT ACCOUNT FOR MICRO-DEFECTS INTERACTIONS

NONMETALLIC STRUCTURAL MATERIALS
 APPROACH

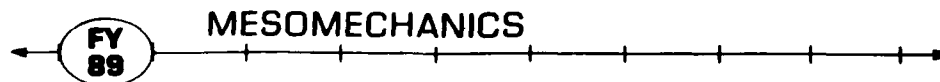
Elements of Science Base





NEEDED: NON-CONTINUUM MECHANICS

<u>CURRENT</u>	<u>ULTIMATE GOAL</u>	<u>APPROACH</u>
CONTINUUM MECHANICS	NON-CONTINUUM MECHANICS	SMOOTHED MEDIUM
critical volume $dv \rightarrow 0$ therefore $\bar{f} = -\bar{\nabla}V$	dv is finite (non-local)	Retain non-local effects but allow $dv \rightarrow 0$ $\bar{f} = -\bar{\nabla}V$
V is continuous in dv	V is not continuous	V is continuous in dv
dV exists	dV does not exist	dV exists
local discontinuities	dispersed discontinuities	introduce mathematical local discontinuities

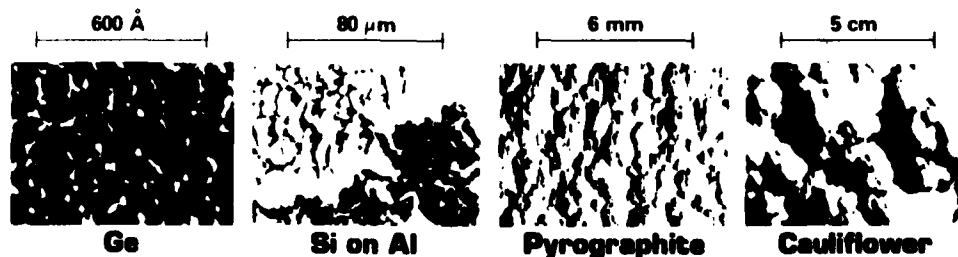


Mathematical Description of Microstructure

Fractal Geometry — A Non-Euclidian Representation
That Has an Infinite Perimeter
and a Finite Area

Characteristic Length, $L = Ks^{D-1}$

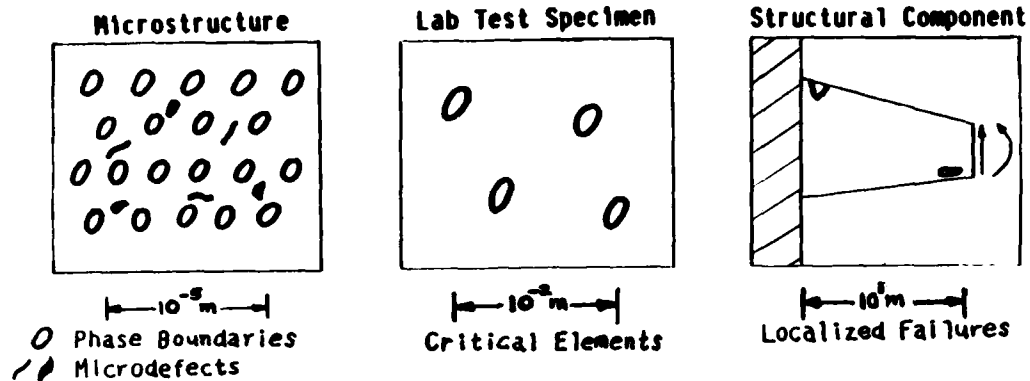
s = Scaling Unit
 K = Constant
 D = Fractal Dimension



Single D Describes All These Structures



FROM CONSTITUTIVE DESCRIPTION TO LIFE PREDICTIONS



Research

- Develop Generalized Field Theories Incorporating Damage Parameters as Dependent Variables
- Theories Must Obey Fundamental Axioms of Physics, e.g., Conservation of Mass, Energy, Momentum



REALISTIC CONSTITUTIVE DESCRIPTIONS

EXPERIMENTAL OBSERVATIONS

- Microstructure
 - Phases, Shapes, Sizes, etc
- Microstructural Defects
 - Nature (Chem, Phys, Mech)
 - Distribution
- Damage Evolution
 - Mechanisms (Defect Population, Sizes, etc)
 - Interactions

MECHANISTIC MATHEMATICAL MODELS

- Describe Microstructure Mathematically
- Simulate Defect Distribution
- Develop Phenomenological Models for Damage Growth



Develop Generalized Field Theory which Incorporates
Damage Parameters as Dependent Variables

and

Obeys Fundamental Axioms of Physics:

- Conservation of Energy, Momentum, Mass



Research Areas

- Design of Multi-Phase Structural Materials
- Mathematical Description of Microstructure Including Granular Materials
- Non-Continuum, Time- and Temperature-Dependent, Nonlinear Behavior
- Damage-Evolution Based Failure Criteria
- Nonlinear Dynamic Response Phenomena

**THE SENSITIVITY OF KEVLAR/EPOXY AND GRAPHITE/EPOXY STRUCTURES
TO DAMAGE FROM FRAGMENT IMPACT**

Paul A. Lagace

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Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

The response of composite laminates to impact is an important consideration in assessing the overall damage response (damage resistance and damage tolerance) of a composite structure. Laminated composites are sensitive to impact due to their tendency to delaminate. Furthermore, this damage often goes undetected although it may cause considerable performance (e.g. strength, stiffness) reduction in the composite part. The effort in this program is directed toward first establishing the basic response of composites to impact via generic specimens (i.e. coupon type), analysis of the impact event, and the response of the composite to the damage induced by the impact. Once the basic mechanisms are established and better understood, the work is progressing to structures typically used in aircraft such as stiffened panels, pressurized cylinders (which model fuselages) and the like.

The current presentation focuses on the analysis and basic response (via experimentation on coupons) segment of the work. In this work, the impact and post-impact response of graphite/epoxy and Kevlar/epoxy laminates was investigated over a wide range of parameters. The parameters considered were impactor kinetic energy, target boundary conditions, impactor mass, material types, and the influence of preload on the impact event. The study included analytical and experimental investigations for impact response and post-impact residual strength. After having inflicted impact damage with 12.7 mm spheres, the specimens were evaluated using dye-penetrant-enhanced X-ray and ultrasonic C-scan techniques. The specimens were loaded monotonically to failure to determine the post-impact residual strength. An analytical methodology using a global model to predict the impact event and a local model to predict the damage was developed and compared with the measured damage data. The global structural model is based on a Rayleigh-Ritz energy method to develop a set of coupled, ordinary differential equations in time. The local model is an analytic, theory of elasticity approach to the region near the impact. An equivalent membrane model for the damaged region with an average strain criterion was used to predict the post-impact residual strength given the damage state. The concepts of damage resistance and damage tolerance are, thus, considered independently. The results from the analytical impact models followed the same trends in predicting damage as the experimental data. The analytical residual strength predictions followed the same trends as the measured residual strength for in-plane dominated fracture. The results show that both the structural and material behavior must be considered in predicting damage. Residual strength was found to be a function only of the damage present for in-plane tensile fracture.

A consistent analytical design philosophy for composite structures subjected to impact is proposed. This partitioning of the problem into global and local phenomena effectively separates structural and material effects. This is illustrated for the present case of coupon specimens.

PROBLEM STATEMENT

- Composite structures can experience damage from impact in field
- Laminated composites are particularly sensitive to out-of-plane loadings (such as impact)
- This damage may result in structures which cannot meet performance requirements

PROGRAM OBJECTIVES

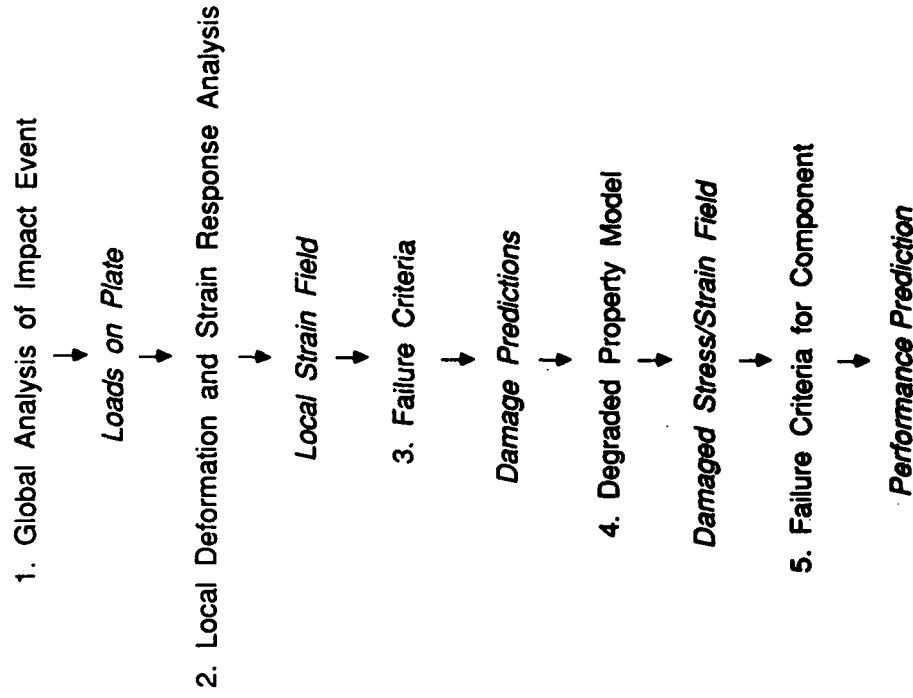
Develop Analytical Models to determine

- Impact response of filamentary composite laminates
- Induced damage due to impact
- Post-impact residual strength

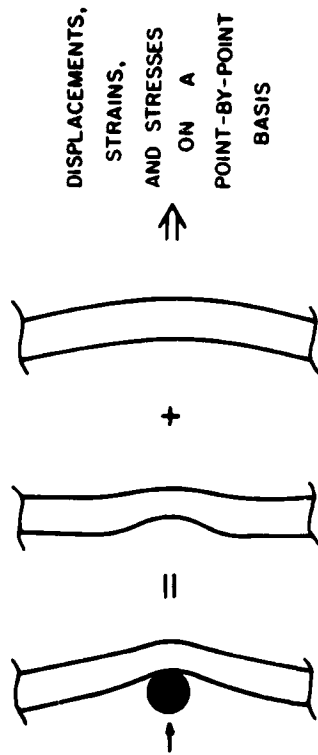
Develop a Controlled Empirical Data Base

- Parametric studies
- Verification of analytical models

APPROACH OVERVIEW

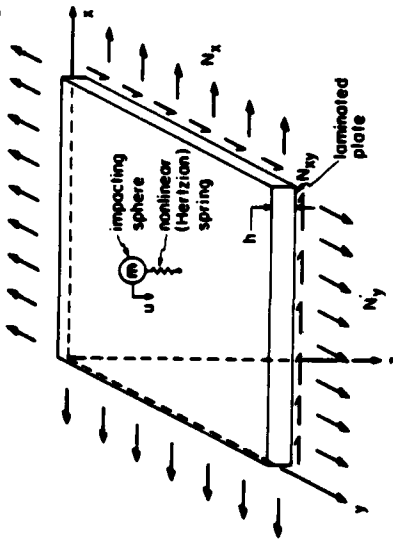


DEFORMATION RESPONSE OF LAMINATE TO LOW VELOCITY IMPACT



Projectile Impact = Local Contact Problem (Includes transverse shear effects) + Overall Structural Response (Includes global plate bending problem)

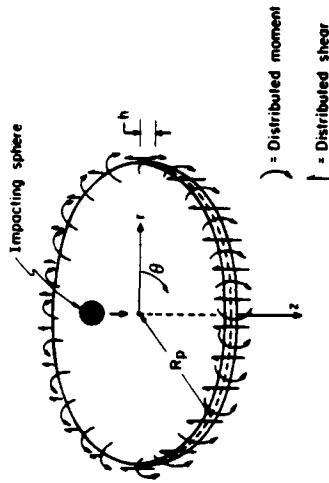
IMPACT EVENT GLOBAL MODEL



Assumed Modes Rayleigh - Ritz Analysis

- Reissner - Mindlin Plate Theory (shear deformation)
- Nonlinear Forcing Function (Hertzian Spring)
- Effect of In - Plane Loading (N_x , N_y , N_{xy})
- Bending - Twisting Coupling (D_{16} , D_{26} terms)

LOCAL CONTACT PROBLEM



- Constitutive properties are smeared through-the-thickness
- Axisymmetry assumed
- D' Alembert inertial terms included in z-direction

DAMAGE PREDICTIONS

- Applied on a ply-by-ply-basis
- Maximum Strain Criterion:

$$\frac{\epsilon_{11}}{\epsilon_{11ult}} > 1 \quad \frac{\gamma_{12}}{\gamma_{12ult}} > 1$$

$$\frac{\epsilon_{22}}{\epsilon_{22ult}} > 1 \quad \frac{\gamma_{13}}{\gamma_{13ult}} > 1$$

$$\frac{\epsilon_{33}}{\epsilon_{33ult}} > 1 \quad \frac{\gamma_{23}}{\gamma_{23ult}} > 1$$

- Mode of failure indicated

DEGRADATION ASSUMPTIONS

- Delaminations and isolated transverse splits do not cause significant degradation under tensile loading
- Only fiber breakage creates a significant reduction in constitutive properties
- All elastic constants set to zero in regions of fiber breakage

RESIDUAL STRENGTH PREDICTIONS

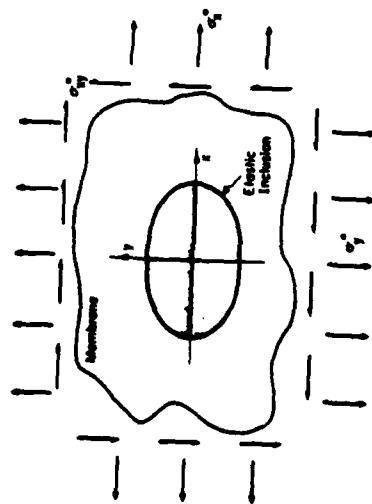
- Utilize strain from Equivalent Membrane Model
- Average strain concept applied on laminate basis
- Maximum 0° fiber strain assumed to control failure

$$S.R. = \frac{\bar{\epsilon}_x^0}{\frac{1}{a_0} \int_0^{a_0} \bar{\epsilon}_x(x,y) dx}$$

where $\bar{\epsilon}_x^0$ = far field laminate strain
 $\bar{\epsilon}_x(x,y)$ = strain distribution
 a_0 = material parameter

DAMAGED LAMINATE STRAIN ANALYSIS

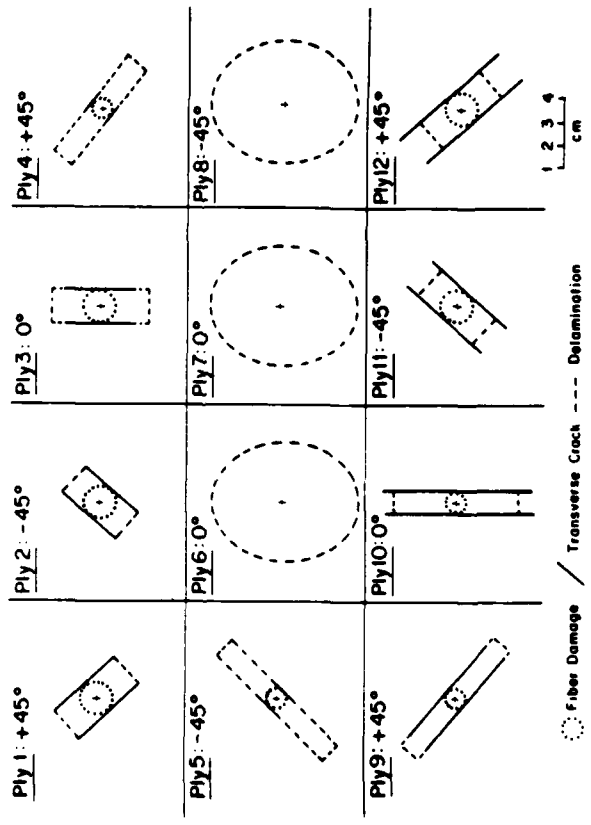
EQUIVALENT MEMBRANE MODEL (anisotropic inclusion)



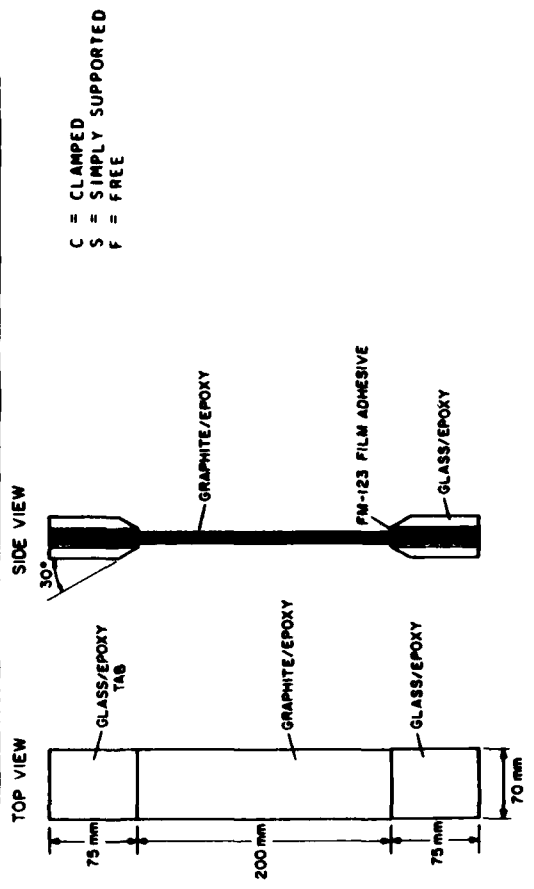
Model Based on Lekhnitskii's Complex Potentials

EXPERIMENTAL PARAMETRIC STUDIES

DAMAGE PREDICTION: $[\pm 45/0]_{2s}$

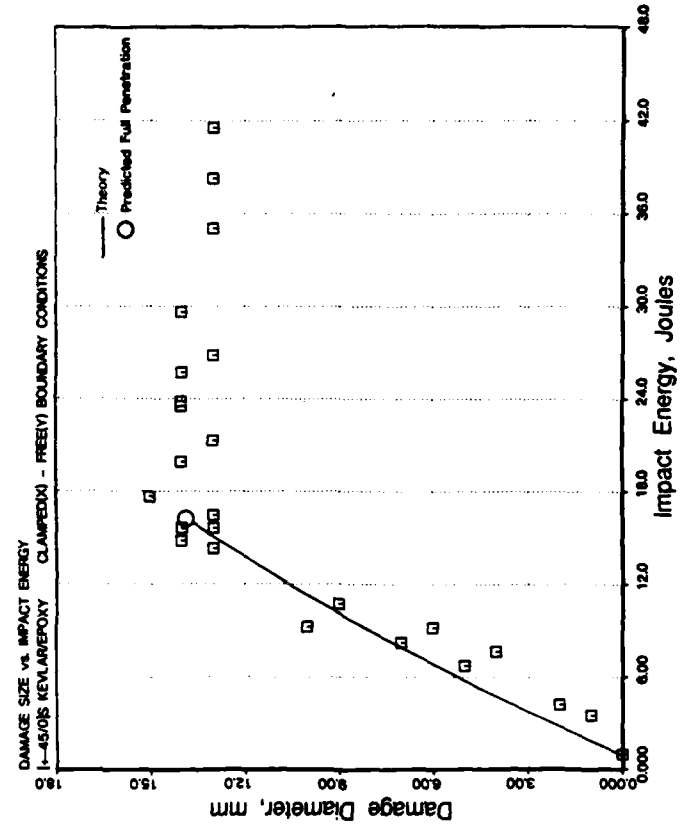
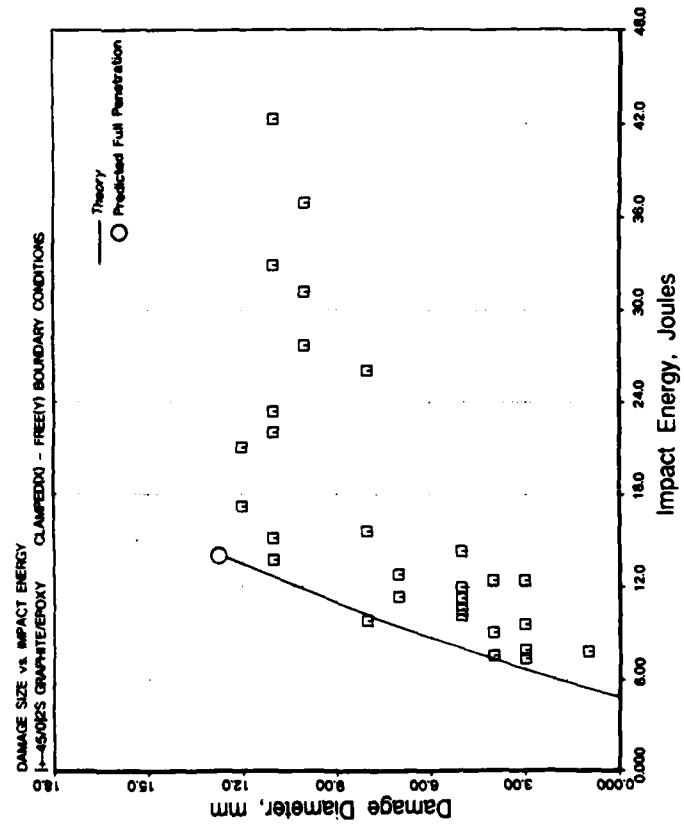


ENERGY LEVEL	VELOCITY LEVEL	IN-PLANE TENSILE LOAD	BOUNDARY CONDITIONS	
			END	SIDE
E ₁	V ₁	0	C	F
E ₂	V ₁	0	C	F
E ₃	V ₁	0	C	F
E ₁	V ₂	0	C	F
E ₁	V ₃	0	C	F
E ₁	V ₄	0	C	F
E ₁	V ₁	L ₁	C	F
E ₁	V ₁	L ₂	C	F
E ₁	V ₁	L ₃	C	F
E ₁	V ₁	0	C	C
E ₁	V ₁	0	C	S
E ₁	V ₁	0	S	C
E ₁	V ₁	0	S	F



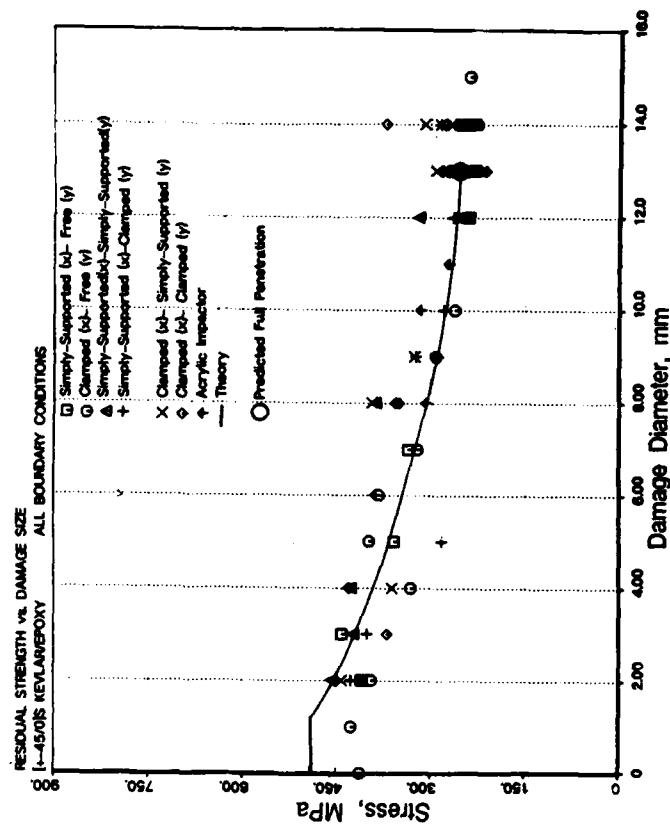
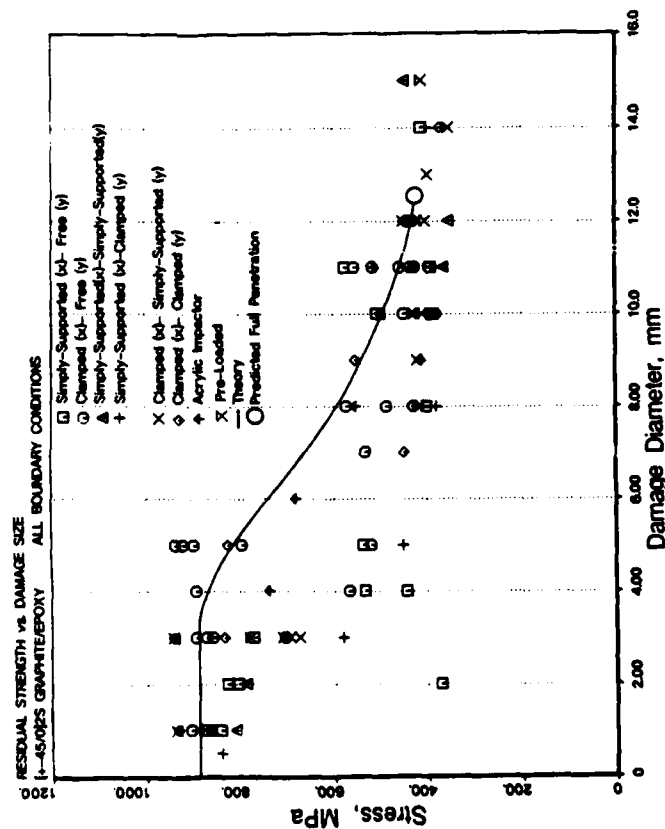
IMPACTOR ENERGY

Changes Impact Loads and Subsequent Damage to Structure

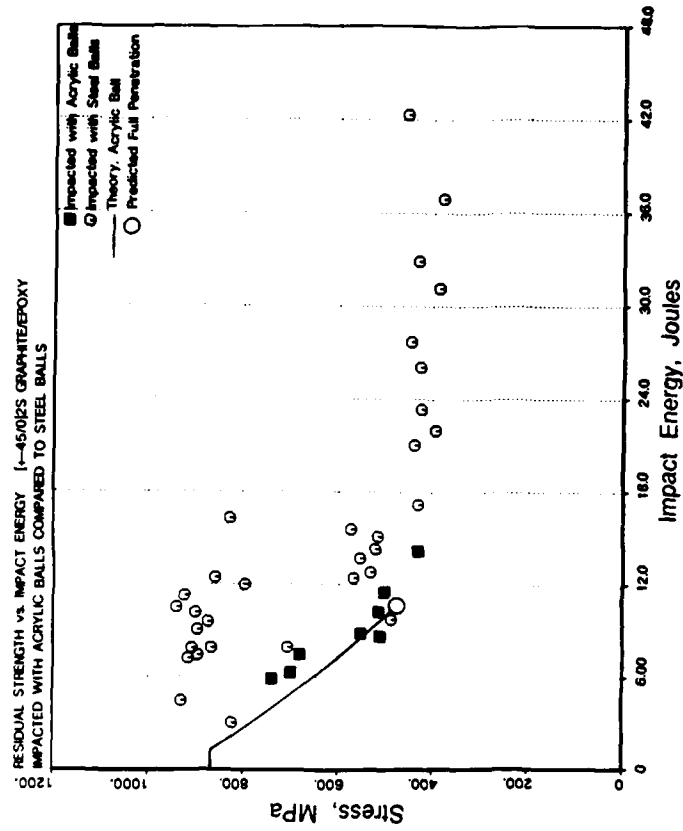
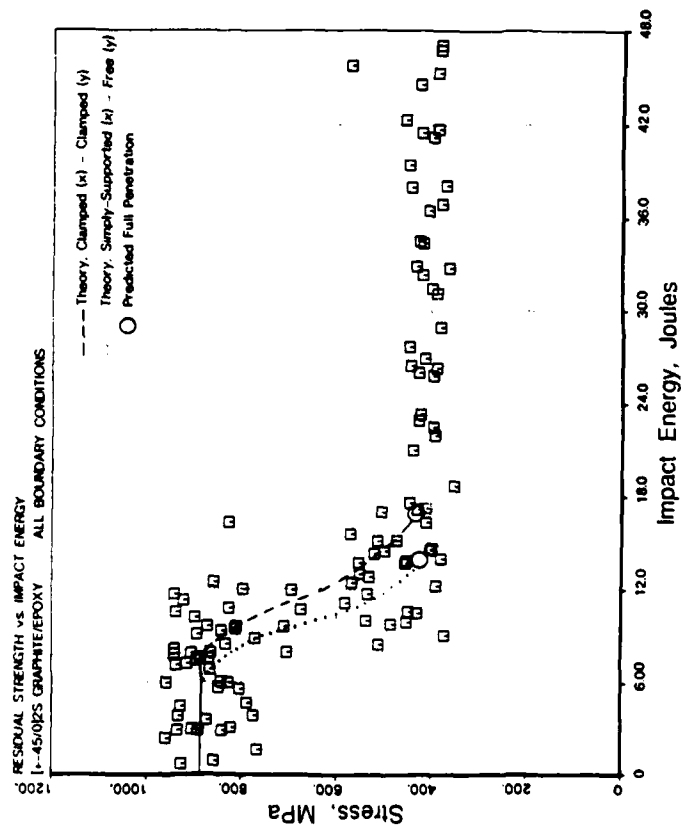


POST-IMPACT RESIDUAL STRENGTH

*Function of damage present
(independent of introduction)*



DESIGN METHODOLOGY



CONCLUSIONS

Damage Resistance

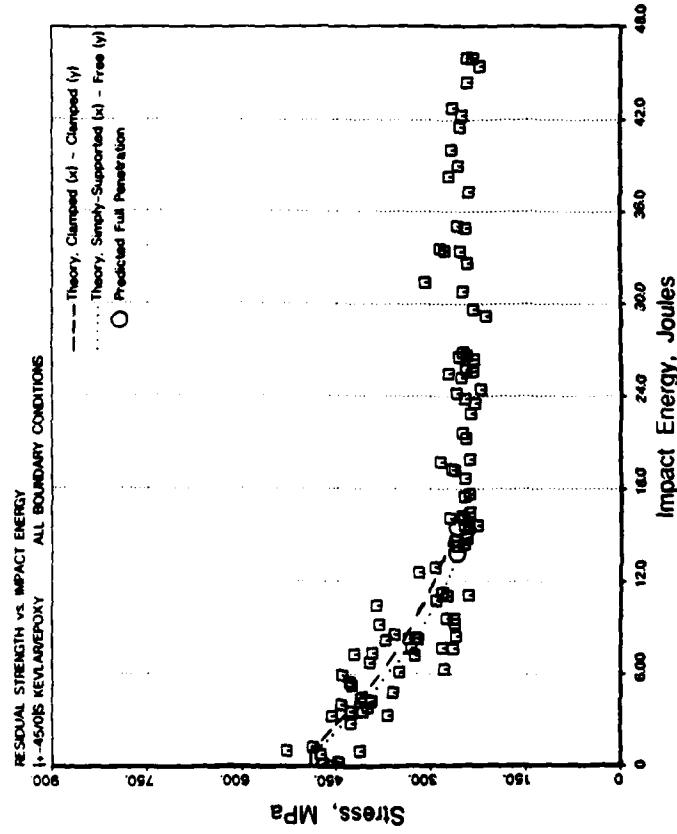
- Energy
 - Increasing energy increases damage
- Impactor mass and velocity play a significant role
 - impactor kinetic energy is not the only consideration
- Boundary Conditions
 - Have little influence in this study
 - Caution: For very low velocity impact, they play a dominant role*
- Preload can decrease damage resistance

Damage Tolerance

- Strength is a function of damage and independent of damage resistance

Design Methodology

- A framework and consistent approach for the treatment of composite materials subjected to impact has been developed here



TENSOR TRANSFORMATIONS AND FAILURE CRITERIA
FOR THE THREE-DIMENSIONAL ANALYSIS OF FIBER COMPOSITE MATERIALS

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Lawrence Livermore National Laboratory
University of California
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ABSTRACT

Classical lamination theory for fiber composites is inherently limited to the 2-dimensional conditions appropriate to thin shell configurations. A new derivation with appropriate tensor transformations is given which provides a fully 3-dimensional lamination theory that is applicable to thick laminates involving "out-of-plane" stress terms. The form taken by the lamina stress strain relations which permits the development of the 3-dimensional lamination theory is given by

$$\sigma_{ij} = \lambda \epsilon_{kk} \delta_{ij} + 2\mu \epsilon_{ij} + (E_{11} - E) \delta_{1i} \delta_{1j} \epsilon_{11} \quad (1)$$

where

$$E = 2(1 + \nu_{12}) \mu_{12}$$

$$\lambda = \frac{2\nu_{12}}{1-2\nu_{12}} \mu_{12}$$

and

$$\mu = \mu_{12}$$

It also follows that Poisson's ratio ν corresponding to λ and μ is given by $\nu = \nu_{12}$, where axis 1 is in the fiber direction.

The form (1) is for a transversely isotropic fiber reinforced medium that has properties determined by three measured constants, E_{11} , μ_{12} , and ν_{12} . Relation (1) reveals that the fiber composite can be viewed as an effectively isotropic medium with superimposed one dimensional reinforcement through the last term in (1). This last term shows that the fiber reinforcement has a direct effect in that strain ϵ_{11} (with axis 1 in the fiber direction) causes a stress σ_{11} of amount $(E_{11} - E) \epsilon_{11}$, but otherwise the fiber reinforcement is of an indirect effect, as that of an inclusion phase in a matrix phase. This indirect effect manifests its self through the isotropic terms involving λ and μ which in turn are determined by the measured properties μ_{12} and ν_{12} . This reduced form of the stress strain relation has been evaluated with respect to typical data. The result (1) now renders the tensor transformations to a trivial form, even under 3-dimensional conditions.

The simple, compact, stress strain form (1) for the fiber composite admits the development of a correspondingly simple failure criterion. It is shown that the failure criterion derived from (1) is given by

$$\left. \begin{array}{l} \text{Direct} \\ \text{Fiber} \\ \text{Failure} \end{array} \right\} \epsilon_f^{(-)} \leq \epsilon_{11} \leq \epsilon_f^{(+)} \quad (2)$$

$$\left. \begin{array}{l} \text{Fiber/Matrix} \\ \text{Interaction} \\ \text{Failure} \end{array} \right\} \alpha \epsilon_{kk} + e_{ij} e_{ij} \leq k^2 \quad (3)$$

Parameter $k/\sqrt{2}$ in (3) is the shear strain at failure, while the first term, αI_1 , involves the coupling with dilatational effects. The relations (2) and (3) are the failure criteria derived in accordance with the restricted form of the tensor transformation relations. Thus the overall, three-dimensional criterion, which breaks down into two separate criteria, involves four parameters to be determined from experimental data: $\epsilon_f(-)$, $\epsilon_f(+)$, α and k . Three aspects of the tensor transformation forms contributed to the derivation of the failure criterion. First was the decomposition of direct fiber reinforcement effect in the stress constitutive relation apart from the indirect part wherein the fiber effect is acting as an inclusion phase rather than as a direct load transfer agent. Secondly, the indirect effect of the fiber reinforcement part of the stress constitutive relation took an extremely simple form that is completely isotropic. The third key ingredient in this derivation was the necessity for using strain as the primitive variable, rather than stress. The failure criteria (2) and (3) are evaluated with respect to published data.

*This work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

ANALYSIS OF FATIGUE DAMAGE IN FIBROUS BORON-ALUMINUM LAMINATES

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ABSTRACT

When Boron-Aluminum composite laminates are subjected to cyclic loading in the plastic range, they may exhibit two entirely different types of response [1]. If the applied stress amplitude is such that the composite shakes down, then the laminate will reach a saturation damage state in which no further fatigue cracking takes place and the specimen can then survive two million cycles of loading. On the other hand, if the applied stress amplitude is such that the laminate does not shake down, then the damage process continues to the point where the zero-degree plies are overloaded and the laminate fails.

Modeling of this damage process entails substantial complexity due to the interaction between the composite plastic deformation and the matrix cracking. The alternate approach is to focus on the modeling of the terminal state of damage, i.e., the saturation damage state, without attempting to follow the evolution of damage through the damage accumulation stage.

An equivalent problem is formulated in such a way that the plastic straining and crack density in each layer can be calculated separately to meet the shakedown requirements [2]. If the fibers in the zero-degree layers do not become overloaded in this calculated shakedown state, then the laminate will shake down and the final stiffness loss at this saturation damage state can be found. If the zero-degree fibers become overloaded, then the calculated shakedown state can not be reached and the laminate fails. Comparison with the experiments on laminated B-Al plates shows excellent agreement.

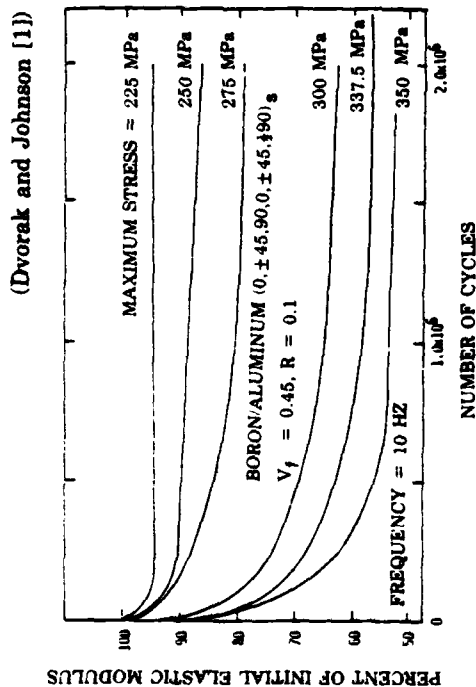
REFERENCE

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2. C.J. Wung, "Strain-space Analysis of Plasticity, Fracture and Fatigue of Fibrous Composites," Ph.D. Dissertation, Department of Civil Engineering, University of Utah, March 1987.
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5. G.J. Dvorak, N. Laws, and M. Hejazi, "Analysis of Progressive Matrix Cracking in Composite Laminates, I. Thermoelastic Properties of a Ply with Cracks," Journal of Composite Materials, Vol. 19, 1985, pp. 216-234.
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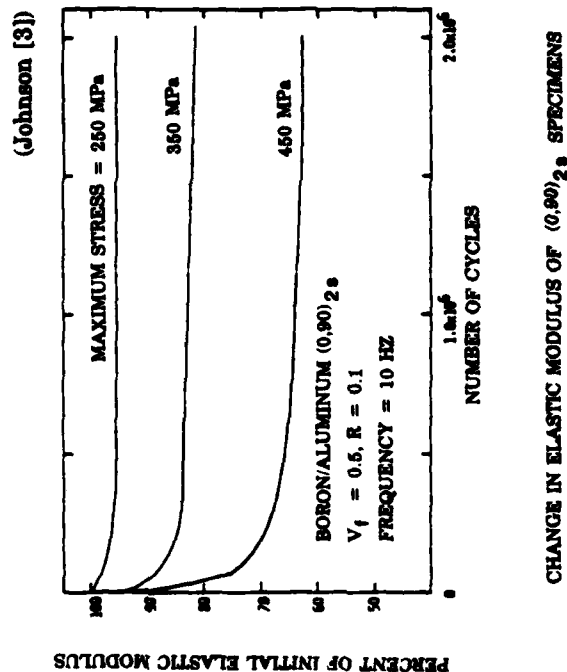
ANALYSIS OF FATIGUE DAMAGE IN FIBROUS BORON-ALUMINUM LAMINATES

C.J. WUNG and G.J. DVORAK

RENSSELAER POLYTECHNIC
INSTITUTE
TROY, NEW YORK 12180

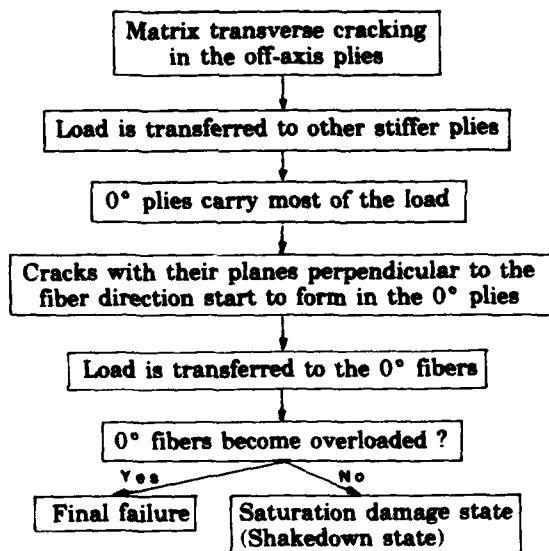


CHANGE IN ELASTIC MODULUS OF (0, ±45, 90, 0, ±45, ±90)₂ₛ SPECIMENS



Fatigue Damage Process in B/Al Laminates

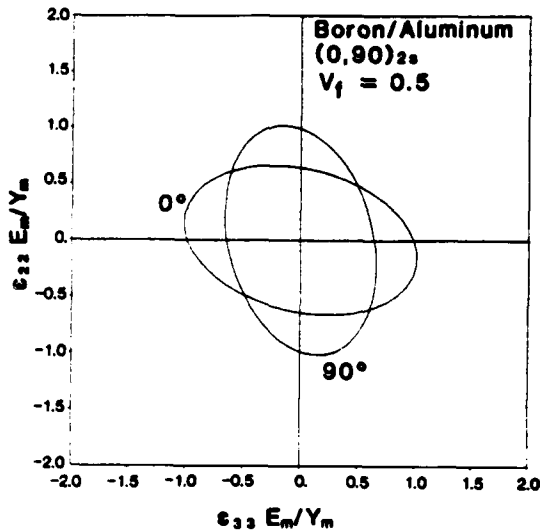
(Dvorak and Johnson [1])



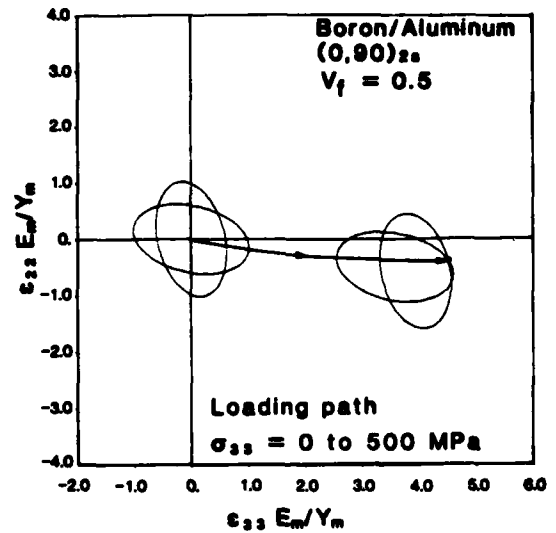
Strain-Space Plasticity of Fibrous Composites (Wung and Dvorak [4])

Aluminum matrix: elastic-perfectly plastic of the Mises type
 Boron fibers: elastic until failure

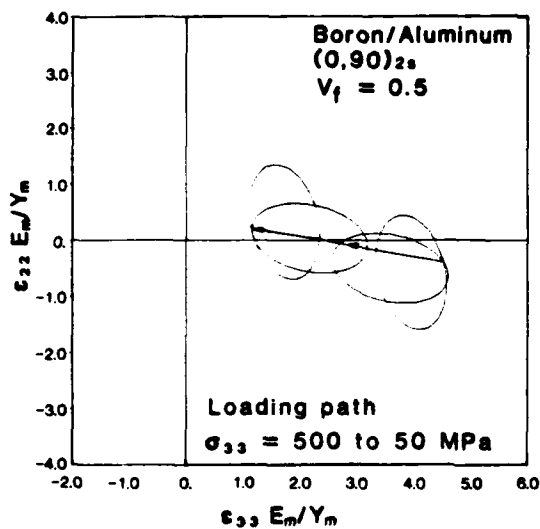
Initial Relaxation Surface



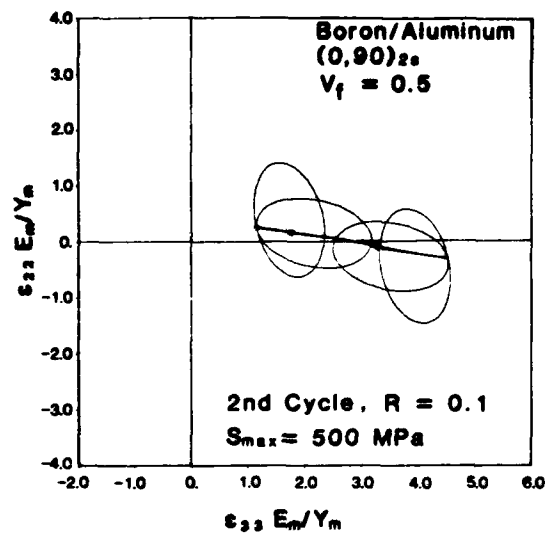
Initial and Subsequent Relaxation Surfaces
 (1st Cycle)



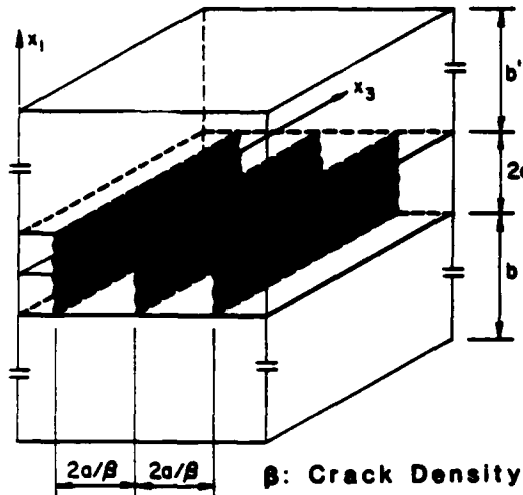
Subsequent Relaxation Surfaces (1st Cycle)



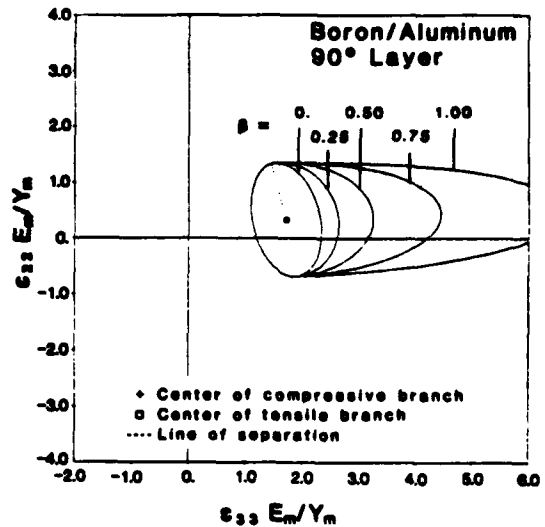
Subsequent Relaxation Surfaces (2nd Cycle)



Matrix Transverse Cracking:
(Dvorak, Laws, and Hejazi [5])



Relaxation Surfaces of a 90° Layer at Different Crack Densities

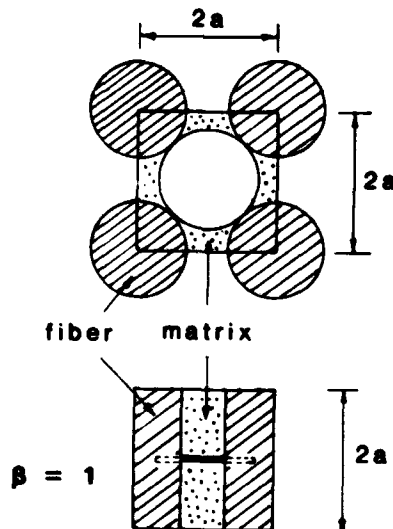


Matrix Cracking in the 0° Plies

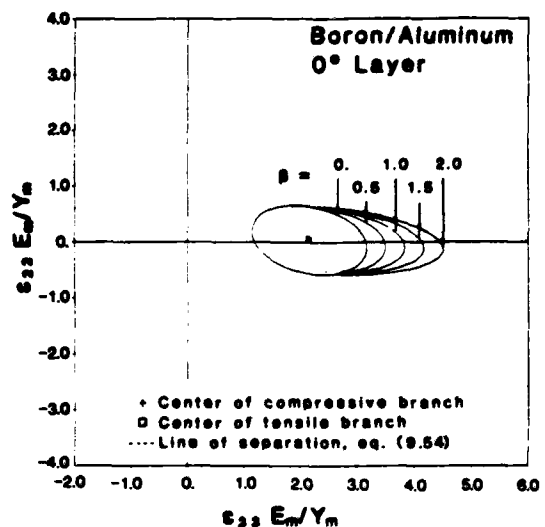
The matrix cracks observed in the 0° plies are aligned cracks with their planes perpendicular to the fibers.

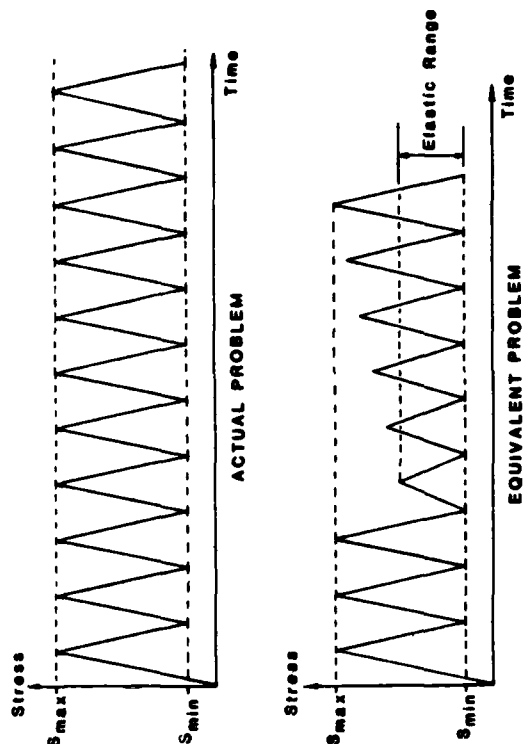
These cracks can be modeled as penny-shaped cracks imbedded in the composite.

Modeling procedure: Laws and Dvorak [6]

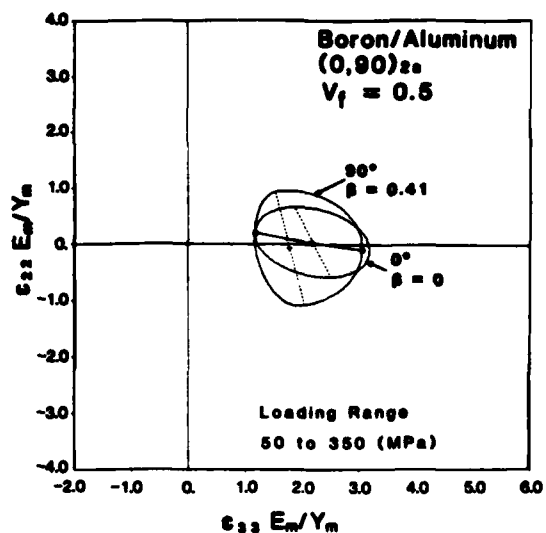


Relaxation Surfaces of a 0° Layer at Different Crack Densities

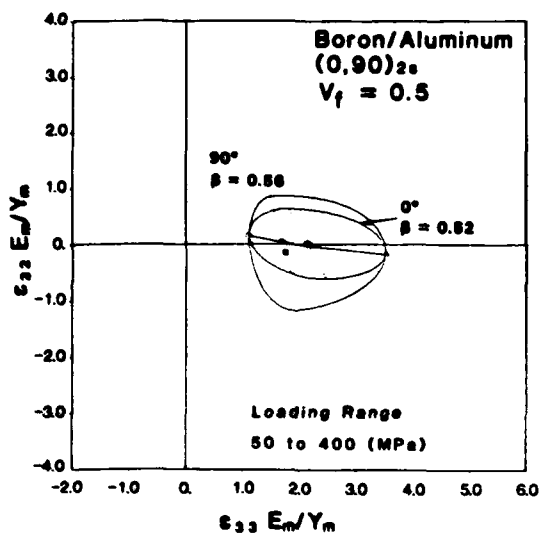




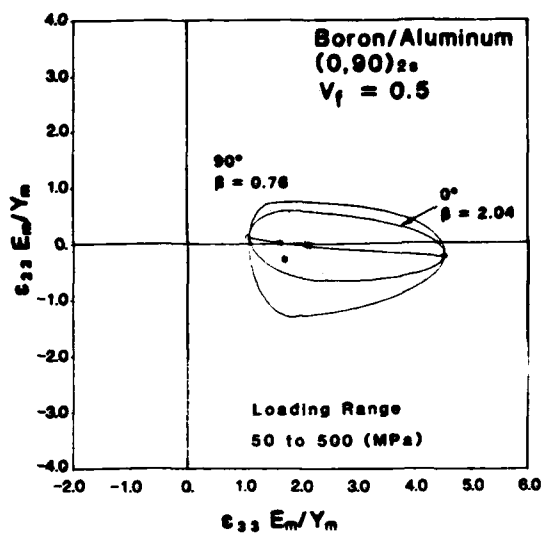
Expanded Relaxation Surfaces for Loading Range Up to 350 MPa



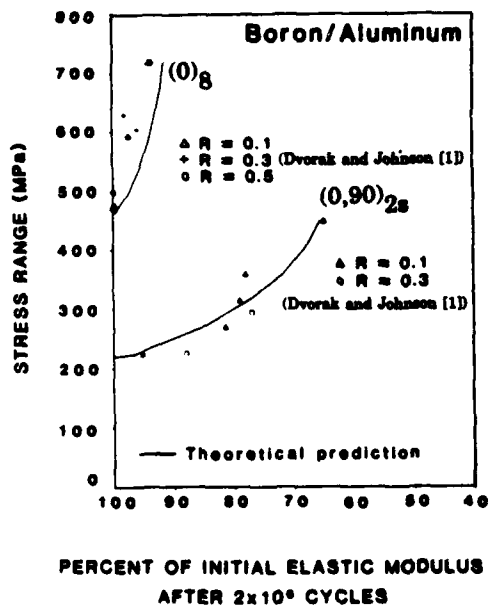
Expanded Relaxation Surfaces for Loading Range Up to 400 MPa



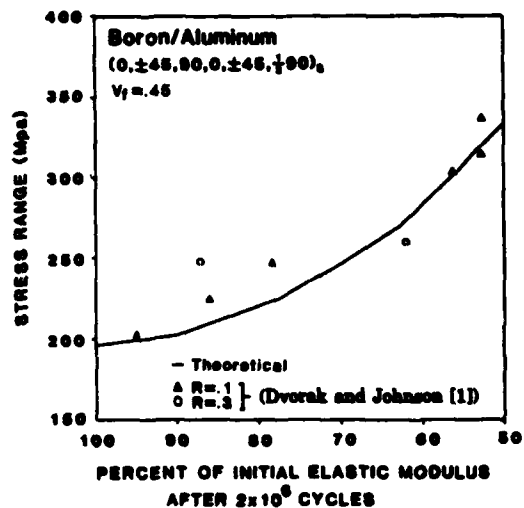
Expanded Relaxation Surfaces: The Final Result



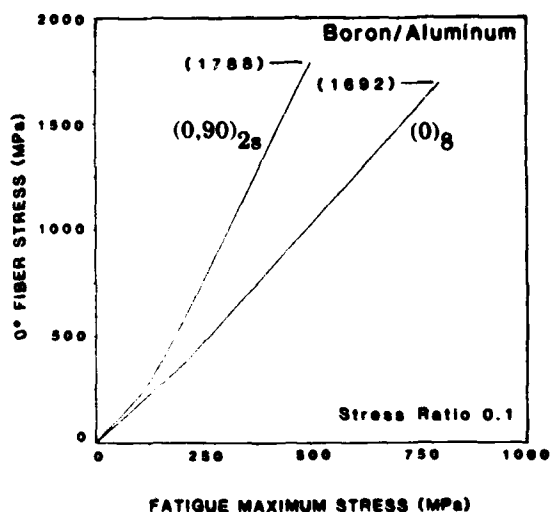
Change in Elastic Modulus of a B-Al Plate
Related to Applied Stress Range



Change in Elastic Modulus of a B-Al Plate
Related to Applied Stress Range



0° Fiber Stress Related to the Maximum
Fatigue Stress



ON MODELLING INTRALAMINAR AND INTERLAMINAR CRACKS
IN GRAPHITE-EPOXY LAMINATES

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Philadelphia, PA 19104

ABSTRACT

This paper gives an overview of a descriptive method which simulates the initiation and growth of matrix cracks in graphite-epoxy laminates. The method is developed by first observing the physical mechanisms of formation and propagation of matrix-dominated cracks at the sublaminate scale, and then modelling these cracks by means of ply elasticity and fracture mechanics concept of strain energy release rate. In each key step of the method development, some results and examples are used to illustrate the main points.

For the class of laminates made of unidirectional plies, two basic forms of matrix cracking are identified: intralaminar cracking and interlaminar cracking. Generally, these two forms of cracking occur interactively. But, in order to study their individual mechanisms, it is possible to design test coupons that yield only one or the other form of cracking. For intralaminar cracking, the $[0/90]_s$ type tensile coupons are used which yield transverse cracks in the 90° layer; for interlaminar cracking, the $[+25/90]_s$ and $[+45/0/90]_s$ tensile coupons are used to yield free edge delamination. Initial effort to simulate these cracking mechanisms individually under static loading conditions was reported in Ref. [1] and [2].

Simulation of multiple transverse cracks as a function of loading needs an additional assumption of non-uniform material strength. Here, the concept of distributed effective flaws in the ply is introduced and incorporated in the energy model. Description of this concept and simulation results were reported in Ref. [3]. Extension of the method to compression induced free edge delamination was reported in Ref. [4], and application to cracks induced by cyclic fatigue loading in Ref. [5] and [6].

When the two basic forms of matrix cracking occur interactively, material damage is usually very localized. To describe such localized damage and damage growth, the energy model requires a truly 3-D stress analysis and a fracture criterion for contoured plane crack growth. Both these requirements are difficult to fulfill, however. Attempts are made here to mimic some of the observed damage forms by a finite element routine, and the results show some promises and disappoints, Ref. [7,8].

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1. A. S. D. Wang and F. W. Crossman, "Initiation and Growth of Transverse Cracks and Edge Delamination in Composite Laminates, Part 1. An Energy Method," Journal of Composite Materials, Vol. 14, 1980, pp. 71-87.
2. F. W. Crossman, W. J. Warren, A. S. D. Wang and G. E. Law, "Initiation and Growth of Transverse Cracks and Edge Delamination in Composite Laminates, Part 2. Experimental Correlation," Journal of Composite Materials, Vol. 14, 1980, pp. 88-106.
3. A. S. D. Wang, P. C. Chou and C. S. Lei, "A Stochastic Model for the Growth of Matrix Cracks in Composite Laminates," Journal of Composite Materials, Vol. 18, 1984, pp. 239-254.
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7. A. S. D. Wang, N. N. Kishore and C. A. Li, "On Crack Development in Graphite-Epoxy $[0_n/90_n]_s$ Laminates Under Uniaxial Tension," Journal of Composite Science and Technology, Vol. 23, 1985, pp. 1-31.
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ON MODELLING INTRALAMINAR AND INTERLAMINAR CRACKS IN GRAPHITE-EPOXY LAMINATES

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DREXEL UNIVERSITY
PHILADELPHIA, PA 19104

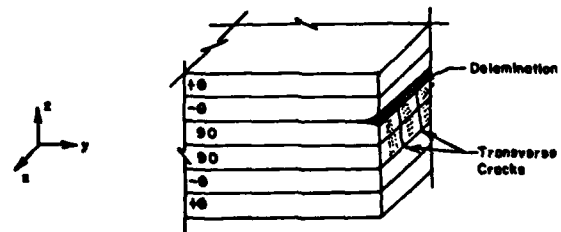
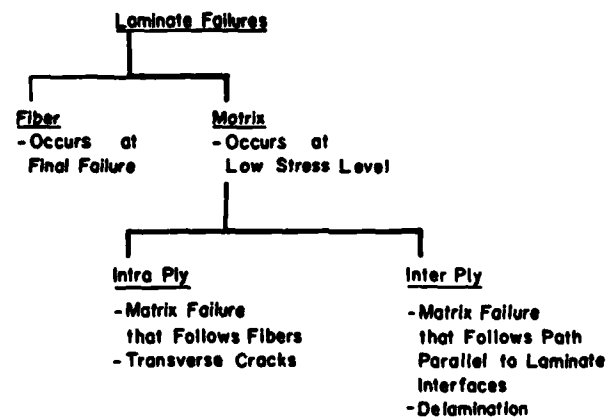
APPROACH

- * Observe matrix cracking mechanisms at the ply level by non-destructive and destructive inspection methods.
- * Identify the individual cracking mechanisms (intralaminar and interlaminar) and simulate each of them by means of 3-D ply elasticity, effective microflaw assumption and elastic fracture mechanics.
- * simulate crack growth due to interactions of the two basic forms of cracking mechanisms.
- * vary controllable influencing parameters of geometric (ply thickness, laminate thickness, stacking sequence, straight and curved free edges, sharp notches, etc.), loading (tension, compression, fatigue) and environmental (temperature, humidity) origins.
- * correlate the experimental and the simulated results.

OBJECTIVE

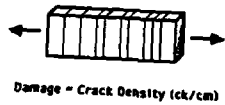
TO DEVELOP A DESCRIPTIVE APPROACH FOR THE INITIATION AND CUMULATIVE GROWTH OF SUB-LAMINATE MATRIX CRACKS, BASED ON FAILURE MECHANISMS THAT OCCUR AT THE PLY LEVEL IN GRAPHITE-EPOXY LAMINATES, AS A FUNCTION OF LOADING AND LOADING HISTORY.

SUBLAMINATE FAILURE MODES -INTRALAMINAR & INTERLAMINAR CRACKS-

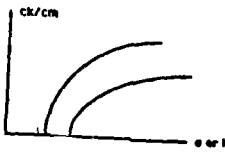


BASIC MATRIX DAMAGE MODES

INTRAPLY CRACKING MODE
(e.g. Transverse Cracks)



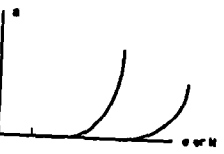
Damage = Crack Density (ck/cm)



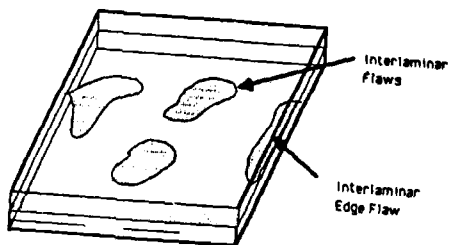
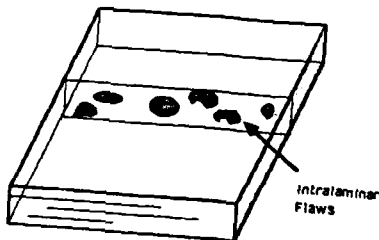
INTERPLY CRACKING MODE
(e.g. Free Edge Delamination)



Damage = Area of Delamination



INFLUENCING PARAMETERS: Ply thickness, Ply stacking sequence,
Loading level, loading history, temperature, humidity, etc.



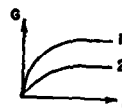
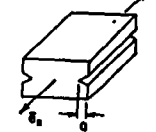
ASSUMPTION OF EFFECTIVE MATERIAL FLAW DISTRIBUTION
- Source for initiation of intralaminar & interlaminar cracks -

2-D AND 3-D MODELS FOR STRESS ANALYSIS

LAMINATION THEORY	PLY ELASTICITY
field stress $\sigma_i = Q_{ij} \epsilon_j$ $i, j = 1, 2 \text{ \& } 6$	field stress $\sigma_i = C_{ij} \epsilon_j$ $i, j = 1 \text{ to } 6$
interface matching: partially satisfied	interface matching: completely satisfied
boundary conditions: partially satisfied	boundary conditions: completely satisfied

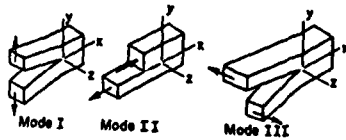
FRACTURE MECHANICS

CRACK GROWTH



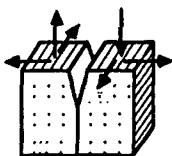
STATIC CRACK GROWTH CRITERIA

$G(\sigma, \epsilon, \Delta T) \geq G_c$
G - Strain Energy Release Rate
 G_c - Critical Strain Energy Release Rate

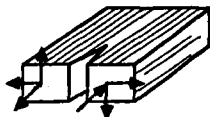
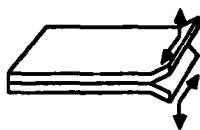


ANISOTROPY OF FRACTURE RESISTANCE

INTRAPLY CRACKING



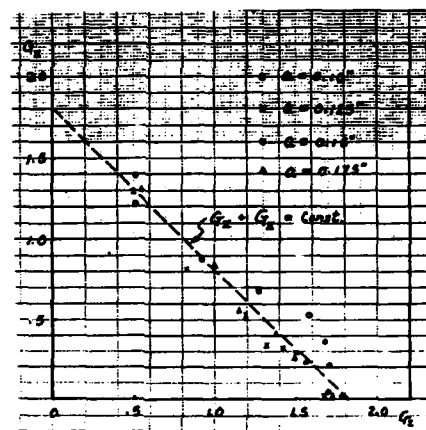
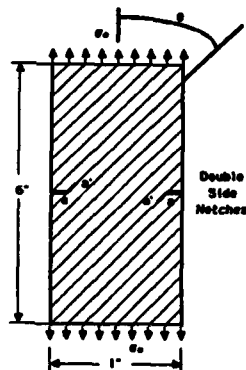
INTERPLY CRACKING



G_c is anisotropic with respect to fiber orientation & is dependent on mixed-mode cracking

UNDER MIXED-MODE CONDITION

$G_{Total} (= G_I + G_{II} + G_{III})$ SEEMS TO CONTROL



CALCULATION OF THE STRAIN ENERGY RELEASE RATE G

IRWIN'S CRACK-CLOSURE INTEGRAL:

$$G = \lim_{\Delta a \rightarrow 0} \int_0^{\Delta a} (\bar{\sigma} \cdot \Delta \bar{u}) da$$

$\bar{\sigma}$ Crack Tip Stress Vector

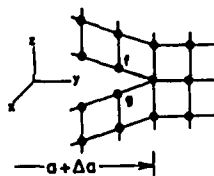
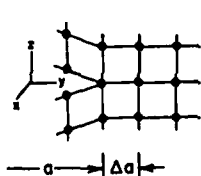
$\bar{u}$ Crack Opening Displacement Vector

NUMERICAL REPRESENTATION OF THE STRAIN ENERGY RELEASE RATE (SERR)

$$G_I = F_z (w_f - w_g) / 2\Delta a$$

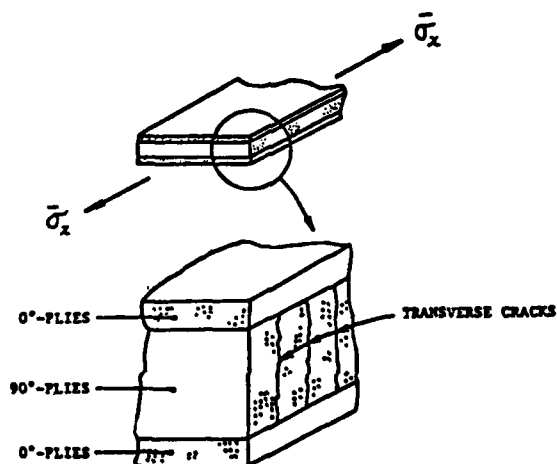
$$G_{II} = F_y (v_f - v_g) / 2\Delta a$$

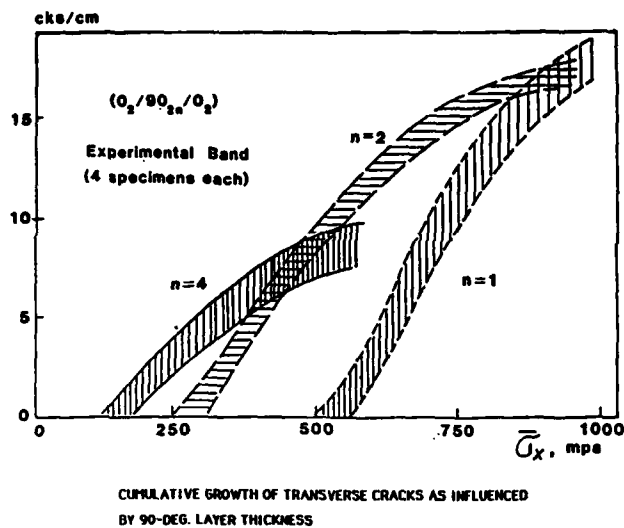
$$G_{III} = F_z (u_f - u_g) / 2\Delta a$$



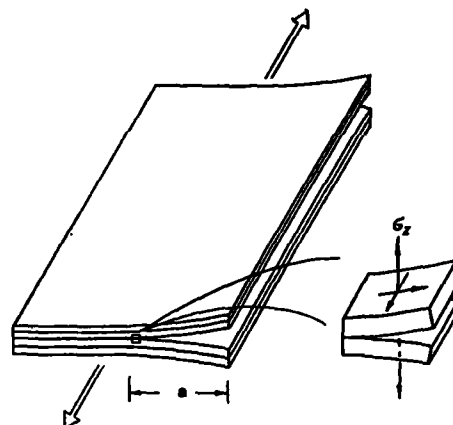
FORMATION OF TRANSVERSE CRACKS IN CROSS-PLYED LAMINATES

- NOT INTERACTING WITH DELAMINATION -





FORMATION OF FREE EDGE DELAMINATION - NOT INTERACTING WITH ANY TRANSVERSE CRACKING -

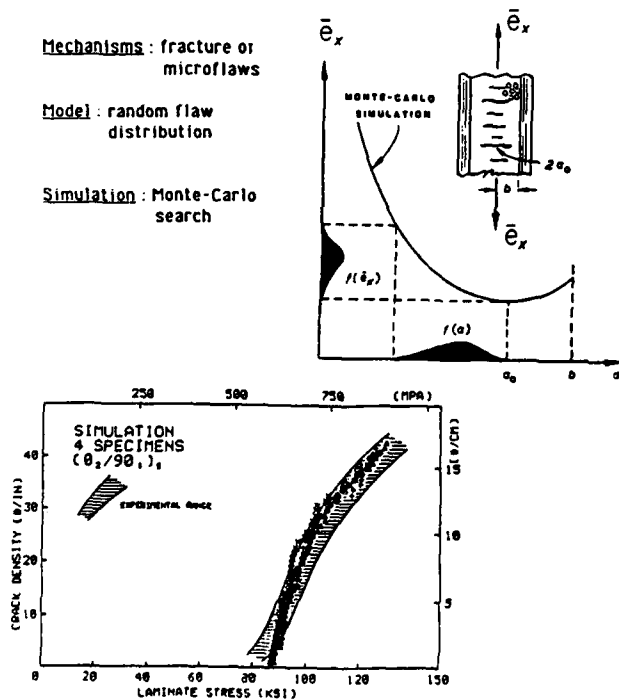


SIMULATION OF TRANSVERSE CRACKS EFFECTIVE FLAW DISTRIBUTION, 3-D STRESS, FLAW-TIP ENERGY RELEASE RATE, INTERACTION WITH NEIGHBORING CRACKS, MONTE CARLO SIMULATION

Mechanisms: fracture or microflaws

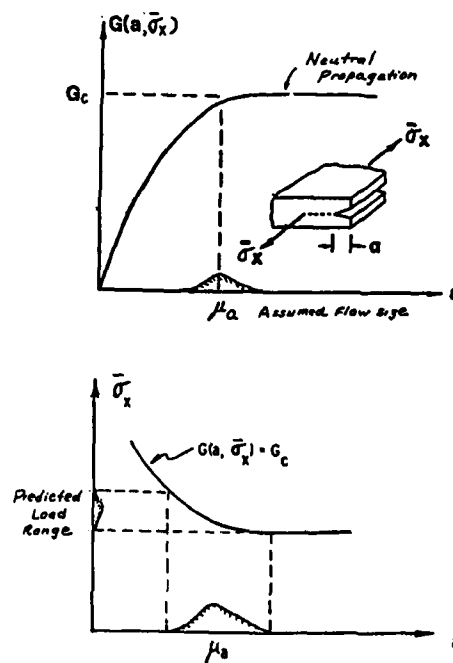
Model: random flaw distribution

Simulation: Monte-Carlo search



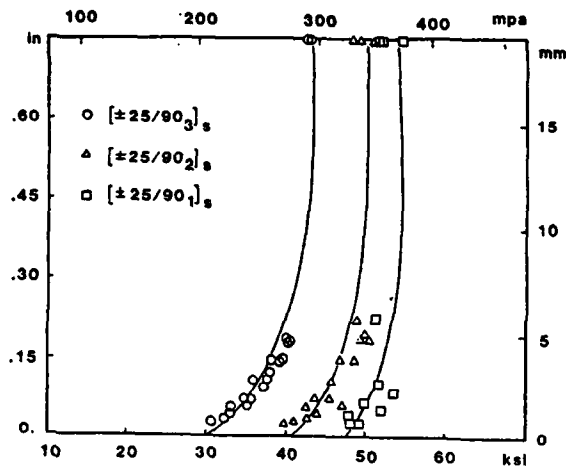
SIMULATION OF FREE EDGE DELAMINATION EFFECTIVE FREE EDGE FLAW DISTRIBUTION, 3-D STRESS ANALYSIS, FLAW-TIP ENERGY RELEASE RATE, NUMERICAL SIMULATION

APPLICATION OF FRACTURE CRITERION

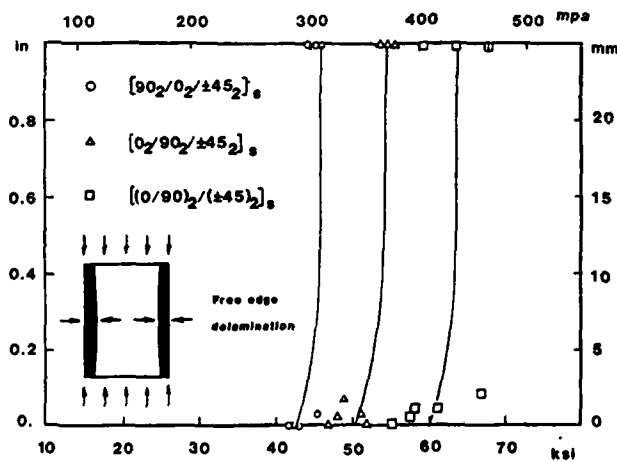


COMPRESSION FAILURE OF A LAMINATE - A GRAPHITE-EPOXY $(0_2/90_2/45_2/-45_2)_3$

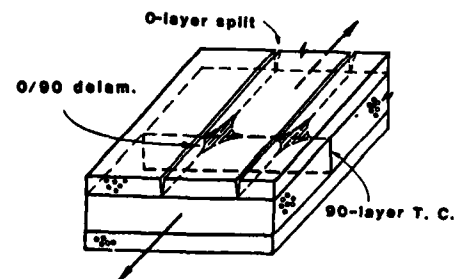
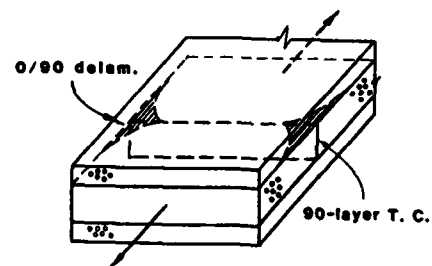
LAMINA THICKNESS EFFECT ON THE ONSET
AND GROWTH OF FREE EDGE DELAMINATION



LAMINA STACKING SEQUENCE EFFECT ON
THE THRESHOLD CONDITION OF FREE EDGE DELAMINATION

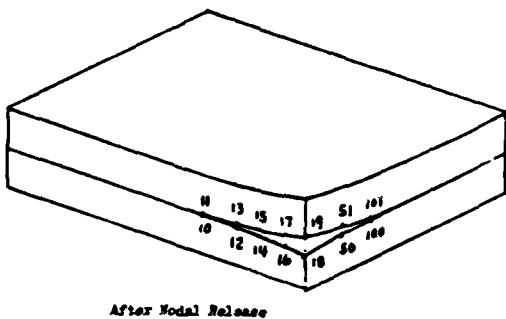
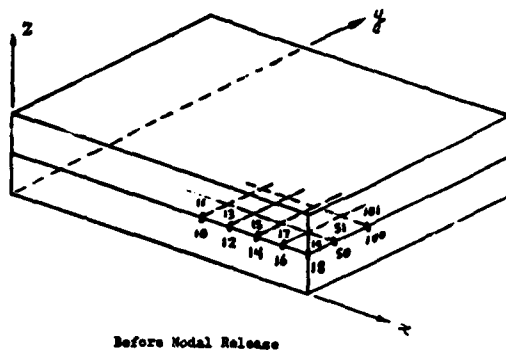


INTERACTIONS BETWEEN INTRALAMINAR
(TRANSVERSE CRACKS) AND INTERLA-
MINAR (DELAMINATION) FAILURES.



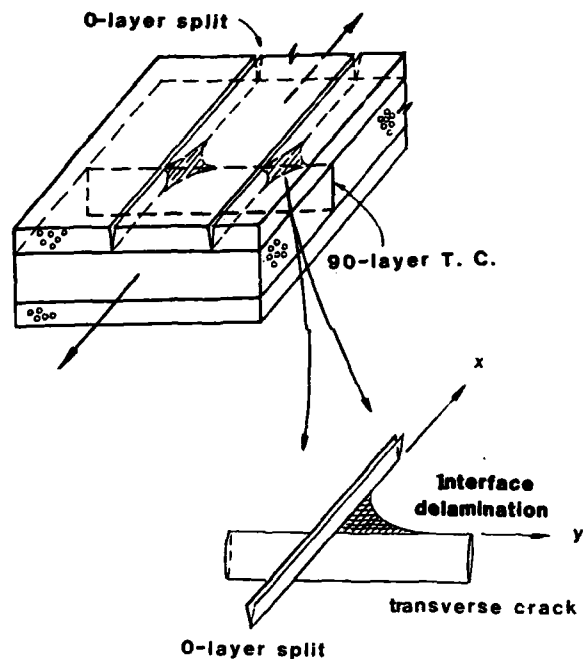
SIMULATION OF CONTOURED DELAMINATION

- 3-D FINITE ELEMENTS & NODAL RELEASE SCHEME -



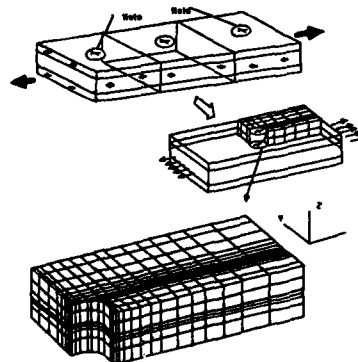
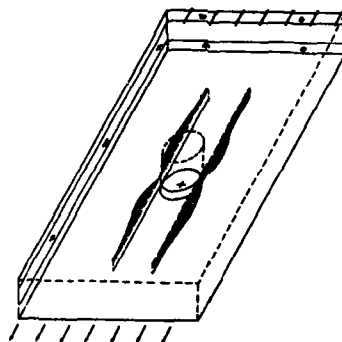
SIMULATION OF LOCAL DELAMINATION

- FROM CROSS-CRACKS IN [0/90]_s UNDER TENSION -



SIMULATION RESULTS VS EXPERIMENT FOR CENTER-NOTCHED SPECIMENS

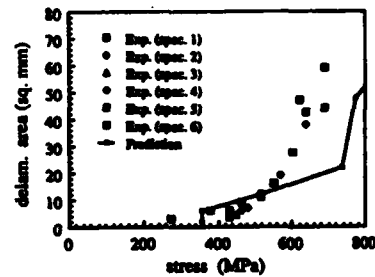
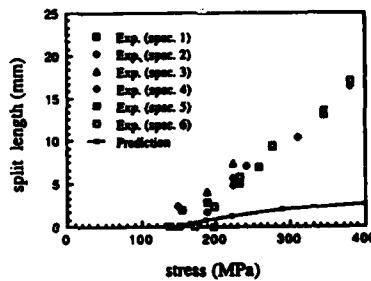
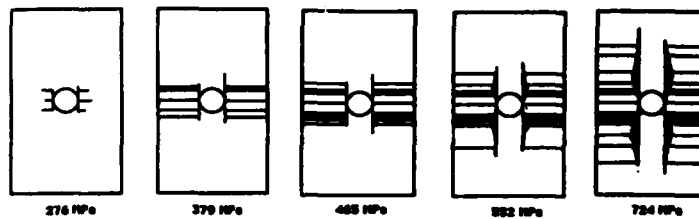
- BASED ON NON-INTERACTION FROM TRANSVERSE CRACKS -



SIMULATION OF MATRIX CRACKING

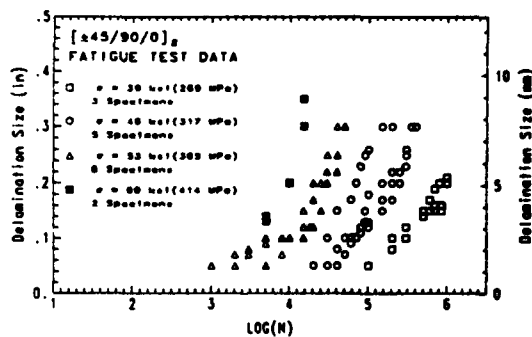
IN NOTCHED LAMINATES

- $[0_2/90_2]_s$ LAMINATES WITH SIDE-NOTCHES OR A SMALL HOLE -



DELAMINATION-FATIGUE

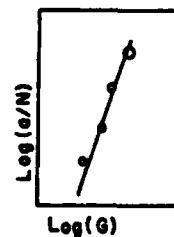
Experimental Results



Growth Criterion

$$da/dN = \alpha (G/G_c)^{\rho}$$

α - scaling parameter
 ρ - power parameter



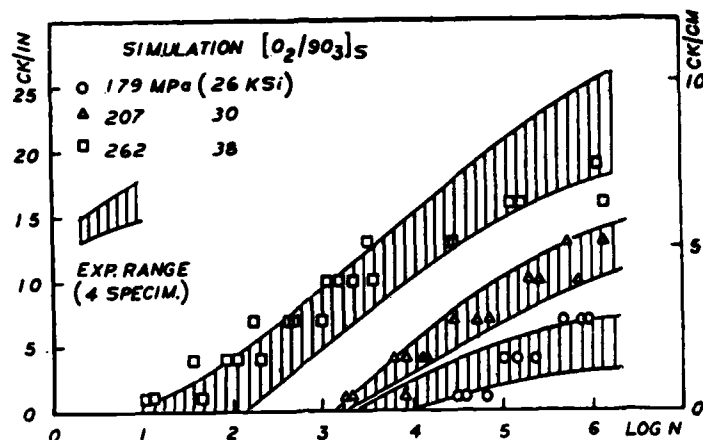
Prediction

$$N = a/\alpha (G/G_c)^{-\rho}$$

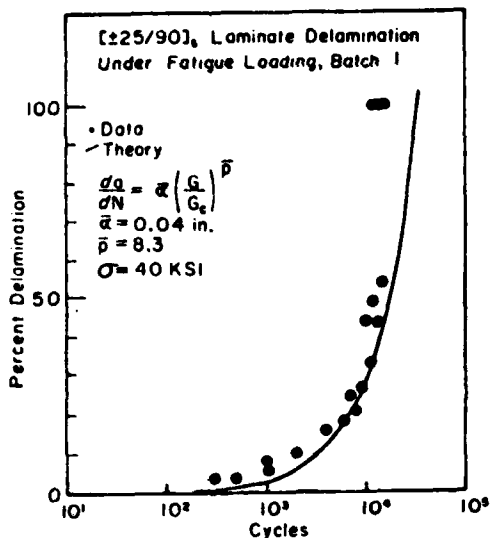
$$= a/\alpha (C_0 \sigma^2 / G_c E^2)^{-\rho}$$

$$= a/\alpha (K^1 \sigma^{-2\rho})$$

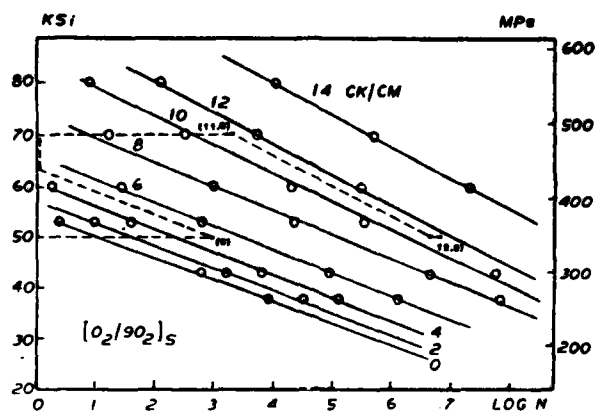
SIMULATION EXAMPLE..... $[0_2/90_2]_5$ COUPONS
LOADED UNDER TENSION-TENSION FATIGUE WITH $R = 0.1$; A
COMPARISON OF PREDICTED AND EXPERIMENTAL TRANSVERSE
CRACKING DENSITY.



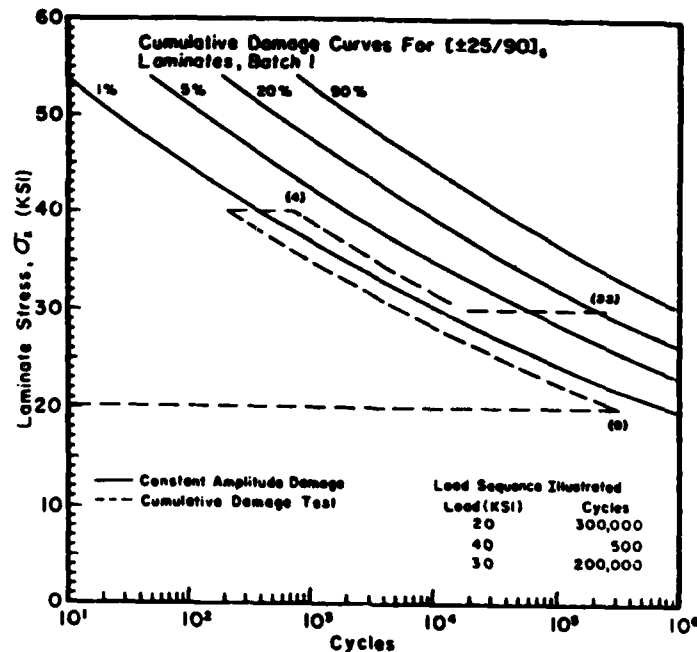
SIMULATION EXAMPLE..... $[25/-25/90]_3$ COUPONS
LOADED UNDER TENSION-TENSION FATIGUE WITH $R = 0.1$. A
COMPARISON OF PREDICTED AND EXPERIMENTAL DELAMINATION
SIZE.



SIMULATION EXAMPLE..... $[0_2/90_2]_5$ COUPONS
LOADED UNDER TENSION-TENSION FATIGUE WITH $R = 0.1$; A
COMPARISON OF PREDICTED AND EXPERIMENTAL TRANSVERSE
CRACKING DENSITY.



**SIMULATION EXAMPLE..... [25/-25/90]₃ COUPONS
LOADED UNDER TENSION-TENSION FATIGUE WITH R = 0.1. A
COMPARISON OF PREDICTED AND EXPERIMENTAL DELAMINATION
SIZE.**



CONCLUSIONS

- * The simulation method (3-D ply elasticity-fracture mechanics) is shown to yield good results for the two basic forms of matrix cracking when they occur non-interactively.
- * When they interact, it causes localized delamination. The present method is shown to be less effective. A criterion based on very localized mechanisms and material properties is so far unavailable.
- * The 3-D finite element routine needs further development in order to treat interactive and localized matrix cracking situations.
- * The Paris-type fatigue rule requires a large data base and is empirical in nature. A generic fatigue growth rule is desirable but so far unavailable.

SOME DAMAGE MODELS FOR COMPOSITES*

D.H. Allen, W.L. Bradley, C.R. Corleto, C.E. Harris, R.A. Schapery, Y. Weitsman

Texas A&M University
College Station, TX 77843

ABSTRACT

Research on four projects is summarized. Projects No. 1 (Allen and Harris) and No. 2 (Weitsman) are presently concerned mainly with constitutive equations and their dependence on quantities ("internal state variables") which reflect the state of damage. Each uses a different type of a physically plausible internal state variable. Project No. 3 (Schapery) deals mainly with damage growth and a method using a "work potential" which characterizes mechanical behavior in damaging processes. Project No. 4 (Corleto and Bradley) covers the use of a J integral (which depends on existence of the work potential) in mode II delamination; also included is a new technique to measure displacement field.

1. D.H. Allen and C.E. Harris have developed a constitutive model for fiber-reinforced laminated composites which includes the influence of microstructural damage on the stress-strain behavior of a composite structure. The effects of microcracks are reflected via internal state variable (ISV's) in the constitutive equations rather than treating each microcrack as a separate internal boundary. Furthermore, the model is phenomenological because only the average macroscale effect of microcracking is modelled rather than the effect of each individual crack. Because cracking is not statistically homogeneous in the coordinate direction normal to the laminate, statistical weighting is necessary in this direction, and this is accomplished via kinematic constraints. Therefore, the constitutive equations are laminate equations, rather than standard stress-strain equations.

The objective of the recent effort is to extend the model to predict the response of laminates with both matrix cracks and interior delaminations. This problem is complicated by two factors. First, because these two damage mechanisms are oriented differently, they require two separate tensor-valued damage parameters. Furthermore, the mechanics of these two damage modes are substantially different. The matrix cracks may be assumed to be statistically homogeneous in the z coordinate direction. This requires that a modification be made to the statistical averaging techniques. Although statistical homogeneity is assumed in the x and y directions, a kinematic constraint similar to the Kirchhoff-Love hypothesis is applied in the z direction. The resulting damage parameter is a weighted measure of damage, with delaminations away from the neutral surface causing a greater effect on laminate properties. Using fracture mechanics concepts to relate the ISV's to the current damage state, model predictions of the degraded axial modulus are compared to experimental results in the accompanying bar chart.

2. A continuum damage formulation is provided by Y. Weitsman for unidirectionally reinforced composites, based upon fundamental principles of irreversible thermodynamics and continuum mechanics. A damage parameter (internal state variable) is introduced which represents the total area of microcracks contained within a characteristic material cell. This representation enables the correlation of damage growth with micro-level fracture processes, which can include the effects of crack interactions. The general formalism leads to stress-strain relations which contain damage softened moduli and the effects of damage on the re-orientation of material symmetry. In addition, coupling phenomena such as the effects of damage on heat conduction, can be incorporated within the theoretical framework. Probabilistic considerations of micro-flaw sizes and distributions can be employed to convert the formalism from a deterministic to a statistical methodology.

*Sponsored by the Air Force Office of Scientific Research

3. Damage growth and its affect on mechanical behavior of composite materials and structures is studied by R.A. Schapery. An energy-based approach is used. The mechanical work input is shown for relatively general damaging processes to be a potential consisting of strain energy plus the work of damage. In turn, the existence of this so-called work potential leads to equations which govern the growth of damage parameters (internal state variables). There is considerable freedom in selecting damage parameters; but if one of the parameters is taken as the work of damage, the equations governing their growth become very simple. Some results from axial-torsional tests of bar specimens (rubber-toughened graphite/epoxy laminates) are shown to provide a check on the theory for proportional straining. Confirmation of the theory for nonproportional straining is presently under study. Viscoelastic effects have been introduced in the model by approximating theoretical results obtained from viscoelastic crack growth theory.
4. A J-integral analysis has been developed by C.R. Corleto and W.L. Bradley for mode II delamination of a split laminate loaded vertically on the split end with the other end rigidly supported against vertical displacement, but free to translate in the horizontal direction. This approach allows one to analyze load-displacement data which is both nonlinear and has an inelastic component. The results for J_{IIC} are identical to G_{IIC} when linear load-displacement data are analyzed. However, J_{IIC} is generally much lower than G_{IIC} for nonlinear load-displacement curves because G_{IIC} may include far field damage when the area method is used. Linear beam theory applied to nonlinear load-displacement curves also gives artificially high values for G_{IIC} .

A new technique also has been developed on the project to directly measure the displacement field around the tip of a growing crack. This technique involves placing a dot map on the surface at 5-10 micron intervals and then directly observing the distortion of the dot map as the crack approaches. Quantitative image analysis allows the original coordinates and the subsequent coordinates of the dots in the map to be found, allowing accurate determination of the displacement of each dot. The resulting displacement field can then be used to calculate a strain field around the crack tip.

DAMAGE MODELLING IN LAMINATED COMPOSITES

by

David H. Allen
Charles E. Harris

Aerospace Engineering Department
Texas A&M University

ESSENTIAL FEATURES OF A CONTINUUM DAMAGE MODEL FOR LAMINATED COMPOSITES

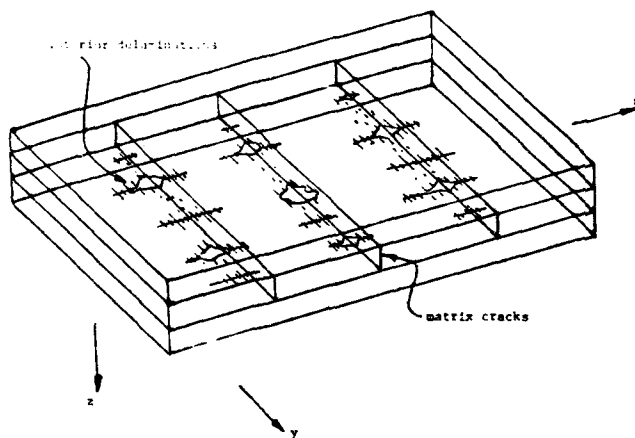
- PHYSICALLY BASED DESCRIPTION OF THE DAMAGE PARAMETERS
- DEVELOPMENT OF STRESS-STRAIN-DAMAGE RELATIONS
- CONSTRUCTION OF LAMINATE EQUATIONS
- DEVELOPMENT OF INTERNAL STATE VARIABLE GROWTH LAWS
- IMPLEMENTATION OF DAMAGE MODEL TO BOUNDARY VALUE PROBLEM SOLVING ALGORITHM
- DEVELOPMENT OF FAILURE FUNCTION

OBJECTIVE OF CURRENT MODEL

- USE THE CONTINUUM DAMAGE MODEL TO PREDICT DAMAGE DEPENDENT STIFFNESS OF GRAPHITE/EPOXY LAMINATES GIVEN THE PROPERTIES OF A SINGLE PLY

SOLUTION APPROACH

- UTILIZE THERMODYNAMICS WITH INTERNAL STATE VARIABLES (ISV'S) TO CONSTRUCT A DAMAGE MODEL
- CONSTRUCT THE CONSTITUTIVE EQUATIONS FOR THE CASE OF MATRIX CRACKS IN A SINGLE PLY
- CONSTRUCT LAMINATE EQUATIONS WITH MATRIX CRACKS AND DELAMINATIONS
- UTILIZE FRACTURE MECHANICS TO RELATE THE CRACK STATE TO THE ISV'S
- COMPARE MODEL PREDICTIONS TO EXPERIMENTAL RESULTS

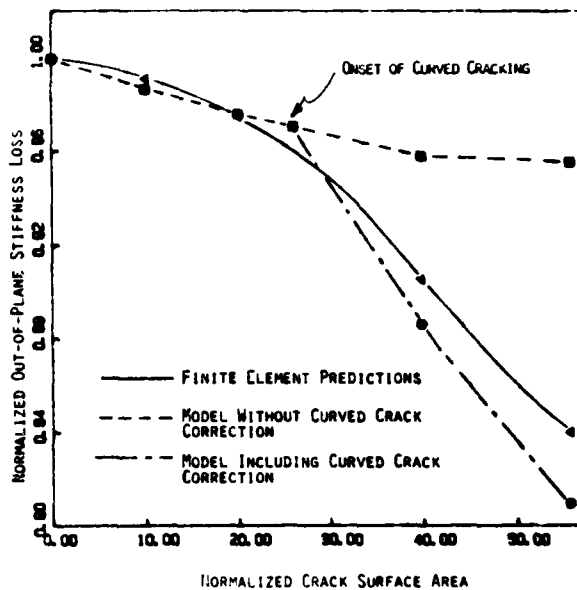


RESULTANT FORCES

$$\begin{aligned}
 & \text{linear elastic terms} \\
 & N = \sum_{k=1}^n [Q]_k (z_k - z_{k-1}) \left\{ \begin{matrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix} \right\} - \frac{1}{2} \sum_{k=1}^n [Q]_k (z_k^2 - z_{k-1}^2) \left\{ \begin{matrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{matrix} \right\} \\
 & + \sum_{i=1}^d [\bar{Q}]_i t_i \left\{ \begin{matrix} 0 \\ 0 \\ 0 \\ a_{1i} \\ a_{2i} \\ a_{3i} \\ 0 \end{matrix} \right\} + \sum_{i=1}^{d+1} (z_i - z_{i-1}) [\bar{Q}]_i \left\{ \begin{matrix} 0 \\ 0 \\ 0 \\ 0 \\ a_{4i} \\ a_{5i} \\ 0 \end{matrix} \right\} \\
 & - \sum_{k=1}^n [Q]_k (z_k - z_{k-1}) \{a^M\}_k \\
 & \text{delamination ISV's} \quad \text{matrix crack ISV's}
 \end{aligned}$$

where the Internal State variable is defined as

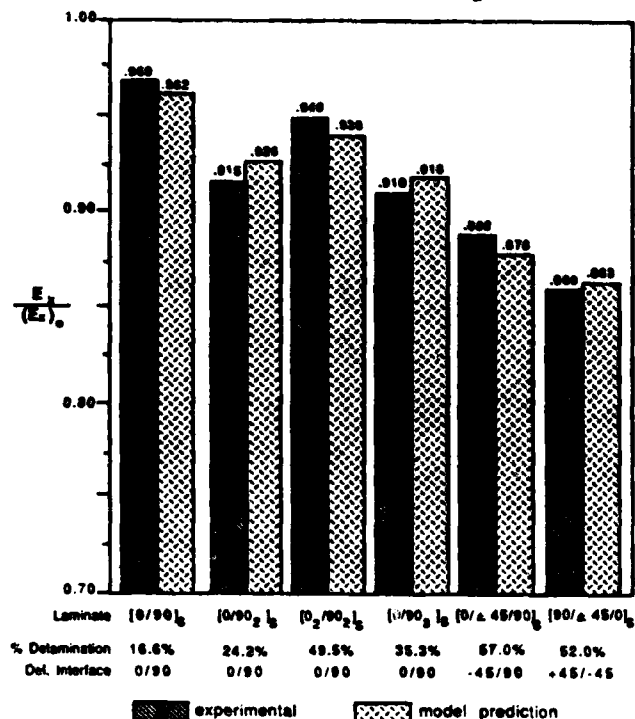
$$a_{Lij}^n = \frac{1}{V_L} \int_{S_2^n} u_i^c n_j^c dS$$



CONCLUSIONS

- STRESS-STRAIN-DAMAGE RELATIONS HAVE BEEN DEVELOPED FOR LAMINATED COMPOSITES
- RESULTS SUGGEST THAT CONTINUUM DAMAGE MECHANICS CAN BE UTILIZED SUCCESSFULLY IN LAMINATED COMPOSITES
- ISV GROWTH LAWS AND FAILURE FUNCTION REQUIRE FURTHER RESEARCH
- THE RESULTING MODEL CAN BE UTILIZED IN A STRUCTURAL ALGORITHM SIMILAR TO WHAT IS USED IN ORTHOTROPIC PLASTICITY
- OUR MODEL IS VERY COMPLEX, BUT, AS EINSTEIN ONCE PUT IT, "A GOOD THEORY SHOULD BE AS SIMPLE AS POSSIBLE BUT NO SIMPLER THAN THAT."

Damage-Dependent Laminate E_x



Comparison of Experimental Results and Model Predictions of the Laminate Engineering Modulus, E_x Degraded by Both Matrix Cracking and Delamination Damage.

REFERENCES

1. Allen, D.H., Harris, C.E., and Groves, S.E., "A Thermomechanical Constitutive Theory for Elastic Composites with Distributed Damage: Part I: Theoretical Development," to appear in *International Journal of Solids and Structures*, 1987.
2. Allen, D.H., Harris, C.E., and Groves, S.E., "A Thermomechanical Constitutive Theory for Elastic Composites with Distributed Damage: Part II: Application to Matrix Cracking in Laminated Composites," to appear in *International Journal of Solids and Structures*, 1987.
3. Allen, D.H., Groves, S.E., and Harris, C.E., "A Cumulative Damage Model for Continuous Fiber Composite Laminates with Matrix Cracking and Interply Delaminations," accepted for publication in the *ASTM STP* for the 8th Composite Materials: Testing and Design, American Society for Testing and Materials.
4. Harris, C.E., Allen, D.H., and Mottorf, E.W., "Modelling Stiffness Loss in Quasi-Isotropic Laminates Due to Microstructural Damage," to appear in *Journal of Engineering Materials and Technology*, American Society of Mechanical Engineers, 1988.
5. Allen, D.H., Harris, C.E., Groves, S.E., and Morvell, R.G., "Characterization of Stiffness Loss in Crossply Laminates with Curved Matrix Cracks," to appear in *Journal of Composite Materials*, 1987.

CONTINUUM DAMAGE MODEL FOR UNI-DIRECTIONALLY REINFORCED COMPOSITES

Y. Weitsman - Civil Engineering Department

Grant AFOSR-87-0128

1. **OBJECTIVE:** Develop constitutive equations for damage, coupled with temperature and moisture.
2. **METHOD:** Employ fundamental concepts of continuum-mechanics, irreversible thermodynamics and fracture mechanics.

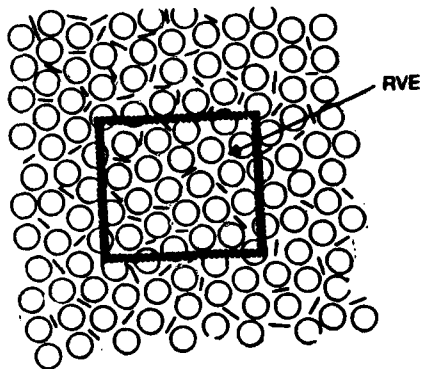


Fig. 1: A Representative Volume Element for a Fiber-Reinforced Composite with Micro-Cracks.

Step 1: Representation of profuse microcracks by a continuum, internal state variable.

Select a statistically representative volume element containing N microcracks. (See Fig. 1)

(a) Crack defined by area, but possesses two faces. Hence employ vector, but sense is immaterial.

Details are known only statistically hence:

$$(N \text{ microcracks}) \sim \left(\sum_{k=1}^N \text{individual cracks} \right)$$

(c) Internal state variable

$$a_{ij} = \sum_{k=1}^N d_i^{(k)} d_j^{(k)} \quad (1)$$

In eqn. (1) $d_i^{(k)}$ is the non-dimensional vector-valued area of the k th microcrack.

(d) Properties of damage variable:

Symmetric second rank tensor. Finite magnitude. Non-dimensional. Provides proper symmetry

results. Also: Has clear physical meaning, hence growth can be inferred from fracture mechanics. Enables accounting for crack interactions and derivation of damage growth relations.

Step 2: Employ basic principles of continuum mechanics and irreversible thermodynamics to derive stress-strain relations, flux-gradient relations, and interaction relations between mechanical, thermal and diffusion quantities.

Step 3: Damage growth laws. Determine damage growth relations from a model fracture-mechanics solution on a micro-level. For instance BVP shown in Fig. 2, where crack orientation ω and crack size a are random variables.

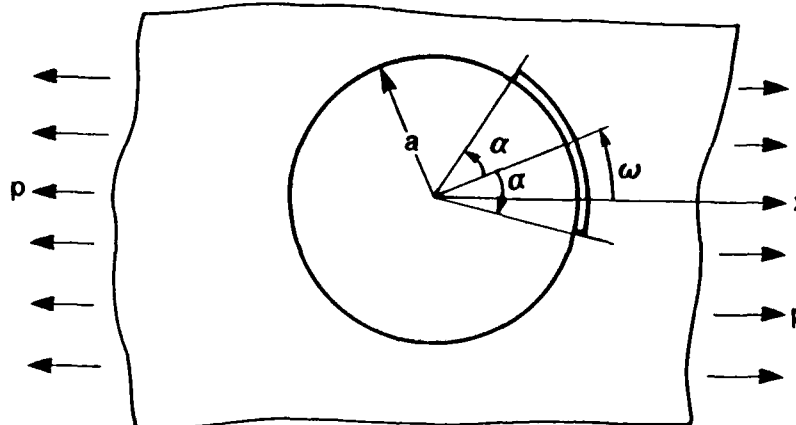


Fig. 2: A Crack at the Interface of a Cylindrical Inclusion and an Exterior Region ($r=a$, $\omega-\alpha < \theta < \omega+\alpha$) Which is Subjected to Remote Uniaxial Tension $\sigma_x = p$.

Solve deterministic problem, via fracture mechanics, to relate crack growth to geometry, material properties and loads, then cast results in a probabilistic context and evaluate probabilistic values of incremental increase in damage parameter Δa_{ij} .

3. RESULTS

(a) Character of stress-strain relations:

$$\epsilon_p = S_{po} + S_{pq} a_q \quad (2)$$

where, for instance, for a uni-directionally reinforced medium one obtains

$$S_{10} = C_2 + C_3(a_{22}-a_{11}), \quad \text{etc}$$

$$S_{11} = 2K_4(a_{11}-a_{22}) + 2(K_7+K_{13}) + 2K_{14}(a_{11}-a_{22})^2, \quad \text{etc.}$$

where $C_2, C_3, K_4, K_7, \dots$ are functions of the transversely isotropic invariants of a_{ij} . Note, that dependence on a_{ij} is generally non-linear, which enables the incorporation of crack-interaction effects. Compliances s_{pq} exhibit softening with damage and symmetry changes under patterned damage. (e.g. when all microcracks are parallel, transverse isotropy switches to orthotropy).

In addition, the thermal and moisture induced strains S_{po} are affected by damage.

(b) Heat conduction and moisture diffusion

$$\frac{\partial T}{\partial t} = (k_{ij} T_{,j}),_{i} + \Delta \quad (3)$$

Thermal diffusivity k_{ij} depends on damage, and dissipation Δ involves damage growth-rate, damage and stress gradients, and stress-rate.

$$\frac{\partial m}{\partial t} = (D_{ij} m_{,j}),_{i} + R_{i,i} \quad (4)$$

Moisture diffusivity D_{ij} depends on damage, and moisture fluxes are deflected into directions of increasing damage.

4. CONCLUSIONS

- (a) Have a self-contained continuum damage model.
- (b) Interactions with moisture and temperature may lead to synergisms.

REFERENCES

- Y. Weitsman: "Coupled Damage and Moisture-Transport in Fiber-Reinforced Polymeric Composites". Int. J. Solids & Struct. (Forthcoming)
- Y. Weitsman: "Damage Coupled with Heat Conduction in Uni-Axially Reinforced Composites". Proc. ASME Symp. on Constitutive Modelling for Nonconventional Materials. (Forthcoming).

A MODEL FOR DAMAGE GROWTH IN COMPOSITES BASED ON WORK POTENTIALS

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OBJECTIVE

DEVELOP A METHOD FOR CHARACTERIZING AND PREDICTING DAMAGE GROWTH EFFECTS IN ELASTIC AND VISCOELASTIC FIBROUS COMPOSITES.

APPROACH

1. DEMONSTRATE THEORETICALLY AND EXPERIMENTALLY THAT MECHANICAL BEHAVIOR WITH GROWING DAMAGE CAN BE DESCRIBED THROUGH A GLOBAL STRAIN-ENERGY LIKE POTENTIAL (CALLED THE "WORK POTENTIAL").
2. USE THE WORK-POTENTIAL THEORY TO ESTABLISH EQUATIONS WHICH GOVERN GROWTH OF DAMAGE, AS DEFINED BY ONE OR MORE PARAMETERS (INTERNAL STATE VARIABLES).
3. OBTAIN MECHANICAL PROPERTIES FROM PROPORTIONAL STRAINING TESTS. INITIALLY USE AXIAL-TORSIONAL LOADING OF BAR SPECIMENS.
4. COMPARE THEORY AND EXPERIMENT FOR PROPORTIONAL AND NONPROPORTIONAL STRAINING.
5. EXTEND WORK TO VISCOELASTIC COMPOSITES.

DEFINE THE TOTAL ENERGY FOR THE ACTUAL (DAMAGING) PROCESS AS

$$W_T = W + W_C \quad (5)$$

WHERE

$$W = W(q_1, A_k(q_1), A_m)$$

$$W_C = W_C(A_k(q_1), A_m)$$

THUS

$$W_T = W_T(q_1, A_m)$$

NOTE THAT

$$\begin{aligned} \frac{\partial W_T}{\partial q_1} &= \frac{\partial W}{\partial q_1} + \left(\frac{\partial W}{\partial A_k} + \frac{\partial W_C}{\partial A_k} \right) \frac{\partial A_k}{\partial q_1} \\ &= \frac{\partial W}{\partial q_1} = Q_1 \end{aligned} \quad (6)$$

WHICH YIELDS

$$Q_1 = \frac{\partial W_T}{\partial q_1} \quad (7)$$

THEREFORE, FOR THE DAMAGING PROCESS

$$\frac{\partial Q_1}{\partial q_j} = \frac{\partial Q_1}{\partial q_j} \quad (8)$$

FROM EQ. (7),

$$W_T = \int Q_1 dq_1 \quad (9)$$

THUS, W_T IS THE WORK INPUT TO A MATERIAL OR STRUCTURE DURING THE ACTUAL PROCESS. IT IS CALLED THE WORK POTENTIAL.

THEORETICAL BASIS FOR A WORK POTENTIAL FOR AN ELASTIC MATERIAL WITH DAMAGE

ASSUME A STRAIN ENERGY FUNCTION EXISTS: $W = W(q_1, A_k)$

WHERE

q_1 = INDEPENDENT GENERALIZED DISPLACEMENTS (STRAINS, CURVATURES, ETC.)

A_k = ALL DAMAGE-RELATED PARAMETERS (SUCH AS SURFACE AREAS OF CRACKS) NEEDED BESIDES q_1 TO SPECIFY STRAIN ENERGY. W MAY ALSO DEPEND ON OTHER PARAMETERS, SUCH AS TEMPERATURE AND MOISTURE.

$$Q_1 = \partial W / \partial q_1 = Q_1(q_1, A_k) \quad (1)$$

DURING A DAMAGING PROCESS, ONE OR MORE OF THE A_k ARE TIME-DEPENDENT. FOR THOSE THAT ARE NOT CONSTANT (DENOTED BY A_k), ASSUME THEY OBEY CRACK-LIKE GROWTH EQUATIONS (AVAILABLE ENERGY = REQUIRED ENERGY)

$$-\frac{\partial W}{\partial A_k} = \frac{\partial W_C}{\partial A_k} \quad (2)$$

WHERE

$$W_C = W_C(A_k) = \text{WORK OF MICRO-OR MACROCRACKING (E.G. } W_C = \mathcal{L} \sum A_k)$$

EQUATION (2) YIELDS (ASSUMING STABLE GROWTH)

$$A_k = A_k(q_1) \quad (3)$$

FROM EQUATION (1),

$$Q_1 = Q_1(q_1, A_k(q_1), A_m) \quad (4)$$

WHERE A_m IS THE SUBSET OF CONSTANT A_k .

APPROXIMATE REPRESENTATION OF W_T USING A SMALL NUMBER OF INDEPENDENT "EFFECTIVE" DAMAGE PARAMETERS, D_n

IT IS REQUIRED THAT THE WORK INPUT W_T BE A POTENTIAL FOR EACH DAMAGING PROCESS:

$$Q_1 = \frac{\partial W_T}{\partial q_1} \quad (10)$$

WHERE

$$W_T = W_T(q_1, D_n)$$

D_r IS THE SUBSET OF D_n WHICH CHANGES

D_s IS THE SUBSET OF D_n WHICH IS CONSTANT

LET $W = W(q_1, D_n)$ BE THE STRAIN ENERGY, SO THAT

$$Q_1 = \frac{\partial W}{\partial q_1} \quad (11)$$

CONSIDERING ONE D_r AT A TIME, IT CAN BE SHOWN THAT (10) AND (11) IMPLY THAT EACH D_r MUST OBEY THE FOLLOWING DAMAGE GROWTH EQUATION:

$$-\frac{\partial W}{\partial D_r} = \frac{\partial W_D}{\partial D_r} \quad (12)$$

WHERE $W_D = W_D(D_n)$. IT ALSO FOLLOWS THAT

$$W_D = W_T - W \quad (13)$$

LET $D_1 = W_D$. USING EQ. (12) THE DAMAGE-GROWTH EQUATIONS BECOME

$$-\frac{\partial W}{\partial D_1} = 1 \quad \frac{\partial W}{\partial D_r} = 0 \quad r=2,3,\dots \quad (14)$$

APPLICATION TO AXIAL-TORSIONAL LOADING OF BAR SPECIMENS



FIGURE 1. LAMINATE SPECIMEN USED IN AXIAL-TORSIONAL TESTS.

$$\begin{aligned} Q_1 &= U & Q_2 &= \Omega \\ Q_1 &= F & Q_2 &= T \end{aligned}$$

FROM EQ. (8) (IF AND ONLY IF A WORK POTENTIAL EXISTS),

$$\frac{\partial F}{\partial U} = \frac{\partial T}{\partial \Omega} \quad (15)$$

INTEGRATING,

$$F = \frac{\partial}{\partial U} \int_0^{\Omega} \Delta T \, d\Omega + F_0 \quad (16)$$

WHERE

$$\begin{aligned} F_0 &= F_0(U) = \text{axial force for } \Omega=0 \\ \Delta T &= T - T_0 \\ T_0 &= \text{torque for } U=0 \end{aligned}$$

FIGURE 2 SHOWS THAT EQ. (16) IS IN GOOD AGREEMENT WITH EXPERIMENTAL RESULTS. ΔT IS FROM FIG. 3.

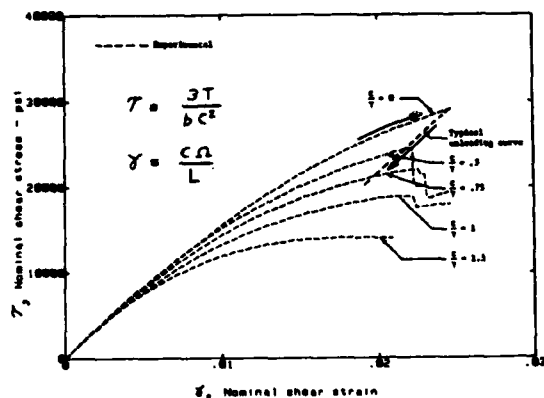


Figure 3. Representative shear stress-strain curves with proportional axial and torsional straining for the same tests used for Figure 2.

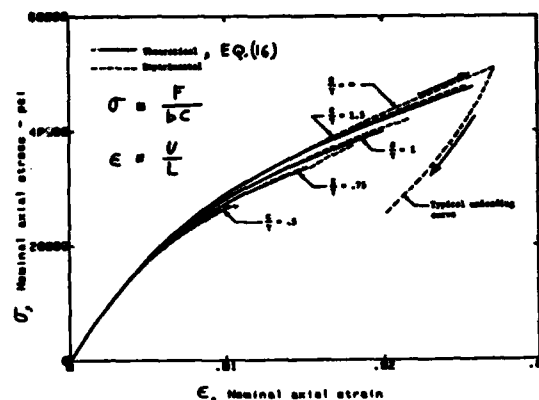


Figure 2. Representative axial stress-strain curves with proportional axial and torsional straining. Uniaxial F155; 24 plies $[\pm 45]_{24}$; 0.5 in. long $\times$ 0.5 in. wide $\times$ 0.145 in. thick.

CONCLUSIONS

1. EXISTENCE OF THE WORK POTENTIAL WAS ESTABLISHED THEORETICALLY AND CHECKED EXPERIMENTALLY FOR PROPORTIONAL AXIAL-TORSIONAL STRAINING OF TWO DIFFERENT GR/EP COMPOSITES. (ALSO CHECKED FOR NONPROPORTIONAL STRAINING OF A PARTICLE-REINFORCED RUBBER.)
2. DAMAGE GROWTH EQUATIONS WERE DERIVED FROM THE WORK-POTENTIAL THEORY.
3. AXIAL-TORSIONAL DATA HAVE BEEN PREDICTED USING ONE DAMAGE PARAMETER (W_0).
4. THE WORK POTENTIAL PROVIDES THE BASIS FOR J INTEGRAL FRACTURE THEORY.
5. THE THEORY HAS BEEN EXTENDED TO VISCOELASTIC MATERIALS USING AN APPROXIMATE METHOD. RESULTS ARE ANALOGOUS TO THOSE FOR TIME-AGING (CYCLE-AGING) ELASTIC MATERIALS WITH MONOTONIC (CYCLIC) LOADING.

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MODE II DELAMINATION FRACTURE OF COMPOSITES: A J INTEGRAL APPROACH

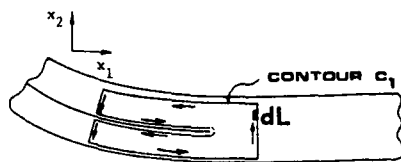
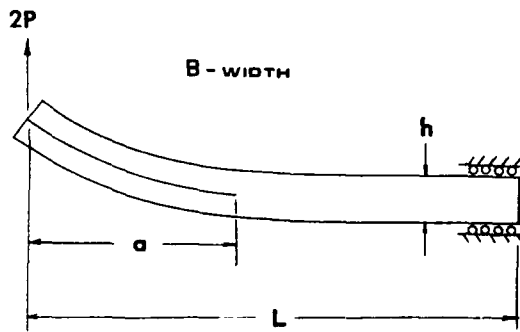
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OBJECTIVES

TO DEVELOP A METHOD TO CHARACTERIZE THE MODE II
DELAMINATION FRACTURE TOUGHNESS OF COMPOSITE
MATERIALS WITH MATERIALLY OR GEOMETRICALLY NON-
LINEAR BEHAVIOR USING A J INTEGRAL APPROACH

APPROACH



$$J = \int_{C_1} [w_0 dx_2 - T_i (\partial u_i / \partial x_1) dL]$$

$$J_{II} = \frac{1}{B} \left\{ \left[2 \int_0^a k dM \right]_{\text{cracked}} - \left[\int_0^a k dM \right]_{\text{uncracked}} \right\}$$

RESULTS

AS4/3502		
G_{IIc}	J_{IIc}	
(lb/in)		
2.53	2.38	
2.61	2.44	
2.68	2.46	
2.7	2.51	
2.68	2.5	
2.71	2.44	
2.85	2.47	
Avg.	2.68	2.46

T6T145/F185		
G_{IIc}	J_{IIc}	
(lb/in)		
14.45	11.66	
15.45	12.45	
14.78	11.76	
14.31	11.99	
14.35	12.02	
Avg.	14.7	12.

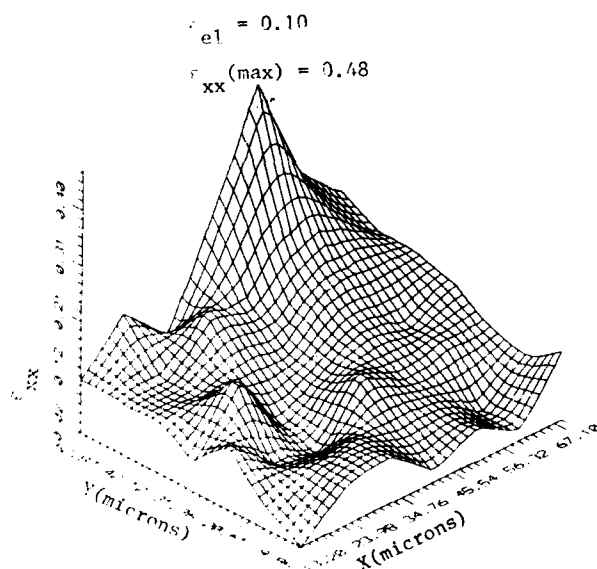
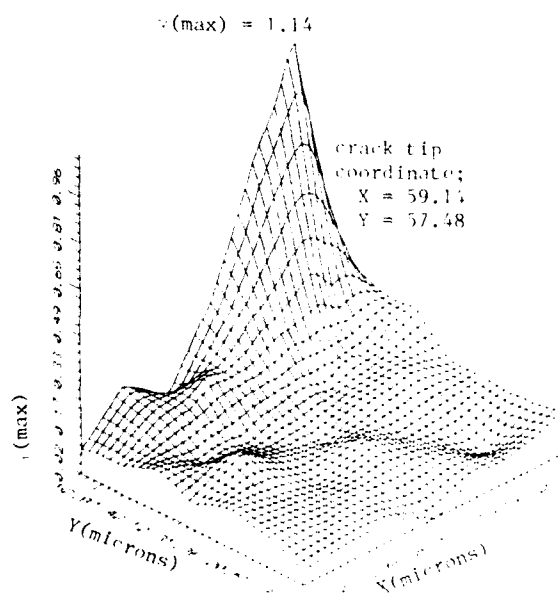
DIRECT DETERMINATION OF STRAIN FIELD AROUND TIP OF GROWING CRACK

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OBJECTIVE: TO MEASURE THE STRAIN FIELD AROUND THE TIP OF A GROWING CRACK



HEXCEL F185 RESIN (COMPACT TENSION SPECIMEN WITH FATIGUE PRECRACK).
LEFT-UNLOADED; RIGHT-LOADED. NOTE X IS VERTICAL AXIS; Y IS HORIZONTAL AXIS.



ANELASTIC DEFORMATION AND FRACTURE OF THERMOPLASTIC-MATRIX FIBER
COMPOSITE AT ELEVATED TEMPERATURES

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ABSTRACT

Recent advances in fiber and polymer science and engineering have made advanced thermoplastic-matrix fiber composites an important class of composite materials for potential critical applications at elevated temperatures in high-performance structures such as aircraft construction. While the thermoplastic composites possess recognized advantages of flexibility in fabrication and processing, high fracture toughness, excellent damage tolerance, and elevated temperature stability, some of the basic problems of deformation and failure of the materials are still not well understood. In this paper, fundamental behavior of deformation and fracture of a neat thermoplastic aromatic polyamide matrix is studied first both at room temperature and at elevated temperatures. X-ray and transmission electron microscopy studies are conducted to examine the morphology of the resin. Dynamic-mechanical properties of the resin are characterized for the later mechanics analysis. Elevated temperature creep behavior also is examined, and constitutive equations for the anelastic deformation are obtained. A fracture mechanics approach is taken to determine the temperature-dependent toughness of the thermoplastic matrix. The results obtained provide a solid basis for the work on the unidirectional composites.

Also in this study, fundamental mechanisms and mechanics of a anelastic deformation and fracture of a unidirectional thermoplastic-matrix composite are presented. In the experimental phase of the study, a graphite fiber-polyamide matrix thermoplastic composite is used. The DSC thermal analysis is conducted to examine the influence of different processing variables and heating/cooling rates. Dynamic-mechanical properties of the unidirectional composite are determined to serve as a reference for detailed creep and relaxation studies. Both in-plane and interlaminar creep behavior have been investigated, and significant difference is observed, apparently due to the microstructural change in the laminate thickness direction. The crack growth and fracture behavior in the unidirectional composite are studied at several levels of elevated temperatures. Mechanisms of large crack-tip plastic deformation and associated crack-growth process are examined for later analytical modeling. In the theoretical part of the study, time-temperature-dependent constitutive equations for unidirectional thermoplastic composite are developed based on anisotropic viscoelasticity in conjunction with several sets of experiments. The opening-mode fracture mechanics study is conducted by the use of a geometrically nonlinear DCB model and analysis. Time-temperature-dependent fracture toughness of the composite is obtained in detail. This research provides important information on the basic mechanisms and mechanics of deformation and failure for this class of composites.

COUPLING OF MOISTURE AND DAMAGE IN COMPOSITES

CONTRACT N00014-82-K-0562
OFFICE OF NAVAL RESEARCH
PRINCIPAL INVESTIGATOR: Y. WEITSMAN, TEXAS A&M
SCIENTIFIC OFFICER: Y. RAJAPAKSE, ONR

OBJECTIVE: INVESTIGATE FUNDAMENTAL ASPECTS OF MOISTURE TRANSPORT PROCESS IN POLYMERIC COMPOSITES AND ITS COUPLING WITH DAMAGE.

METHOD: EXPERIMENTAL AND ANALYTICAL.

EXPERIMENTAL. Expose coupons to fluctuating ambient relative humidity at fixed (moderate) temperature and measure:

1. Weight-gain and weight loss in composites and neat resin.
2. Deformations (curvatures) of anti-symmetric laminates.
3. Variations in delamination fracture toughness.
4. Compressive and shear strengths
5. Inspect for damage via SEM

ANALYTICAL.

1. Solve for elastic and viscoelastic fields in laminated plates under fluctuating humidity.
2. Develop stress-assisted diffusion relations for viscoelastic materials.
3. Develop a continuum damage theory coupled with diffusion.
4. Evaluate micro-level damage phenomena due to moisture employing fracture mechanics.

CONCLUSIONS

1. The diffusion process in viscoelastic materials is non-Fickian. There is an interaction between the transport process and the relaxation behavior of the polymeric material.
2. Damage due to moisture ingress in fiber-reinforced polymeric composites appears as micro-debondings at the fiber/matrix interfaces. The fundamental causes of that damage are not yet known. Mechanical causes are possible but chemical effects are the most likely reasons.
3. Damage is an irreversible phenomenon that depends on moisture history, not merely on current moisture content. More damage is caused under fluctuating humidity than under exposure to constant ambient humidity.
4. Like all fatigue phenomena the above damage exhibits wide scatter. Exposure to humid environments is likely to increase the scatter in material properties (such as strength) more than degrade the average values.
5. Moisture ingress and damage are synergistic mechanisms.
6. Results and conclusions may vary widely among material systems.

SOME ANALYTICAL RESULTS

1. STRESS ASSISTED DIFFUSION

(a) Basic equations

Consider a thermodynamically open system, since matter is added from the ambient.

Balance eqns: $\rho_s + \rho_s \nabla \cdot \underline{v} = 0, \quad \dot{m} = -\nabla \cdot \underline{f}$

$$\frac{d}{dt} \int_V \rho_s u dV = \int_A \sigma_{ij} n_j v_i dA - \int_A q_i n_i dA \\ - \int_A \bar{p} \frac{f_i}{\rho} n_i dA - \int_A \bar{u} f_i n_i dA$$

where ρ_s is mass density of solid, v_i is velocity of solid particles, $\dot{m}$ vapor mass, f_i vapor flux, u energy of solid-vapor mixture per unit mass of solid, σ_{ij} stresses, q_i heat flux. $\bar{p}$, $\bar{\rho}$ and $\bar{u}$ are vapor pressure, density and internal energy, respectively.

Entropy inequality:

$$\frac{d}{dt} \int_V \rho_s s dV \geq \int_A (q_i/T) n_i dA - \int_A \bar{s} f_i n_i dA$$

where s is entropy of solid-vapor mixture per unit solid mass, q_i is heat flux, T is temperature, and $\bar{s}$ is vapor's entropy.

By familiar substitutions obtain the reduced entropy inequality

$$-\rho_s \dot{\phi} - \rho_s \dot{s} T - \epsilon_{ij} \dot{\sigma}_{ij} - (q_i/T) g_i + \dot{m} \mu - f_i \mu_{,i} - \bar{s} g_i f_i \geq 0$$

where ϕ is Gibbs free energy per unit solid mass, ϵ_{ij} strains, $g_i = \partial T / \partial X_i$ temperature gradients, and $\mu = (\bar{p}/\bar{\rho}) + \bar{u} - T \bar{s}$ denotes the chemical potential of the vapor.

(b) Linear viscoelastic response with moisture diffusion.

Consider $\phi = \hat{\phi}(\sigma_{ij}, m, T, \gamma_r)$ where γ_r ($r = 1, \dots, N$) are scalar-valued internal state variables which represent the internal degrees of freedom of molecular motion and configuration within the polymer.

By entropy inequality have $-R_r \dot{\gamma}_r \geq 0$ where $R_r = \frac{\partial \phi}{\partial \gamma_r}$

A basic, "phenomenological" relationship: $R_r = -b_{rs}(m, T, \sigma_p) \dot{\gamma}_s$

From entropy inequality and Onsager's relations b_{rs} are components of a symmetric, semi positive definite matrix.

For small stresses expand ϕ in powers of σ_i , get

$$\phi = a - B_i \sigma_i + B_r \gamma_r - \frac{1}{2} M_{ij} \sigma_i \sigma_j + P_{jr} \gamma_r \sigma_j + \frac{1}{2} V_{rs} \gamma_r \gamma_s \\ (i, j = 1, \dots, 6; \quad r, s = 1, \dots, N).$$

$a, B_i, B_r, \dots, V_{rs}$ depend on m and T .

Considerations of stability of equilibrium states gives $V_{rs} = V_{sr}$ and V_{rs} positive definite.

Growth law $\frac{\partial \phi}{\partial \gamma_r} = -b_{rs} \dot{\gamma}_s$ gives

$$b_{rs} \gamma_s + B_r + P_{jr} \sigma_j + V_{rs} \gamma_s = 0$$

Hence can eliminate γ_r and express it in terms of B_r, σ_i and time in the form of

$$\gamma = C(1 - e^{-\lambda t}) + D_j(1 - e^{-\gamma t}) \sigma_j.$$

Thus $\epsilon_i = -\frac{\partial \phi}{\partial \sigma_i}$ give the desired, linear time-dependent strain-stress relations.

In addition $\mu = \frac{\partial \phi}{\partial m}$ gives

$$\mu = a_{,m} - B_{i,m} \sigma_i + B_{r,m} \gamma_r - \frac{1}{2} M_{ij,m} \sigma_i \sigma_j + P_{ij,m} \gamma_r \sigma_j + \frac{1}{2} V_{rs,m} \gamma_r \gamma_s.$$

Therefore μ depend on time and is quadratic in σ_i .

Boundary condition for diffusion problem is $u(m, T, x) = u^A(x)$ where u^A is the chemical potential of the ambient vapor, and x are boundary points.

Hence equilibrium moisture content is quadratic in σ and the moisture transport process involves drift toward equilibrium.

The simplest modification of a 1-D diffusion process is

$$\frac{\partial m}{\partial t} = D \frac{\partial^2 m}{\partial x^2} \quad -L < x < L, \quad t > 0$$

$$m(x, 0) = m_0(x) \quad \text{Initial Condition}$$

$$m(\pm L, t) = m_b(t) \quad \text{Time Dependent boundary condition even for constant ambient R.H.}$$

Typically, for const R.H., $m_b(t) = m_0 + m_1(1 - e^{-t/\tau_1}) + m_2(1 - e^{-t/\tau_2}) + \dots$ where $\tau_1, \tau_2, \dots$ are of order of viscoelastic relaxation times. (see Figure 8).

2. COUPLING OF MOISTURE AND DAMAGE

(a) Damage Parameter

Consider a volume element of finite size, which represents statistically the geometry of a multi-phase composite, including distributed profuse micro-cracks.

Let "damage" be the resultant of the areas of all micro-cracks contained within the volume, non-dimensionalized by the wall-area of that volume. Express damage by a skew-symmetric second-rank tensor $d_{[pq]}$. Since sense of $d_{[pq]}$ is immaterial results should depend only on even powers of $d_{[pq]}$.

$$\text{Let } \phi = \phi(\sigma_{ij}, m, T, d_{[pq]})$$

For sufficiently small stresses expand ϕ up to second powers of σ_{ij} . However $d_{[pq]}$ is not necessarily small, hence coefficients in Taylor's expansion depend on m, T and $d_{[pq]}$.

Basic principles of irreversible thermodynamics and continuum mechanics give:

(b) Stress-strain relations

$$\epsilon_p = S_{po} + S_{pq} \sigma_q$$

where expansional strains S_{po} and compliances S_{pq} depend on $d_{[pq]}$ (damage softening effect) and global symmetry is influenced by damage orientation.

For instance in the case of initial transverse isotropy, as obtains for unidirectionally reinforced composites, we have

$$S_{10} = \beta_2 + \beta_3(d_{[31]}^2 - d_{[32]}^2), \quad \text{etc.}$$

$$S_{11} = 2[\gamma_2 + \gamma_3(d_{[31]}^2 - d_{[32]}^2)^2 + \gamma_8(d_{[31]}^2 - d_{[32]}^2) + \gamma_{11}] \quad \text{etc.}$$

where $\beta_2, \beta_3, \gamma_2, \gamma_3, \gamma_8, \gamma_{11}$ (etc.) depend on $m, T, d_{[12]}^2$ and $(d_{[13]}^2 + d_{[23]}^2)$.

Note that the terms with $\beta_3, \gamma_3, \gamma_8$ introduce changes in material symmetry.

(c) Moisture transport relations (flux-gradient relations)

General form is

$$f_i = D_{ij} \frac{\partial \mu}{\partial x_j} \quad \text{with diffusivities } D_{ij} \text{ that depend on } m, T, \text{ damage invariants}$$

Also $u = \frac{\partial \phi}{\partial m}$, gives

$$\frac{\partial \mu}{\partial x_i} = A \frac{\partial m}{\partial x_i} + B \frac{\partial(\text{damage invariants})}{\partial x_i}$$

where A, B are functions of m, T and damage invariants. Hence A accounts for damage effects on diffusivity, while B is a "non-classical" term, which couples damage and diffusion. B expresses the reorientation of the moisture flux into regions of higher damage.

Consequently boundary conditions, thus saturation levels, vary with time as damage grows.

In addition, since moisture flux is drawn into directions of higher damage - while damage growth is enhanced by moisture, have a theoretical indication of a synergistic mechanism.

SOME EXPERIMENTAL RESULTS

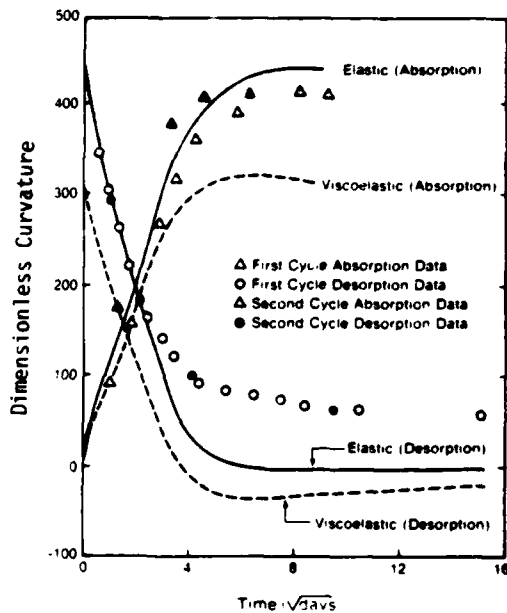


Fig. 1.: Time-dependent curvature changes of anti-symmetric $[0/90/0_4/90_4/0/90]_T$ AS4/3502 laminates during absorption and desorption of moisture. $T = 346^\circ\text{K}(163^\circ\text{F})$, absorption at R.H. = 95% desorption at dry.

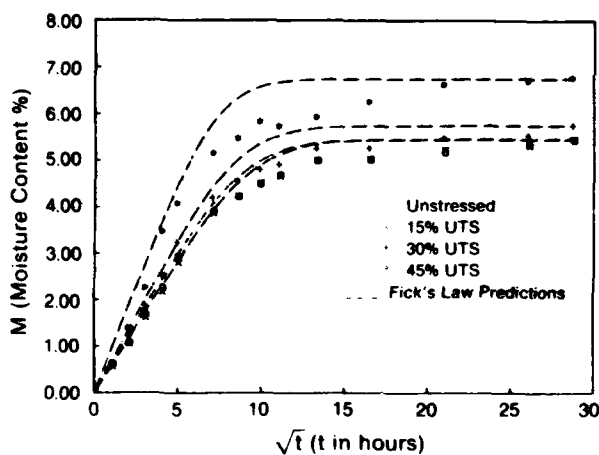


Fig. 3: Moisture content (average of 2 to 4 specimens) Vs. $\sqrt{t}$ in 3502 epoxy coupons subjected to various stress levels during absorption. $T = 40^\circ\text{C}$, $R_h = 97\%$.

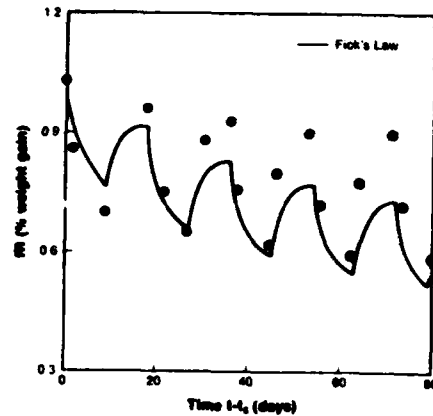


Fig. 2: Total moisture content (in % weight-gain) in anti-symmetric $[0/90/0_4/90_4/0/90]_T$ AS4/3502 laminates during exposure to cyclic R.H. after saturating at time t_s . $T = 130^\circ\text{F}$. Humid R.H. = 95%, dry R.H. = 0%. Cycle interval = 16 days.

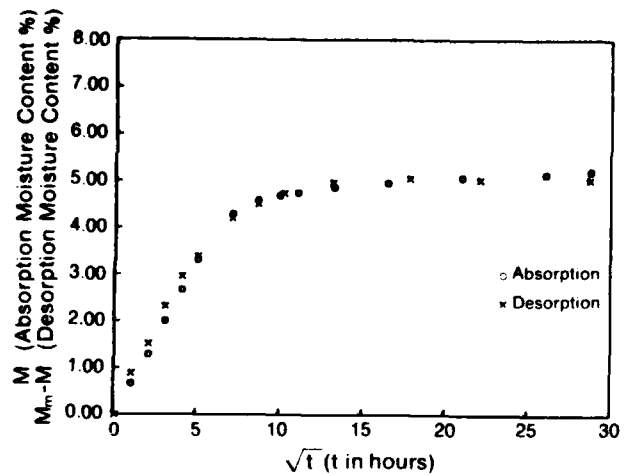


Fig. 4: Superimposed values of moisture content Vs. $\sqrt{t}$ in unstressed 3502 epoxy coupons during absorption (at $R_h = 97\%$) and desorption (at $R_h = 0\%$). $T = 40^\circ\text{C}$.

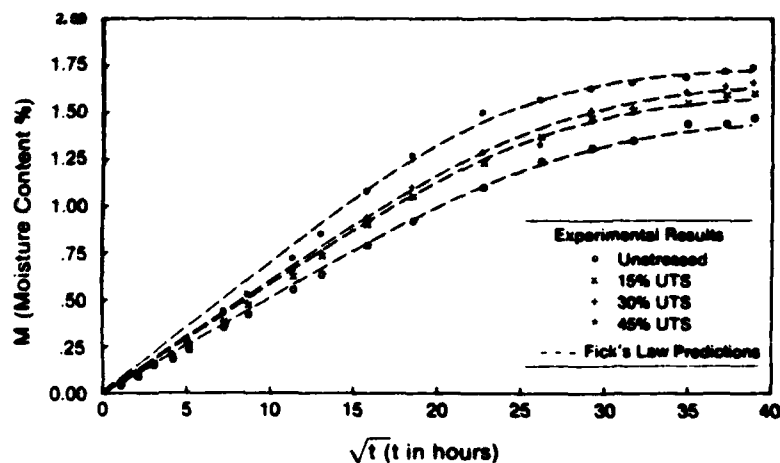


Fig. 5: Moisture content (Average of 2 to 4 specimens) Vs. $\sqrt{t}$ in unidirectionally reinforced AS4/3502 composite coupons during absorption. Coupons subjected to various levels of stress transversely to fiber direction. $T = 40^\circ\text{C}$, $R_h = 97\%$.

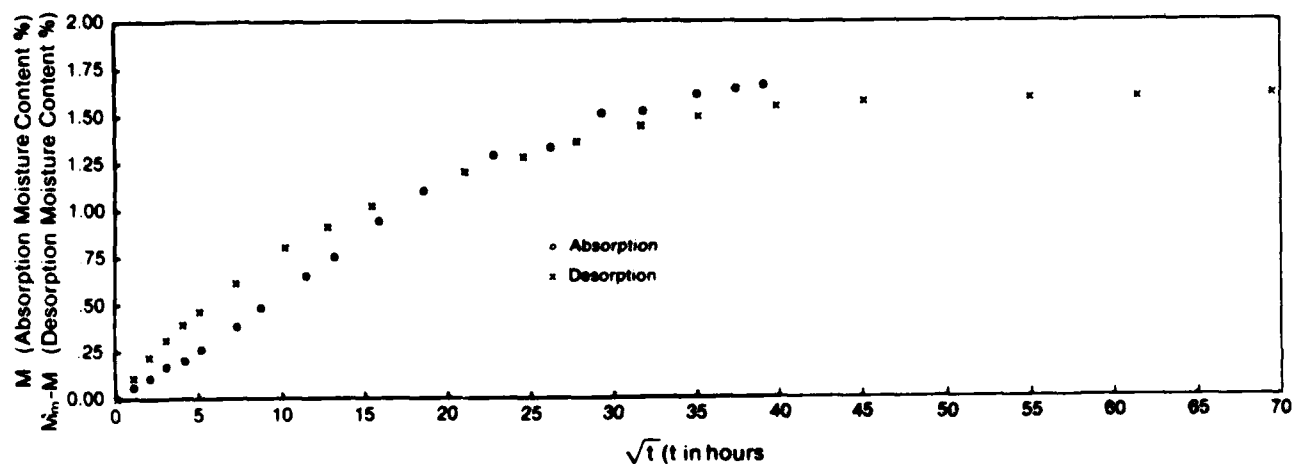


Fig. 6. Superimposed values of moisture content Vs. $\sqrt{t}$ in unidirectionally reinforced AS4/3502 composite coupons during absorption (at $R_h = 97\%$) and desorption (at $R_h = 0\%$), with $T = 40^\circ\text{C}$. Coupons subjected to uniaxial tension of $\sigma = 30\% \sigma_{ult}$.

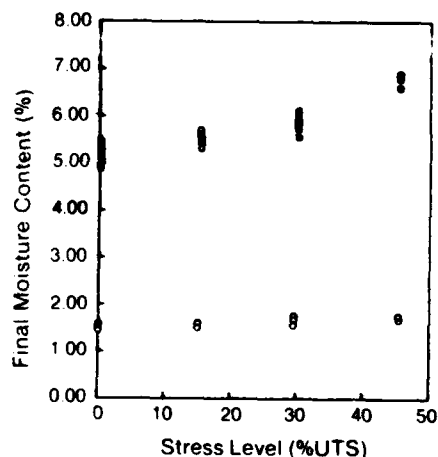


Fig. 7: Stress-dependence of maximal moisture content in neat epoxy (upper values) and transversely uni-directional AS4/3502 composite (lower values). $R.H. = 97\%$, $T = 40^\circ\text{C}$.

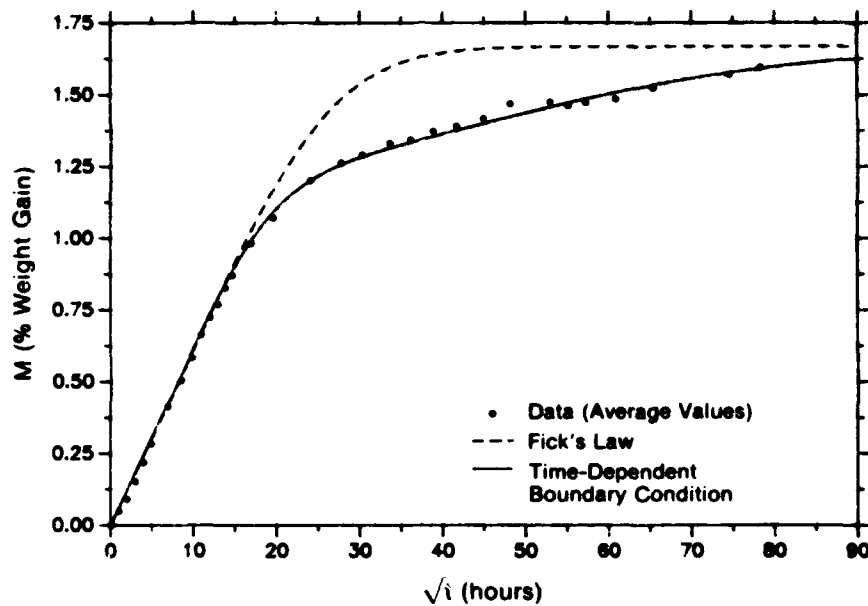


Fig. 8: Moisture weight gain in unidirectional AS4/3502 coupons vs. $\sqrt{t}$. Data, Fick's Law, and time-dependent boundary condition results.



Fig. 9: Typical moisture-induced damage by debondings at fiber/matrix interfaces of AS4/3502 composite. $[0/90/0_4/90_4/0/90]_T$ laminate exposed to cyclic humidity.



Fig. 10: Moisture-induced damage in a uni-directional AS4/3502 laminate. Individual debonding and coalesced micro-cracks after several humidity cycles.



Fig. 11: Moisture-induced damage after extensive cycling of humidity. Individual micro-crack coalesced to form a long continuous crack.
 $[0/90/0_4/90_4/0/90]_T$ AS4/3502 lay-up.

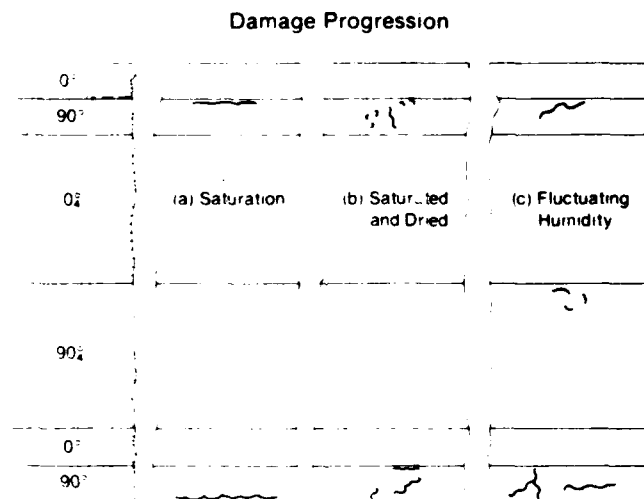


Fig. 12: The assumed scenario for damage progression in the $[0/90/0_4/90_4/0/90]_T$ anti-symmetric AS4/3502 composite laminates. Shown at each stage are new cracks, in addition to those observed earlier.

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ADVANCED CONCEPTS FOR COMPOSITE STRUCTURES

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ABSTRACT

Graphite-epoxy replacements for conventional metallic medium-primary and secondary structures have demonstrated that organic-matrix composite materials can reduce the structural weight of transport aircraft. However, the full potential of these composite materials has not yet been realized. The full potential of composite materials can be realized by developing optimally-designed composite structures that are both more structurally efficient and more cost effective than current metallic or state-of-the-art composite structures. Creative research on new and innovative structural concepts, in particular concepts for wing and fuselage primary structure, is needed to achieve this potential for future transcentury aircraft. These new structural concepts should take advantage of advanced materials and of new and emerging fabrication techniques. In addition, the validated structures technology associated with these new structural concepts is needed to provide the confidence essential for the use of composite materials for future primary aircraft structures.

Advanced concept composite structures are described in figure 1 as being: (1) optimally-designed to exploit the unique characteristics of composites; (2) fabricated from advanced materials and material forms; and/or (3) processed using cost-effective techniques. The results of preliminary studies for advanced concept composite structures are presented herein. Analytical results are described for several advanced concept cover panels. Experimental results for filament-wound plates, for small scale cover panels, and for large scale cover panels are also described. The structural efficiencies of these cover panels are compared.

The structural efficiency of optimally-designed, compression-loaded graphite-epoxy, cover panel concepts was analyzed. Typical material properties for the analyses are presented in figure 2, and the analytical results are shown in figures 3-7. These results were obtained using the PASCO (Structural Panel Analysis Sizing Code) computer code [1] and were compared with existing structural efficiency results for aluminum aircraft compression panels [2].

Structural efficiency results for hat-stiffened cover panels are shown in figures 3 and 4. Panels using advanced material forms such as woven fabric, braided fibers, and quasi-isotropic stitched and unstitched laminates are evaluated. Results for panels fabricated from unidirectional graphite-epoxy tape are also included for comparison. The braided fiber constructions have the best structural efficiency of the advanced material forms: the unidirectional tape constructions have the best structural efficiency of all the cases considered. Structural efficiency results for stiffened cover panels fabricated from two material systems are shown in figures 5-7. The results indicate that panels made of IM6-1808I material are more structurally efficient than panels made of AS4-3502 for all load levels. Hercules Incorporated manufactures AS4-3502 graphite-epoxy and IM6 graphite fiber, and American Cyanamid Company manufactures 1808I epoxy matrix. The results also indicate that changes in panel configuration affect the structural efficiency. Other cover panel configurations such as a NACA-Y stiffened panel, an octagon stiffened panel, and a multi-cell cover panel are evaluated.

Experiments were conducted on filament-wound plates and on stiffened panels fabricated from advanced material systems. All specimens were loaded in axial compression to failure, and the results are shown in figures 8-15. Asymmetric filament-wound plates made of Celion-6K fiber and Shell Epon 9400 resin and containing holes are shown in figure 8. Two types of filament-wound plates were tested: (1) single circuit specimens that minimize fiber crossovers and that are similar to tape specimens; and (2) multi-circuit plates that contain many fiber crossovers. The specimens were tested to determine the effect of holes on the compressive strength of filament-wound laminates, and the results are shown in figure 9. Analytical and experimental studies for two types of stiffened panels, a fluted core panel and a thermal expansion molded (TEM) panel, were conducted and the results are shown in figures 10 and 11. The fluted core panel consists of two face sheets and a woven triangular core. The TEM panel was

constructed using a potentially cost-effective processing technique. Closed-cell specimens are shown in figure 12. Structures that use this closed-cell concept may be fabricated by filament winding or by pultrusion. Results for a compression-loaded pultruded specimen are shown in figure 13. A damaged tolerant, blade-stiffened cover panel is shown in figure 14. Two of these panels were designed and built by the Douglas Aircraft Company using IM6-1808I. The first panel had no detectable damage and the second panel was severely impacted between stiffeners before testing. These results are shown in figure 15 and indicate no strength reduction due to impact damage.

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2. Williams, Jerry G.; Anderson, Melvin S.; Rhodes, Marvin D.; Starnes, James H., Jr.; and Stroud, W. Jefferson: Recent Developments in the Design Testing and Impact-Damage Tolerance of Stiffened Composite Panels. *Fibrous Composites in Structural Design*, Edward M. Leno, Donald W. Oplinger, and John J. Burke, eds., Plenum Publ. Corp., 1980, pp. 259-291.

ADVANCED CONCEPTS FOR COMPOSITE STRUCTURES

- Optimally-designed structures
- Cost-effective processing
- Advanced material systems

Figure 1. Advanced Concepts for Composite Structures

Description	E_{11} , Msi	E_{22} , Msi	G_{12} , Msi	ν_{12}	ρ , lb/in. ³
AS4-3502 tape	18.50	1.64	0.87	.30	.057
AS4-3502 Quasi-isotropic unstitched	7.42	7.42	2.80	.30	.057
IM6-18081	25.00	1.70	.60	.21	.060
T300-934 8H satin weave 0°- 90° fabric	9.20	9.00	.80	.057	.0567
T300-3501-6 Quasi-isotropic stitched	6.50	6.50	2.80	.29	.0567
Celion 12k 3501-6 ± 20° braided fiber	11.00	1.50	2.40	1.06	.057

Figure 2. Typical Material Properties

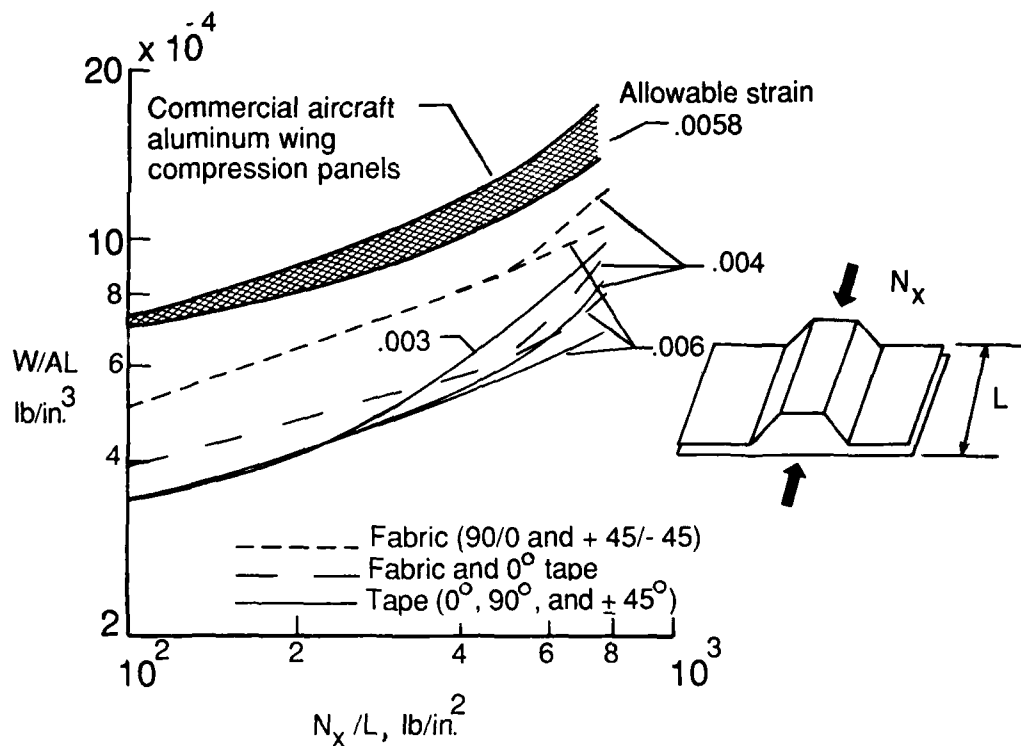


Figure 3. Structural Efficiency of Hat Stiffened Panels made of Graphite-Epoxy Woven Fabric and/or Tape

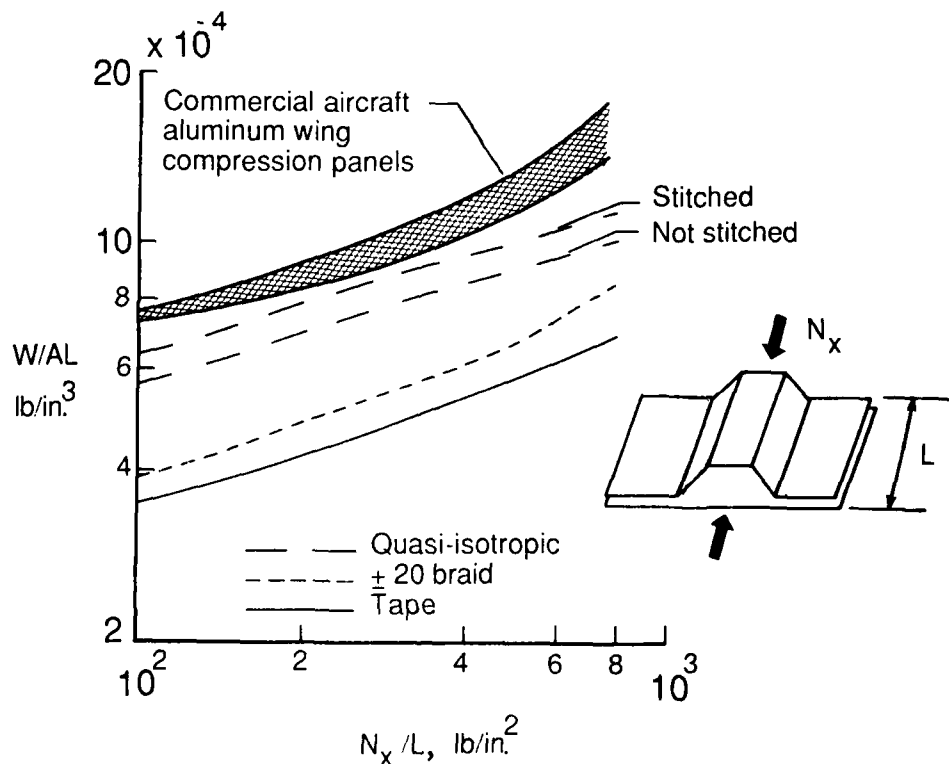


Figure 4. Structural Efficiency of Hat Stiffened Panels Made of Quasi-Isotropic Tape AS4-3502, or ±20 Braided Layers with a Maximum Allowable Strain of .006.

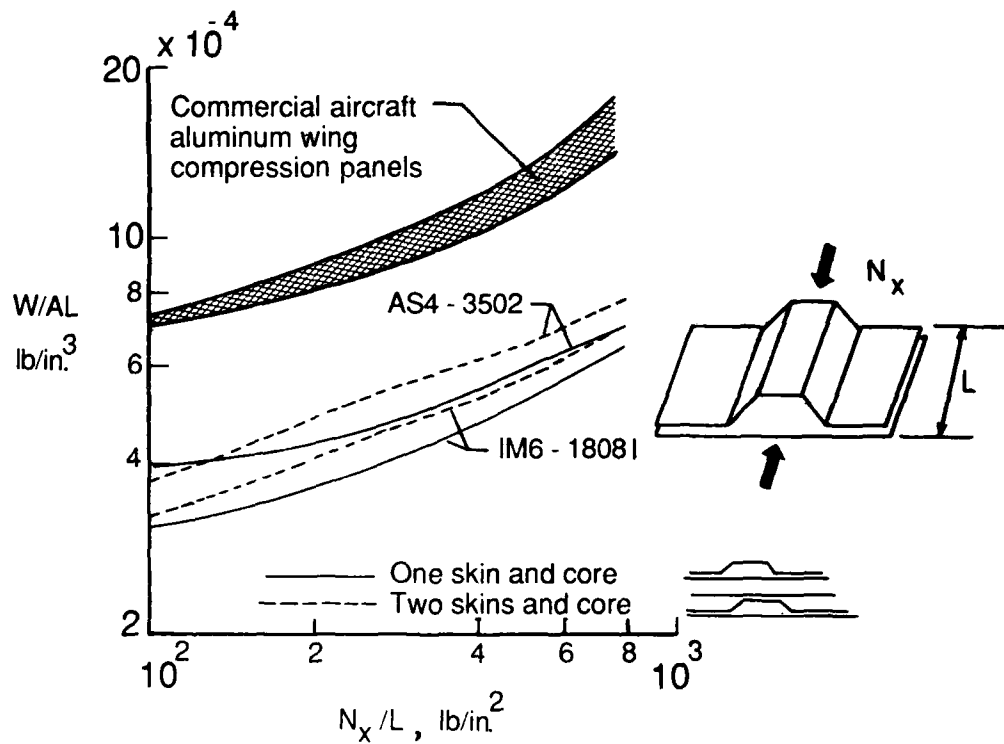


Figure 5. Structural Efficiency of Truss-Core Panels with One and Two Skins Made of AS4-3502 or IM6-1808I with a Maximum Allowable Strain of .006

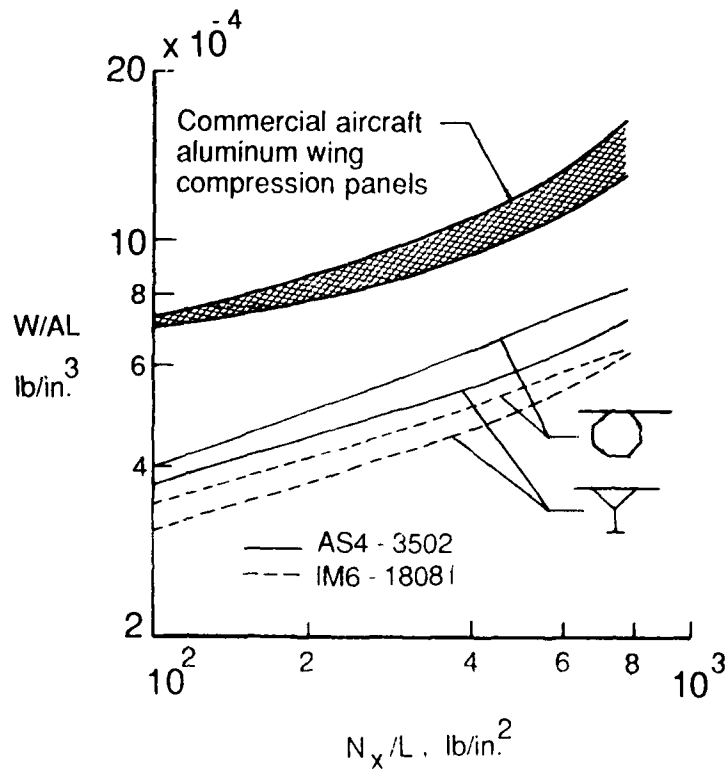


Figure 6. Structural Efficiency for NACA-Y Stiffened and Octagon-Stiffened Cover Panels

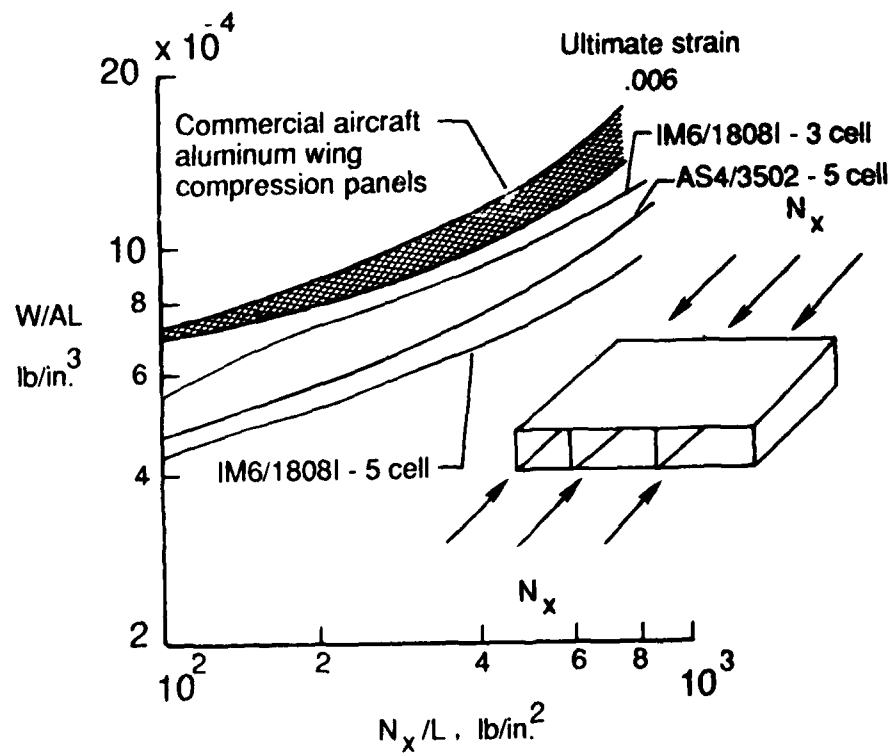


Figure 7. Structural Efficiency of Multi-Cell Panel

Fiber
cross-over

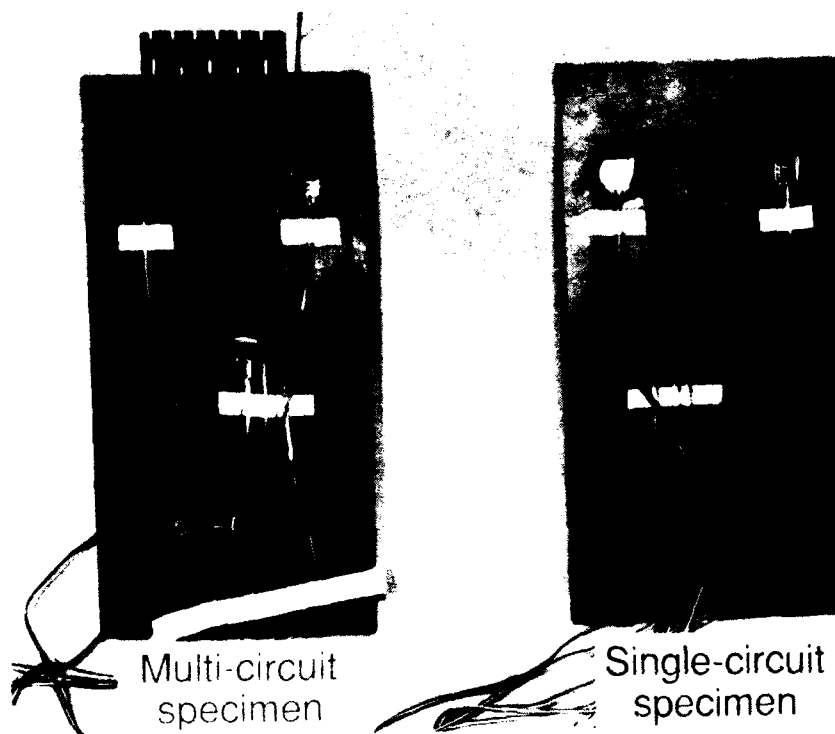


Figure 8. Filament-Wound Plates with Cutouts

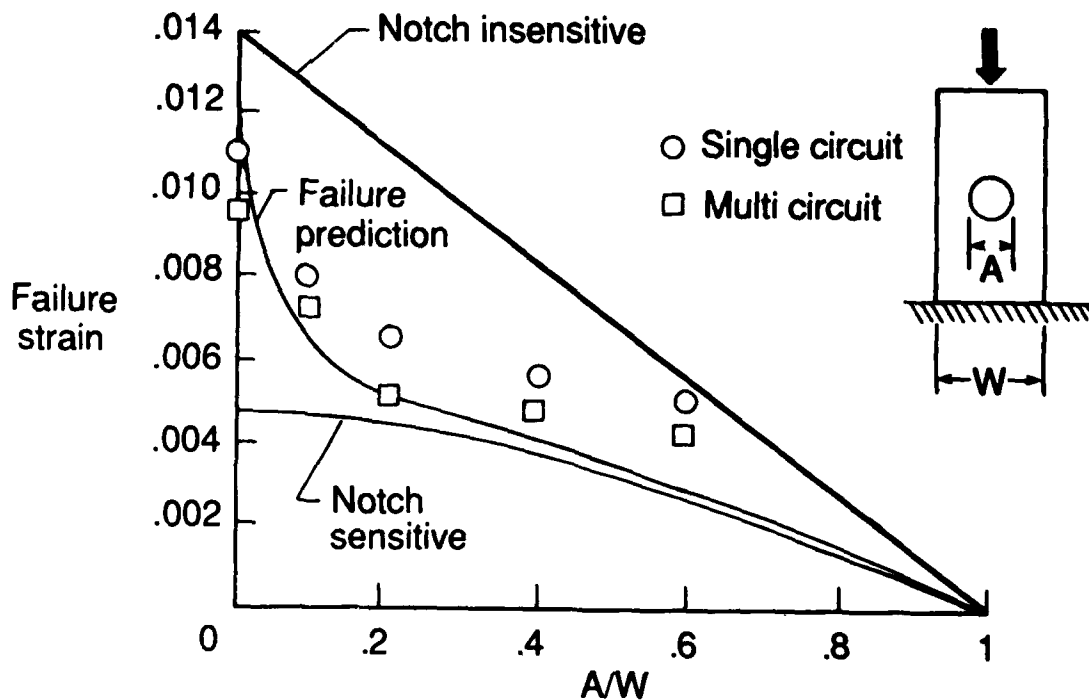


Figure 9. Open Hole Compression Strength of $[(\pm 30/90)_{10}]_T$ Filament-Wound Panels

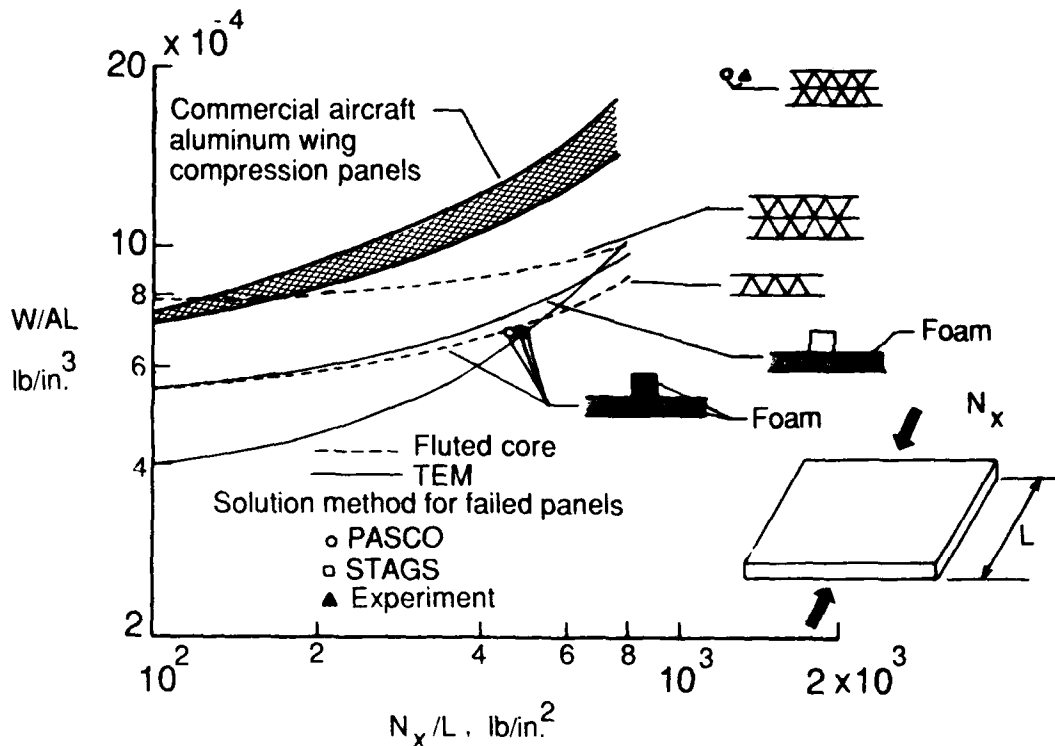


Figure 10. Structural Efficiency of Graphite-Epoxy TEM (Thermo-Expansion Molded) and Fluted Core Panels

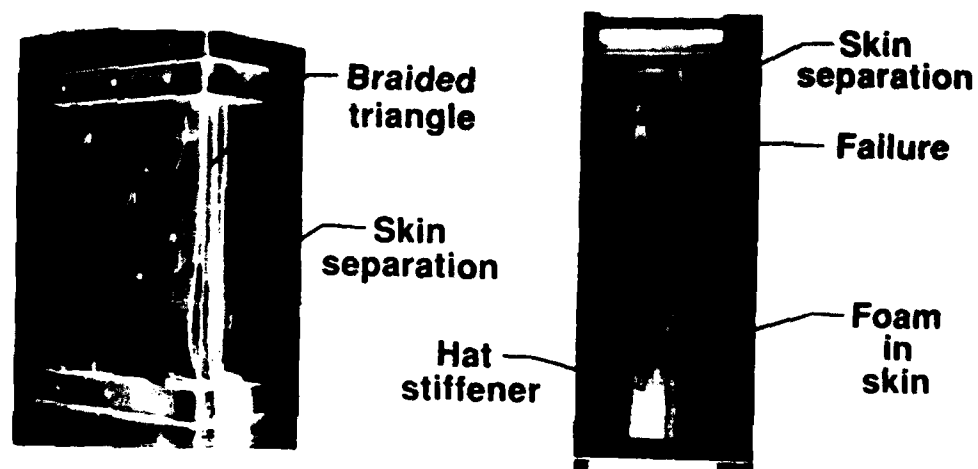


Figure 11. Failure of Fluted Core and TEM Panels

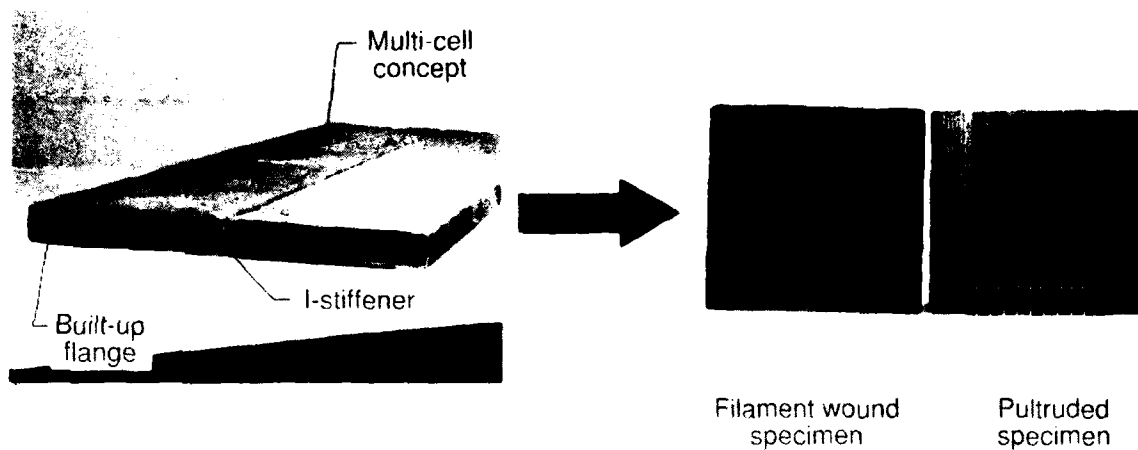


Figure 12. Multi-Cell Panel Concept for Fuselage Technology

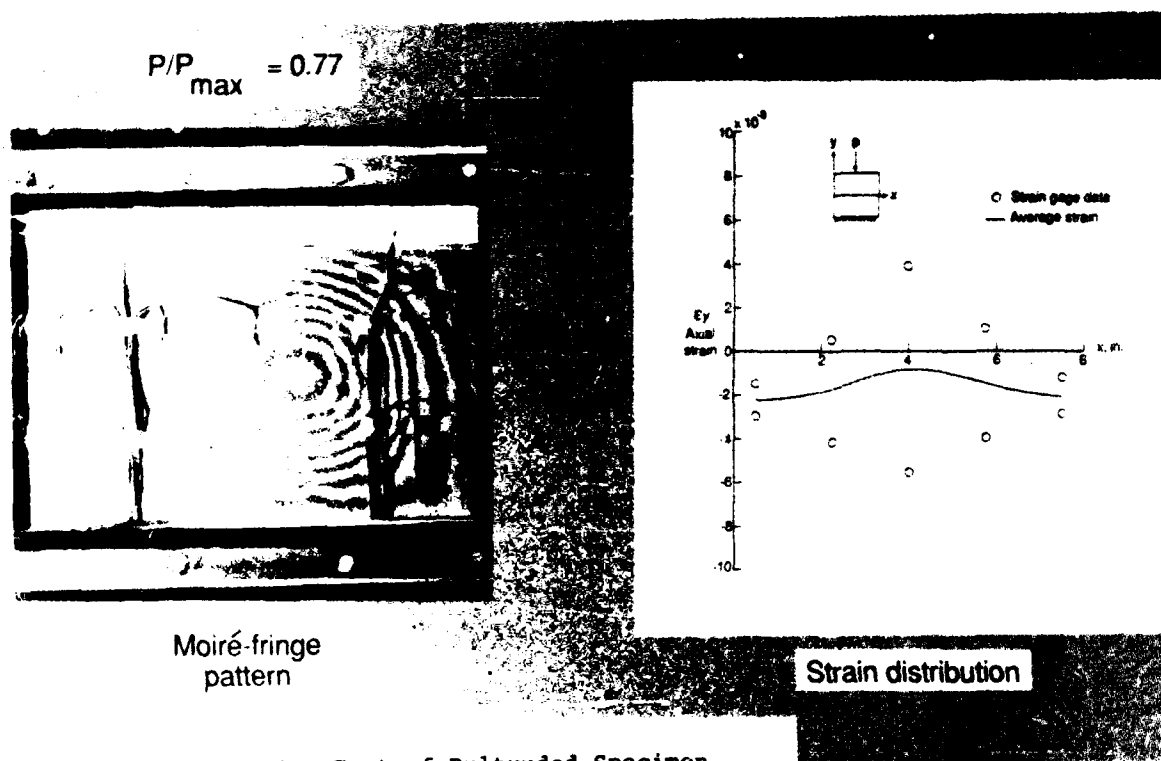
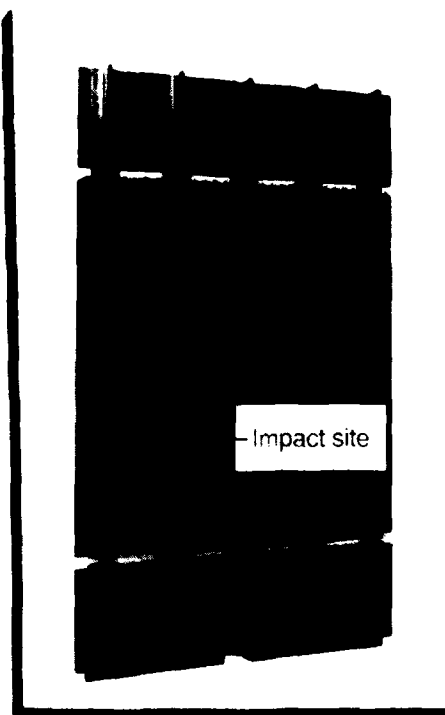
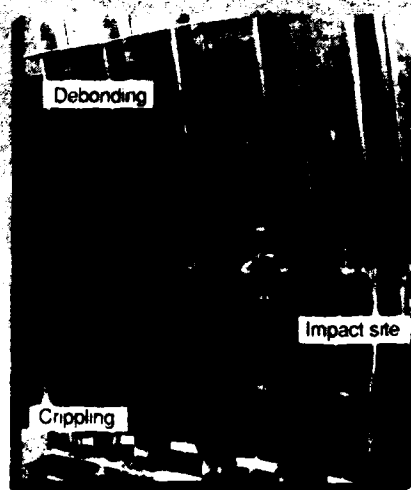


Figure 13. Compression Test of Pultruded Specimen



- IM6/1808I, blade-stiffened, orthotropic laminates, 56 in. long, 33 in. wide
- Compression-loaded, rib stations 37 in. apart
- 100 ft-lb impacts
 - 1.0-in.-dia impactor: undetectable
 - 0.25-in.-dia impactor: 4.9 in.² damage
- Design ultimate strain: 0.0045 in./in.

Figure 14. Composite Transport Wing Technology



- No damage growth
- Panels buckled prior to failure
- Failure:
Stiffener rolling, debonding, crippling
- Normalized end shortening at failure
DAC-1 .00410 in./in.
DAC-2 .00424 in./in.

Figure 15. Damage-Tolerant Cover Panel
Unaffected by Impact Damage

URI CENTER ON MANUFACTURING SCIENCE OF
COMPOSITE MATERIALS

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Research Triangle Park, North Carolina 27709

ABSTRACT

The objective of the initiative in Manufacturing Science is to establish a science base for advanced, automated manufacturing processes for future Army material needs. In an effort to fulfill this requirement, the University of Delaware was selected as a Center to address fundamental issues in the manufacturing science, reliability and maintainability of composite structures. The program is integrated with the National Engineering Research Center for Composite Materials, established in 1985 by the National Science Foundation. While the program addresses the entire area of manufacturing, reliability, and maintainability, it strongly emphasizes the goals of controlling and building in quality, long life, predictable and reliable performance, durability and lower cycle costs instead of minimum reliance upon repair or rejection of poor quality after manufacture is complete.

The approach employed under the Manufacturing Science initiative involves an integrated multidisciplinary effort on thick section laminates and woven forms, using both thermosetting and thermoplastic matrix materials. Research thrusts in the areas of manufacturing and processing science, mechanics and materials design, and durability are being pursued to address issues associated with the fabrication, non-destructive evaluation, reliability, and durability of these materials. Particular emphasis is being given to cure sensing and control of thick section thermosetting composites, thermal and mechanical characterization, structure-property relationships, mechanics of thick section composite laminates, and methods for non-destructive evaluation. The identification, sensing, active control, and integration of each of these key components into a processing scheme is central to the final development of a truly "intelligent" manufacturing cycle for these advanced materials.

In keeping with the central theme of this symposium, current research efforts in mechanics and materials design under the Manufacturing Science initiative are essential in designing thick section composite laminates which are tough and damage tolerant. In order to identify and optimize the factors controlling this behavior, a fundamental understanding of the processing/property/performance relationships as they relate to stiffness, strength, and fracture toughness is required. Research which is being supported in addressing this goal include the architectural and microstructural design of fiber preforms, the characterization and modeling of the response of composites to uniaxial and biaxial loadings, the determination of failure modes and toughening mechanisms under static and dynamic loadings, the characterization of in-plane and interlaminar properties, and the effect of processing and three-dimensional state of stress on strength and fracture of thick section composites.

**DEPARTMENT OF THE ARMY
UNIVERSITY RESEARCH INITIATIVE PROGRAM**

**A RESEARCH PROGRAM
IN
MANUFACTURING SCIENCE, RELIABILITY
AND MAINTAINABILITY TECHNOLOGY**

**COLLEGE OF ENGINEERING
UNIVERSITY OF DELAWARE
NEWARK, DELAWARE**

**MANUFACTURING SCIENCE, RELIABILITY
AND MAINTAINABILITY ENHANCEMENT**

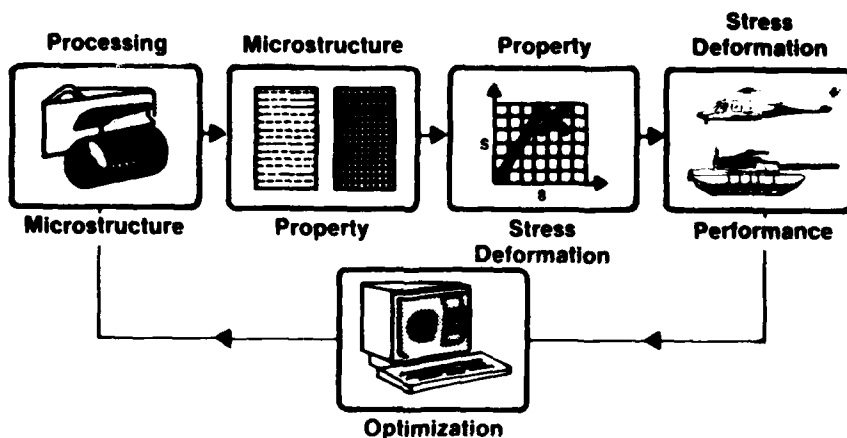
University of Delaware



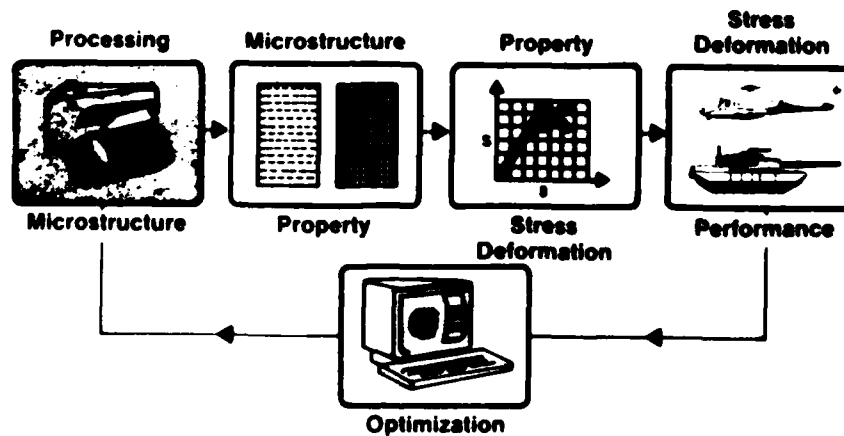
ESSENTIAL FEATURES

- Interdisciplinary In Character
- State-Of-The-Art Instrumentation
- Graduate Fellowships (U.S. Citizens)
\$13K - \$15K Per Year To Student
\$2K Plus Tuition & Fees To University
- Strengthen University - Army Ties
Informational Exchange
Scientific Personnel Exchange

ARMY-URI PROGRAM MANUFACTURING SCIENCE (UNIVERSITY OF DELAWARE)

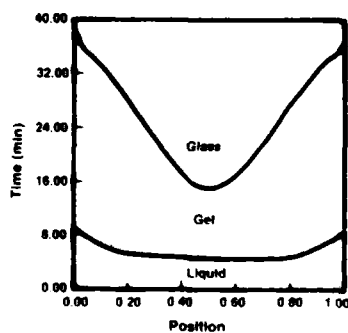


MANUFACTURING AND PROCESSING SCIENCES

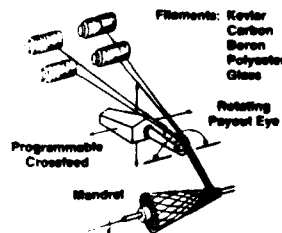


ARMY-URI PROGRAM MANUFACTURING SCIENCE (Manufacturing and Processing Science)

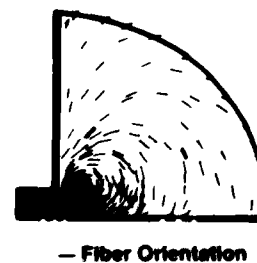
**Epoxy Cure
State Diagram**



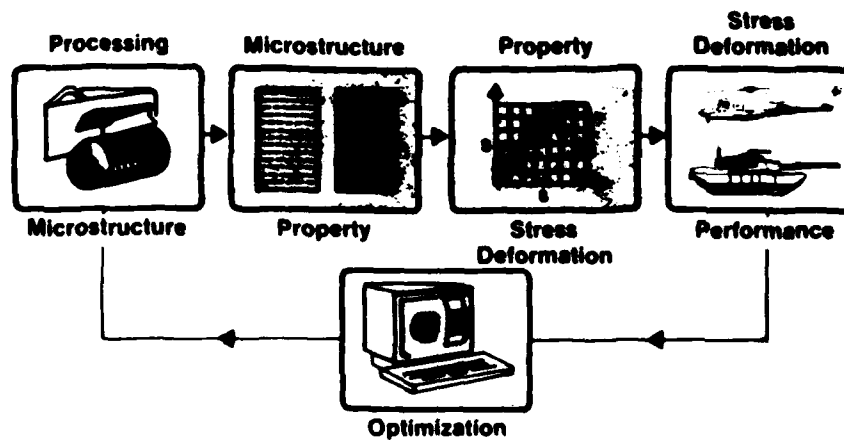
**Filament
Winding**



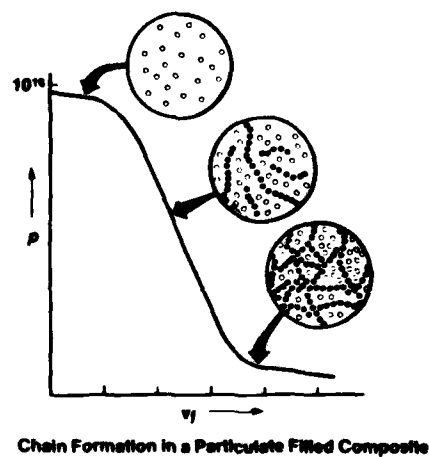
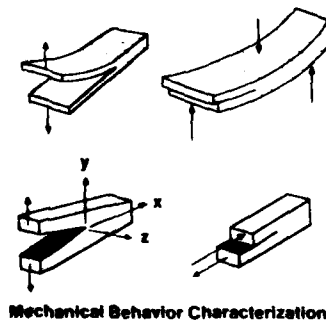
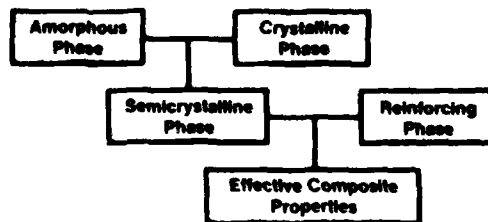
**Computational
Prediction**



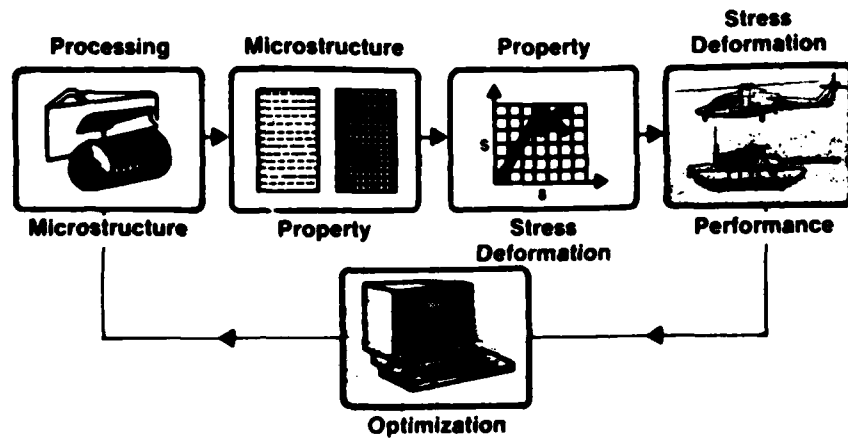
MECHANICS AND MATERIALS DESIGN



ARMY-URI PROGRAM MANUFACTURING SCIENCE (Materials Design and Mechanics)



DURABILITY

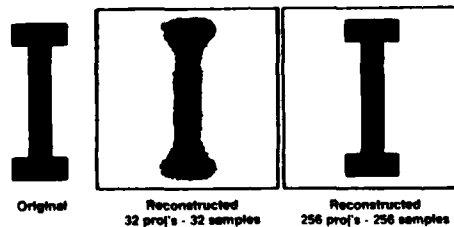


ARMY-URI PROGRAM MANUFACTURING SCIENCE (Materials Durability)

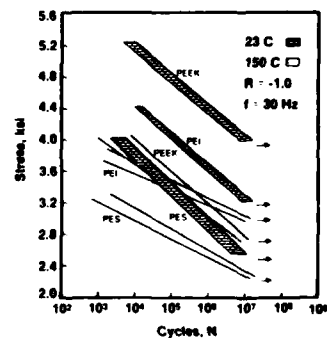
Simulation Process



Computerized Tomography



Flexural Fatigue Behavior of Composites



STRUCTURE-PROPERTY RELATIONSHIPS OF TEXTILE STRUCTURAL COMPOSITES

Research Goals

- **Engineering of tough composites for applications under static and dynamic loads**
- **Optimizing composite toughness through the design of 2-D and 3-D textile composites**
- **Optimizing composites damage tolerance by fiber hybridizations and tough thermoplastic matrices**

Current Mechanics Related Research

- **Fracture resistance of 3-D fabric composites**
- **Modeling of thermo-elastic properties of 3-D interlocked fabric composites**

FRACTURE MECHANICS ANALYSIS

Investigation of the influence of structural form on the fracture resistance of 3-D fabric composites.

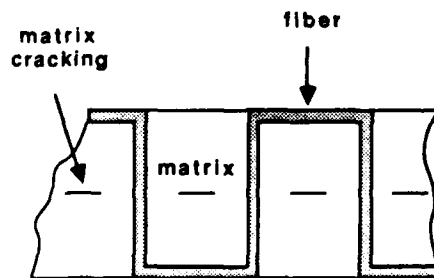
Key parameters:

- Volume fraction of reinforcement as affected by bundle size and spacing
- Orientation of reinforcement
- Constituent material properties

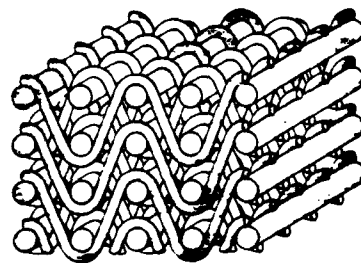
THERMO-ELASTIC PROPERTIES

Modeling the thermo-elastic properties of composites reinforced with 3-D textile preforms; constructing "performance maps" for various preform geometries, such as braids and angle-interlocks; extending the model to "thick section" composites.

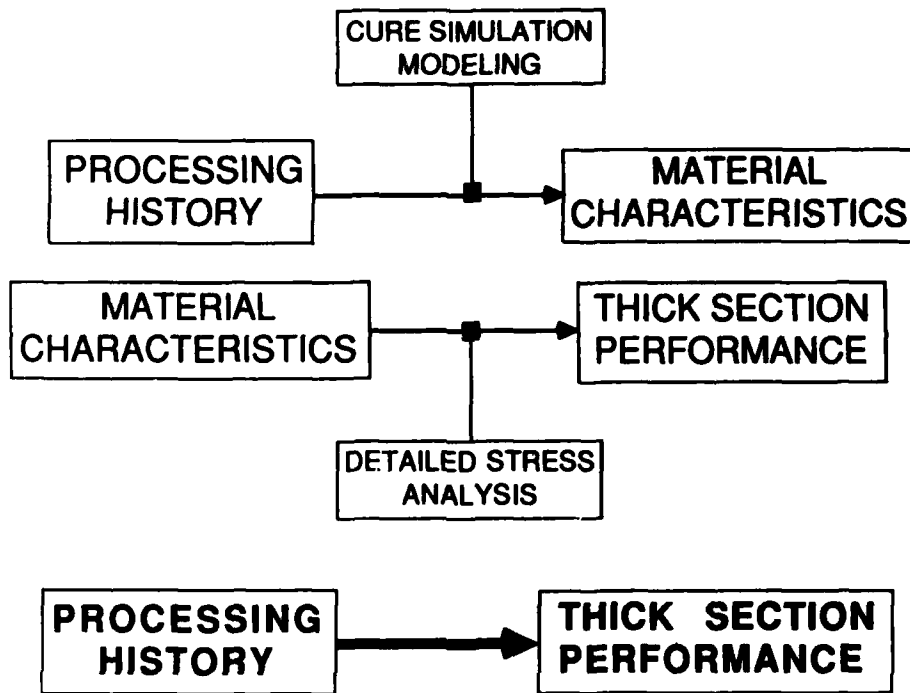
Example model systems:



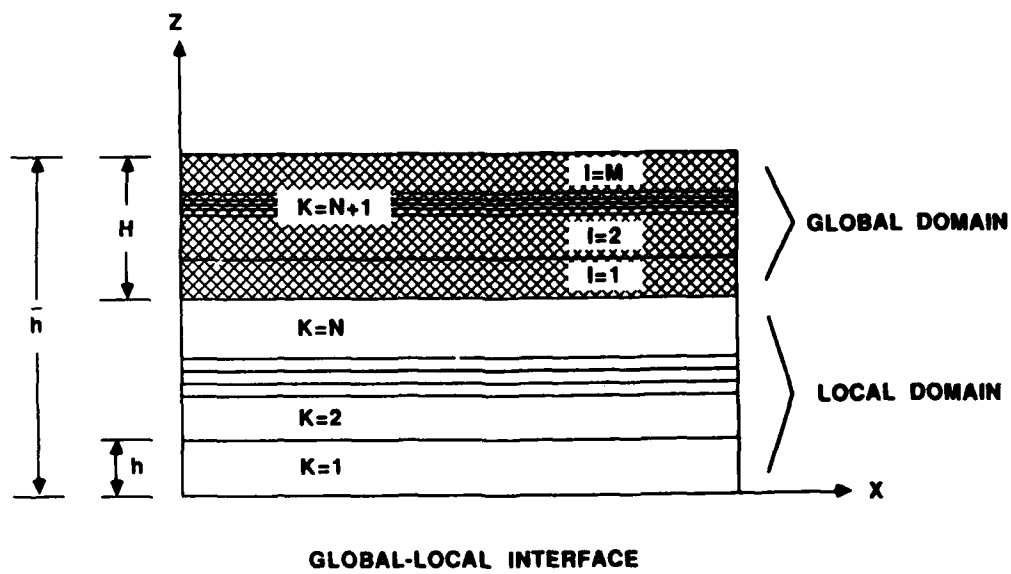
**Cracked Orthogonal
Fabric Composite**



Angle Interlock Fabric



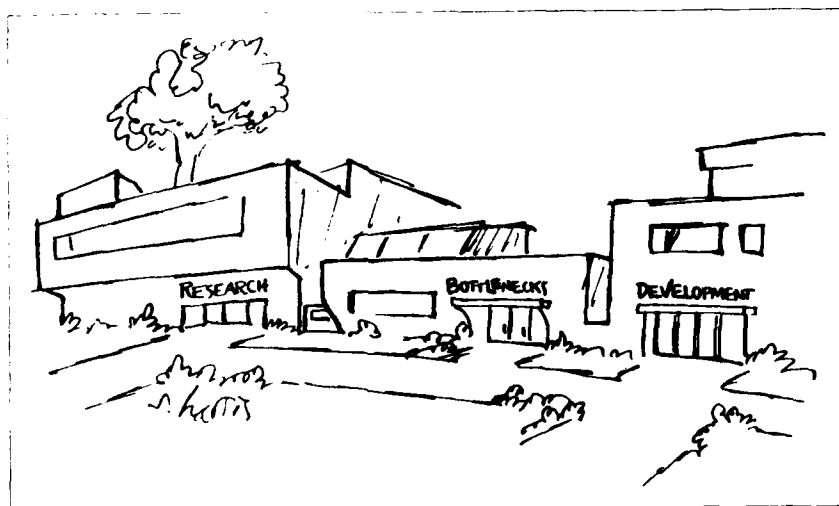
GLOBAL - LOCAL APPROACH TO DETAILED STRESS ANALYSIS



IMPACTS OF ARMY/URI PROGRAM

- **Initiate New Research In:**
 - On-line Intelligent NDE
 - Computer-Aided Manufacturing for Filament Winding
 - Mechanics of Thick Section Composites
 - Structural Performance and Durability
 - Integrated Engineering for Durable Structures
- **Expand Research Efforts In:**
 - Cure Characterization and Monitoring
 - Process Simulations
 - Structure-Property Relationships for
 - ◊ Textile Structural Composites
 - ◊ Hybrid Composites
 - ◊ High Performance Thermoplastic Composites
- **Create:**
 - Residency Program for Center Personnel in Army Laboratories
 - Intern Program at Center for Army Personnel
 - Eight New Army Fellowships
- **Establish a Center for Manufacturing Facilities**

TECHNOLOGY TRANSFER



RECENT DEVELOPMENTS IN MECHANICS OF COMPOSITES AT THE
MATERIALS TECHNOLOGY LABORATORY

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Army Materials Technology Laboratory
Watertown MA 02172

ABSTRACT

Current Army interests in composite materials stem from potential applications to flight hardware such as that addressed under ACAP and the Blackhawk rear fuselage, as well as a number of missile systems. In addition there is growing interest in application to ground-based materiel, including light-armored vehicles of the Bradley class, lightened artillery systems, tactical vehicles and miscellaneous equipment such as tow bars for field recovery of tanks and other vehicles, roll bars, trailer side panels and others. Moreover, current activity related to development of MIL HDBK 17B of which a first draft is to be issued soon, has instigated a number of efforts and development of statistical methodology for structural allowables which are of interest.

Mechanics research at MTL is aimed at the needs of such applications. The MTL mechanics of composites effort currently falls into the categories indicated in Fig. 1. Names of appropriate Points of Contact are included in the Figure for the convenience of those who wish to obtain information on the items listed. The following discussion will treat these item-by-item. (References cited in square brackets at the beginning of each section below are listed in the corresponding Figures.)

IMPROVED FE METHODS FOR SINGULARITIES[1-3] This effort is aimed at improved methods for predicting failure modes in composites where stress singularities may be crucial in failure initiation, ie., interfaces, boundaries, cracks and delaminations. (Fig. 2). The discussion will treat an efficient finite element approach for evaluating the singularities which characterize stresses in such situations, based on an iterative approach for solving eigenvalue problems of the finite element stiffness matrix used to model them. The method involves repeated multiplication of an arbitrary displacement vector by the inverted (ie. flexibility) matrix to extract the eigenvector of the stiffness matrix naturally associated with the singularity; a method for dealing with complex eigen-vectors and -values associated with cracks in dissimilar media and other problems of interest will be described.

IMPROVED THICK PLATE FINITE ELEMENT APPROACHES[4-6] Thick plate effects are especially important in organic-matrix composites because of the low interlaminar shear and transverse normal stiffness. The effort is based on so-called "anisoparametric" interpolations for improving transverse shear representation while completely removing "membrane-" and "shear locking". A major recent development is the inclusion of thickness normal deformations based on C^0 -continuous kinematic approximations. Representative results shown in Fig. 3 illustrate pertinent static and dynamic analyses.

APPLICATION OF MOIRE METHODOLOGY TO COMPOSITES[7-10] Moire has provided a foundation for much of the mechanics of composites activities at AMMRC/MTL over the years [7] The discussion will cover applications to nonlinear in-plane response of pin-loaded plates [8,9], thickness-wise response of pin loaded plates, and impact

damage tolerance in composites. Recent work on nonlinear response in pin loaded 0/90 and +/- 45 laminates [9] will be extended to include the modelling of initial damage effects.

APPLICATION OF FE METHODS TO FRINGE PATTERN ANALYSIS [11] A new method of moire fringe pattern analysis based on the use of finite element methods for interpreting 2D optical density and elastic displacement fields will be discussed. The method represents a considerable advance over a finite-element based approach first proposed in the late 60's using least-squares fitting of optical fringe patterns. It employs a new penalized least-squares variational principle which gives rise to low-order, high-efficiency smoothing/differentiating finite elements. The method involves finite element reconstruction of both the optical density field from a digitized version of the fringe pattern and the displacement field from the reconstructed fringe pattern.

IMPROVED METHODS FOR STRESS ANALYSIS OF ADHESIVE JOINTS [12-14] A thick plate analysis method similar to the "BONJO" and "BOND4" [13,14] programs developed in the early 70's will be discussed in terms of efficient procedures for analyzing stresses in lap joints. Comparisons with FE methods will be described. (Fig. 6). A particular objective is the development of alternative methods to FE analysis for bonded joints. In particular, an approximate model analogous to a Volkersen shear lag type model in which thickness-wise displacements of adherends are ignored but the Volkersen model is extended to include adherend deformations will be discussed.

STATISTICAL METHODOLOGY FOR DESIGN ALLOWABLES [15-17] This work in support of MIL H'BOOK 17 [15] has recently been directed toward more efficient non-parametric methods for attaining allowables. In Fig. 7 is shown a comparison of allowables obtained by the new version of the non-parametric approach with that obtained assuming a Weibull distribution. The "MARS" code which has been developed over about ten years for providing a variety of statistical analyses related to allowables determination is continuously being updated as new developments are perfected; this has been made available to the FAA and a number of other outside organizations.

CONSTITUTIVE EQUATION REPRESENTATION FOR COMPOSITE MATERIALS [18,19] Also in support of MIL H'BOOK 17 is a methodology which has been developed for easy representation of stress-strain data for composites. The method involves fitting individual stress-strain curves as generated by chart recorders, using one of 7 choices of analytic function, determined by a best fitting process, and averaging the curves for all tests in a given set to provide a representative curve. Examples are shown in Fig. 8. A tutorial workshop on the code which has been developed to produce this type of analysis is planned. A data base representing the typical spectrum of mechanical properties for several hundred composite materials has been generated.

ENVIRONMENTAL EFFECTS IN COMPOSITES [20,21] Recent efforts have been directed toward: (1) improved torsion testing methods for filament wound tubes (Fig. 9 [20]); (2) influence of processing effects such as braiding vs. filament winding in aramid and glass fiber composites on mechanical properties; (3) effects of prepreg exposure to elevated temperature to mechanical properties of composites [21].

DEVELOPMENT OF NDE METHODOLOGY FOR COMPOSITES [22] Current efforts in the area of NDE for composites involve development of ultrasonic methods for fiber volume and porosity determination. A new method under development (Fig. 10) involves development of C-scan plots of ultrasonic dilatational and shear wave velocity vs. position, and using appropriate equations, translating these to fiber volume and porosity plots. B scan plots also are providing information on layer boundaries and delaminations.

DAMAGE ZONE CHARACTERIZATION IN NOTCHED LAMINATES [23-25] Over the years MTL has pursued models for characterizing progressive damage in notched laminates in terms of "damage zones" analogous to yield zones in metals as a means of characterizing progressive damage in notched laminates. The work described in [23] is in support of this effort. Related work being conducted at MIT on embedded strain gages in the vicinity of sharp notches will be mentioned in passing. A brief review of work presented some years ago on failure in angle ply laminates [25] will be given. A film strip showing dynamic crack propagation using moire for crack-front visualization in an angle ply laminate will be shown in the presentation.

ACTIVITY	POINT OF CONTACT	PHONE NO.
1. IMPROVED FE METHODS FOR SINGULARITIES	R. Barsoum	(617) 923-5166
2. THICK PLATE FINITE ELEMENT METHODOLOGY	A. Tessler	" " -5356
3. APPLICATIONS OF MOIRE ETC. TO MECHANICS OF COMPOSITES	S. Serabian	" " 5260
4. APPLICATION OF FE METHODS TO MOIRE PATTERN ANALYSIS	A. Tessler	" " 5356
5. IMPROVED METHODS FOR STRESS ANALYSIS OF ADHESIVE JOINTS	D. Oplinger	" " 5303
6. STATISTICAL METHODOLOGY FOR DESIGN ALLOWABLES	D. Neal	" " 5166
7. CONSTITUTIVE EQUATION REPRESENTATION FOR COMPOSITE MATERIALS	R. Papirno	" " 5274
8. ENVIRONMENTAL EFFECTS IN COMPOSITE MATERIALS	M. Roylance	" " 5514
9. DEVELOPMENT OF NDE METHODS FOR COMPOSITES	R. Brockleman	" " 5333
10. STUDIES OF DAMAGE DEVELOPMENT IN POLYMER MATRIX COMPOSITES	D. Oplinger/ J. Mandell(NIT)	" " 5303

Fig. 1 SUMMARY OF MTL MECHANICS OF COMPOSITES ACTIVITIES

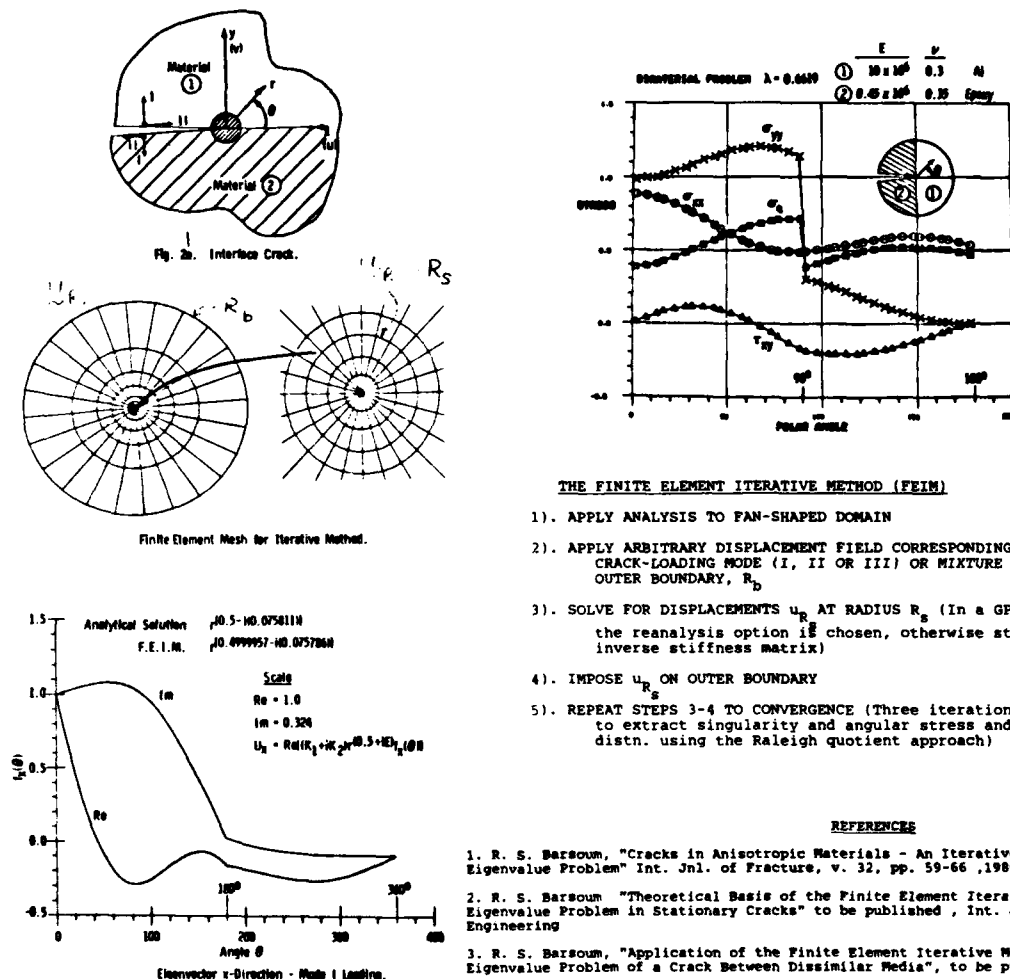


Fig. 2 IMPROVED FINITE ELEMENT METHODS FOR STRESS SINGULARITIES

THICK BEAM FE ANALYSIS BY HIGHER ORDER PLATE THEORY ("HOT")

- A SIMPLE AND EFFECTIVE HIGHER-ORDER BENDING THEORY; INCLUDES TRANSVERSE SHEAR AND THICKNESS NORMAL STRAINS.

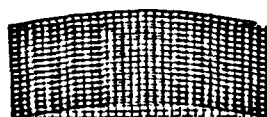
- HOT THEORY DERIVED FROM 3D ELASTICITY VIA VARIATIONAL PRINCIPLE

- LEGENDRE POLYNOMIALS APPROXIMATE THROUGH-THICKNESS DISPLACEMENT, STRAIN AND STRESS.

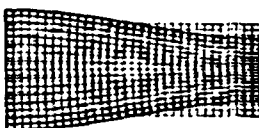
- C¹-CONTINUOUS ANISOPARAMETRIC KINEMATIC APPROXIMATIONS USED IN FE IMPLEMENTATION.

- THEORY AND FEA VALID THROUGHOUT THE RANGE FROM THICK (SHEAR-COMPLIANT) TO EXTREMELY THIN (KIRCHHOFF) BEAMS, PLATES AND SHELLS

1st BENDING MODE



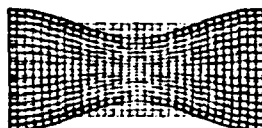
2nd TRANSVERSE MODE



2nd BENDING MODE



3rd TRANSVERSE MODE



PREDICTION OF REPRESENTATIVE BEAM MODES BY ABAQUS 2D SOLUTION (8 NODE ELEMENTS: 512 EL/3266 DOF)

Mode	S-MODE/2D (ABAQUS) ($n_{el}=512$, $n_{dof}=3266$)	S.O.T. 2-MODE ($n_{el}=64$, $n_{dof}=321$)	% Difference
	$u_{10}/10^3$ rad/sec	$u_{10}/10^3$ rad/sec	$(u_{10}/u_{10})-1 \times 100$
1(b)	0.8751	0.8607	-0.57
2(b)	13.742	13.664	-0.58
3(b)	21.119	19.641	-6.58
1(t)	26.340	26.546	0.75
2(t)	26.317	26.064	-2.25
4(b)	26.462	26.740	1.02
3(t)	32.213	32.671	1.42
5(b)	35.863	33.588	-6.34
4(t)	37.108	37.224	0.31
1(a)	39.821	39.629	-0.52

EX: n_{el} = number of elements, n_{dof} = number of degrees-of-freedom
b = bending mode, t = transverse mode, a = axial mode.

COMPARISON OF PREDICTIONS -- 2D VS. "HOT" APPROACH (64 EL/ 120 DOF)

Fig. 3 IMPROVED FINITE ELEMENT METHODS FOR THICK PLATE/SHELL ANALYSES

6676 N (1500 Psi)

MOIRE ANALYSIS

LINEAR ELASTIC FINITE ELEMENT ANALYSIS

V FIELD



.008 TENSILE MISMATCH
.0254 mm (.001 in) CONTOUR INTERVAL

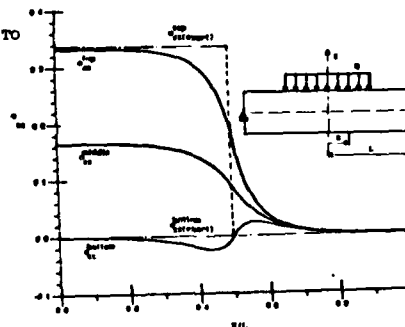
U FIELD



.008 TENSILE MISMATCH
.0254 mm (.001 in) CONTOUR INTERVAL

Experimental/Finite Element Displacement Contours (6676 N)

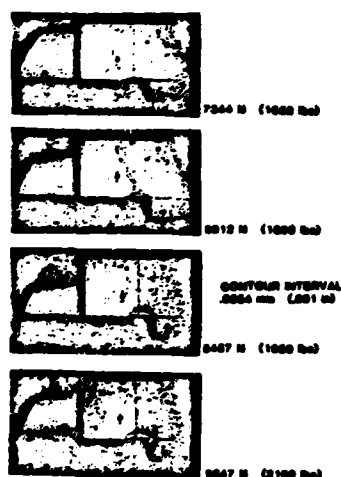
APPLICATION OF "HOT" TO CENTER LOADED BEAM



ANMRC/MTL MOIRE EFFORTS [7]

- EDGE EFFECTS
- IOSEFESCU SHEAR SPECIMEN
- PIN LOADED JOINTS
 - ELASTIC RESPONSE
 - NONLINEAR RESPONSE
 - THICKNESS-WISE RESPONSE
- DAMAGE DETECTION IN IMPACTED PANELS
- METHODOLOGY DEVELOPMENT
 - OUT-OF-PLANE DISPLACEMENTS
 - AUTOMATED PATTERN ANALYSIS

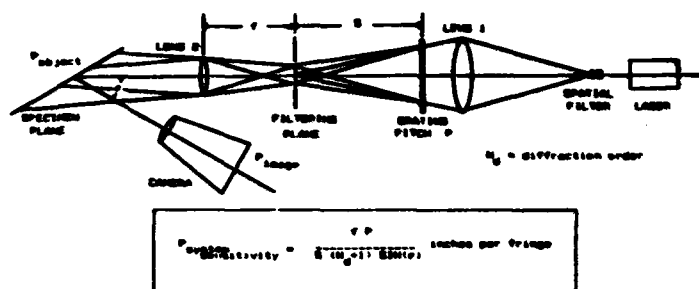
Fig. 4 APPLICATIONS OF MOIRE TO MECHANICS OF COMPOSITES.



OUT-OF-PLANE DISPLACEMENT CONTOURS:

- PIN LOADED PLATE,
- (0/90/±45)_{2s} GLASS EPOXY

Fig. 4 APPLICATIONS OF MOIRE TO MECHANICS OF COMPOSITES (cont.).



OUT-OF-PLANE DISPLACEMENT MEASUREMENT

- PRODUCE PROJECTED SPECIMEN GRATING BY FOURIER OPTICS
- PHOTOGRAPH GRATING AT PROGRESSIVELY INCREASING LOAD
- SUPERPOSITION WITH OPTICAL FOURIER PROCESSING GIVES OUT-OF-PLANE DISPLACEMENT CONTOURS

REFERENCE

7. D. Oplinger, "Application of Moire Methods to Evaluation of Structural Performance of Composite Materials" OPTICAL ENGINEERING, v. 23, pp. 636-638, 1982
8. D. Oplinger, C. E. Prosser and K. R. Gandhi, "Experimental and Analytical Evaluation of Nonlinear Mechanical Response of Notched Laminates" IN Annual Mechanics of Composites Review, 1984
9. S. Sarabian and D. Oplinger, "An Experimental and Finite Element Investigation into the Mechanical Response of 0/90 Pin Loaded Laminates", J. Compos. Mat. Aug. 1987
10. S. Sarabian, "Experimental Verification of Bolted Joint Methodologies", Army Solid Mechanics Symposium 1974, Army Mat. & Mech. Res. Ctr. Manuscript Report AMMC-MS-84-3, 1984

APPLICATION OF FE APPROACH TO MOIRE PATTERN ANALYSIS [11]

1. AUTOMATED SCANNER FOR FRINGE FIELD DIGITIZATION (Hamamatsu C1000; 1024x1024 pixels)
2. 1ST SMOOTHING FE STEP: CONSTRUCT 2D LEAST-SQUARES REPRESENTATION OF OPTICAL DENSITY FIELD
 - USE FE TRACKING CONTOUR POST-PROCESSOR TO CONSTRUCT FRINGES (i.e. contours of zero optical density gradient)
3. 2ND SMOOTHING FE STEP: FIT LEAST-SQUARES 2D DISPLACEMENT FIELD TO FRINGE PATTERN (Step 2 may be bypassed with sufficiently noise-free fringe patterns)
- OBTAIN DISPLACEMENT GRADIENTS FOR STRESS ANALYSIS

REFERENCE

11. A. Tessler, C. E. Prosser, S. Sarabian, R. Anastasi, D. Oplinger and A. Katz, "Least Squares Penalty Constraint Finite Element Method for Generating Strain Fields for Moire Fringe Patterns", SPIE Proceedings, v. 814, International Conf. on Photomechanics & Speckle Metrology, San Diego, Aug. 1987

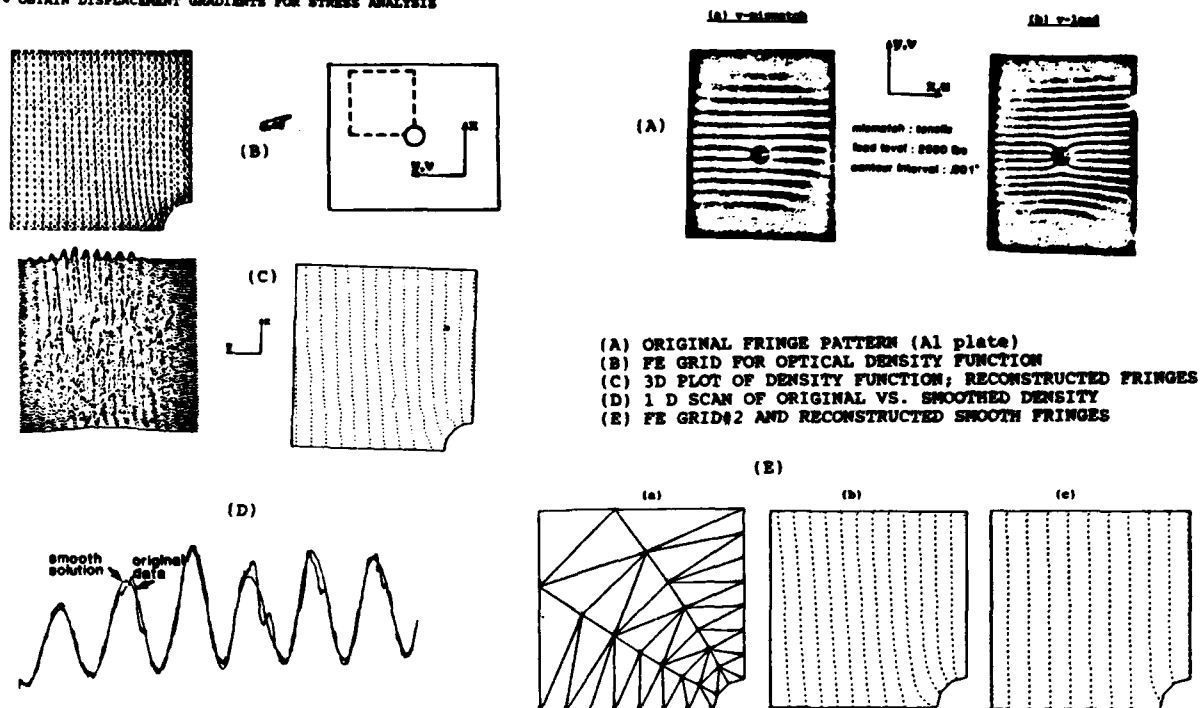
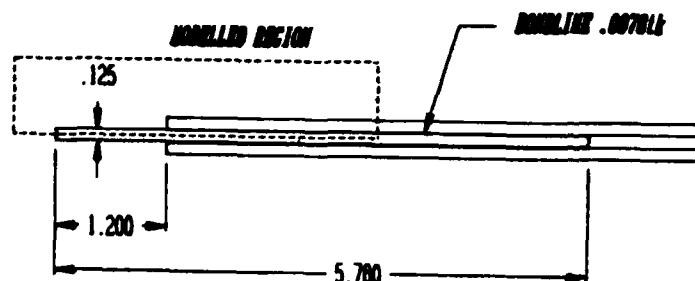
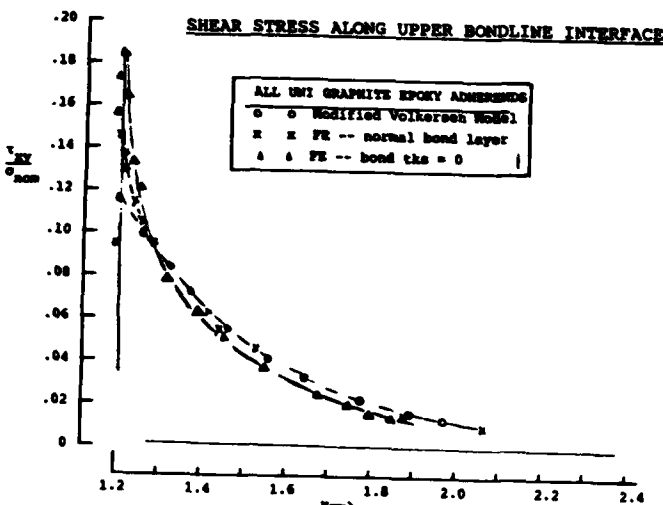
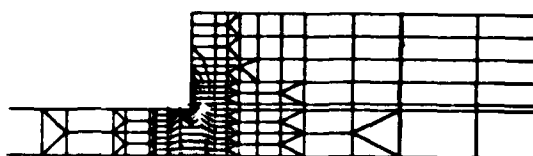


Fig. 5 APPLICATION OF FINITE ELEMENT APPROACH TO MOIRE ANALYSIS



FINITE ELEMENT INVESTIGATIONS

- PROVIDE BASELINE SOLUTIONS FOR EVALUATING APPROXIMATIONS
- SOLUTIONS OBTAINED FOR UNI GRAPHITE EPOXY LOWER ADHEREND WITH UPPER ADHEREND OF:
 - ALL UNI GRAPHITE EPOXY WITH NORMAL BONDLINE
 - " " " " " 8 THICKS "
 - 90/90/0/0, 0/0/90/90, 0/90/90/0 UPPER ADHEREND
 - ALUMINUM UPPER ADHEREND



APPROXIMATE MODELS

ADVANCED VOLKERSSEN MODEL FOR ADHEREND SHEAR DEFORMATIONS

$$\tau_{xz} = \int \sigma'_{xz,x} dz ; \sigma'_x = \int \tau_{xz,x} dz ; \sigma'_x = \frac{E_x u}{b} ; \sigma'_x \text{ independent of } z$$

$$\tau_{xz} = E_{xz,x} (1 - \frac{z}{t}) ; t = \text{adherend thickness}$$

$$\tau_{xz}(z=0) = \tau_b \text{ (bond shear stress)}$$

RESULTING DIFF. EQUATION:

$$\tau_{b,xx} + \alpha^2 \tau_b = 0 ; \tau_b = \tau_b^{\max} \exp(-\alpha x)$$

$$\alpha^2 = \frac{G_b}{t_b(1+\eta)} \left(\frac{1}{b_1} + \frac{1}{b_2} \right) ; b_1/u = \int_0^{t/2} \frac{E_x}{1-\nu_{xy}} dz$$

$$\eta = \frac{1}{3} \left(\frac{t_1 G_b}{t_b G_1} + \frac{t_2 G_b}{t_b G_2} \right) ; G_{t/u} = G_{xz} \text{ of adherends}$$

(classical Volkersen analysis: $\eta = 0$)

ADVANCED APPROXIMATION: MODIFIED GOLAND REISSNER

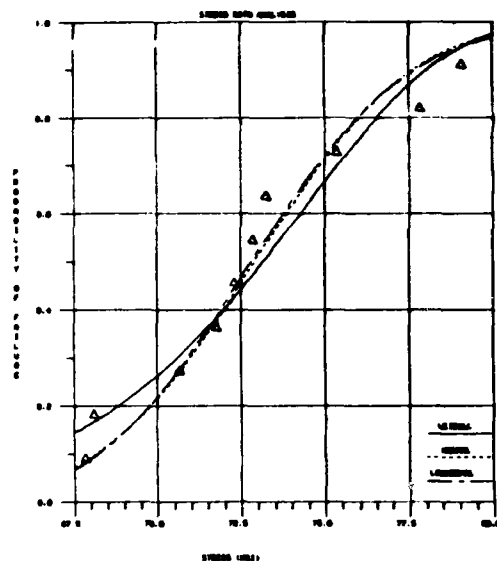
- ALLOWS FOR THICKNESS/NORMAL AS WELL AS SHEAR DEFORMATIONS
- SIMILAR TO BOND4/BONJO [13,14] OF EARLY 70'S BUT DEVELOPMENT BASED ON INTEGRATING σ'_x TO GET τ_{xz} DISTRIBUTION AS ABOVE
- STARTS WITH ASSUMPTION:

$$\sigma'_x = E_x \left[\frac{u}{b} + \left(\frac{z}{2} - z \right) \frac{u}{D_x} \right] \text{ (membrane + bending stresses)}$$
- ABOVE EQUILIBRIUM EQUATIONS GIVE PARABOLIC SHEAR STRESS DISTRIBUTION AS IN BOND
- PROVIDES FOR SIGNIFICANT EFFECTS OF STACKING SEQUENCE

REFERENCES

12. D. Oplinger, "Stress Analysis in Composite Joints" ADVANCES IN JOINING TECHNOLOGY, Proceedings of 4th Army Materials Technology Conference pp. 405-450 1975
13. J. W. Renton and J. R. Vinson, "Analysis and Design of Composite Material Bonded Joints Under Static and Fatigue Loadings", AFOSR Report AFOSR-TR-73-1627, 1973
14. J. W. Dickson, T. Wu and J. McKinney, Air Force Flight Dynamics Laboratory Report AFFDL-TR-72-64 v. I, 1972

Fig. 6 STRESS ANALYSIS METHODS FOR ADHESIVE JOINTS



MARS CODE ANALYSIS OF 10-SPECIMEN DATA SET:
B ALLOWABLE ESTIMATE:
WEIBUL -- 61.14 KSI
NONPARAMETRIC -- 62.15 "

REFERENCES

15. D. Neal, M. Vangel and B. Harris, MIL-HDBK-17B, PLASTICS FOR AEROSPACE VEHICLES, Part 1. COMPOSITE MATERIALS FOR AIRCRAFT AND AEROSPACE APPLICATIONS, V. 1 GUIDELINES, Chapt. 7, Analysis and Presentation of Data, to be issued Fall 1987
16. D. Neal and M. Vangel, ENGINEERING MATERIALS HANDBOOK, V. 1, Composites, Sect. 5, Tests of Composite Materials, Section on "Statistical Analysis of Mechanical Properties", ASM, Metals Park OH to be published late 1987
17. D. Neal and M. Vangel, "Statistical Evaluation of Composite Material Strength Data", Proceedings of Army Symposium on Solid Mechanics 1986, Materials Technology Laboratory Manuscript Report MS-86-3, pp. 221-244 1986

AVERAGE STRESS STRAIN CURVES FOR RESIN MATRIX COMPOSITES

- PROCEDURE
 1. BEST FIT OF ONE OF 7 FUNCTIONAL FORMS:
 - LINEAR
 - PARABOLIC
 - INVERSE PARABOLIC
 - RAMBERG-OSGOOD
 - BILINEAR
 - PARABOLIC-LINEAR
 - PARABOLIC-EXPONENTIAL
 TO INDIVIDUAL STRESS-STRAIN CURVES
 2. AVERAGED FIT OF SEVERAL STRESS-STRAIN CURVES REPRESENTING ONE MATERIAL PROPERTY OF ONE MATERIAL
- PROCEDURE INCORPORATED INTO MIL HDBK 17B
- CODE AVAILABLE -- TUTORIAL WORKSHOP PLANNED

AVE. COMPRESSION CURVES FOR KEVLAR/HEXCEL F-161 16-PLY

REFERENCES

18. R. Papirno, "Algebraic Approximations of Stress-Strain Curves for Kevlar Reinforced Composites", J. Testing and Evaluation, v. 13 pp. 115-122, 1985
19. R. Papirno, "Average Stress-Strain Curves for Resin Matrix Composites" J. Composites Technology and Research, v. 8, pp. 107-116, Fall 1986

Fig. 8 AVERAGE STRESS STRAIN CURVES FOR RESIN MATRIX COMPOSITES

Fig. 8 AVERAGE STRESS STRAIN CURVES FOR RESIN MATRIX COMPOSITES

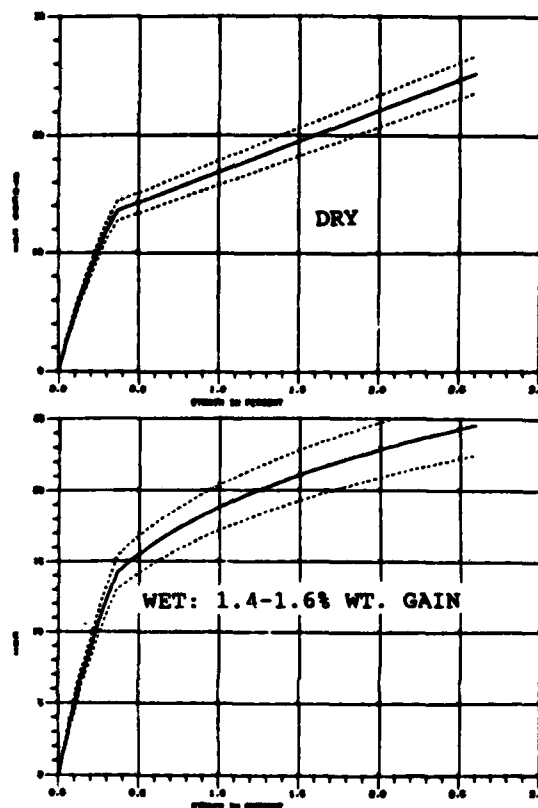
METHODS DEVELOPED FOR MIL-17B WORK STATISTICS CHAPTER

- SMALL SAMPLE (< 30 TEST POINTS) NONPARAMETRIC "B" BASIS ANALYSIS
- MULTI BATCH ANOVA (Anal. of Variance) SOLUTION
- STATISTICAL MODEL SELECTION
- TEST BATCH-TO-BATCH VARIABILITY
- EXPLORATORY DATA ANALYSIS
- REGRESSION ANALYSIS
- WEIBUL/NORMAL MODELS FOR SINGLE BATCH
- DATA BASE DEVELOPMENT
- STATISTICALLY DESIGNED QA TEST
- ASM COMPOSITES VOLUME[16]
- MARS(Material Analysis using Reliability and Statistics) GENERAL PURPOSE STATISTICAL CODE FOR COMPOSITE STRENGTH DATA

MARS CODE USERS

- FAA
- FORD MOTOR CO.
- WPAB MATERIALS LAB/BALLISTICS LAB
- GENERAL DYNAMICS FT. WORTH
- LTV (Dallas)
- HERCULES
- UNIV. OF WISCONSIN

Fig. 7 STATISTICAL RELIABILITY EFFORTS IN COMPOSITE MATERIALS



AVE. COMPRESSION CURVES FOR KEVLAR/HEXCEL F-161 16-PLY

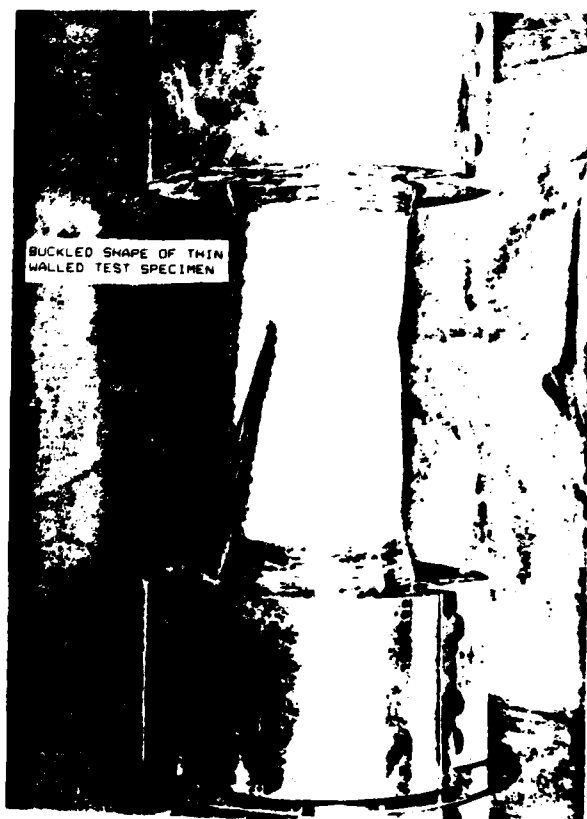
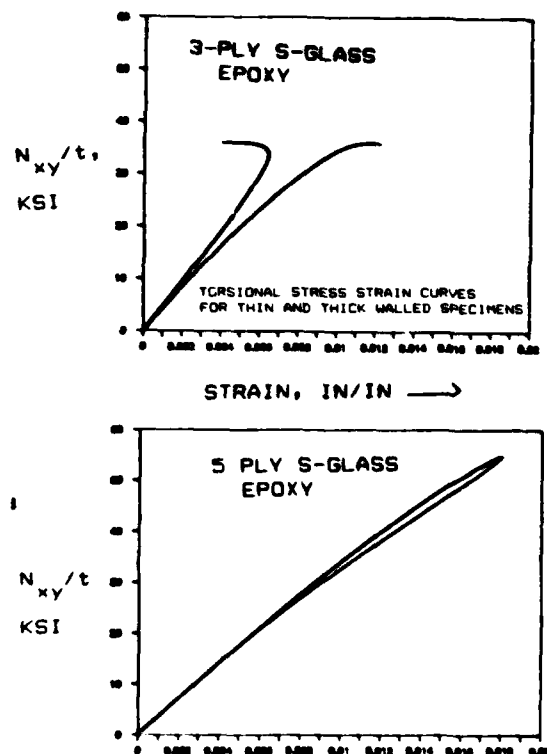
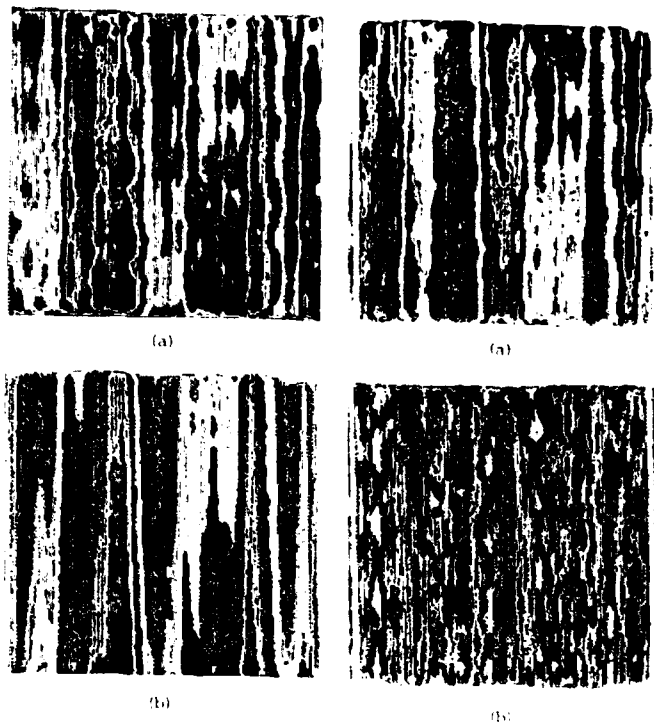


Fig. 9 ENVIRONMENTAL EFFECTS
IN COMPOSITE MATERIALS



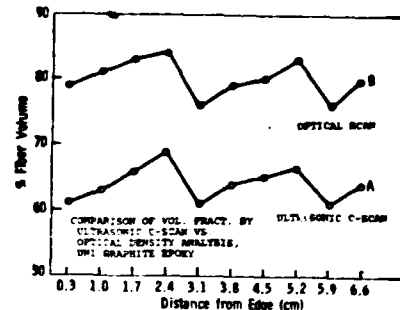
REFERENCES

20. W. Boylance, G. Foley and W. Boughton, "Test Methods for Torsion Testing of Filament Wound Tubes" Proceedings of Second Symposium on Test Methods and Design Allowables for Composites, Phoenix Az, Nov. 1986. To be published.
21. W. Boylance, W. Boughton and D. Dunn, "Effect of Prepreg Aging on Composite Materials", Proceedings of Third International Environmental Degradation of Engineering Materials Conference, Penn. State Univ. April 13-15, 1987. Library of Congress No. 87-80619.



ULTRASONIC SHEAR
DILATATIONAL WAVE
COLORGRAMS

RECONSTRUCTED VOL. FRACT.
AND POROSITY PLOTS



REFERENCES

- 122 J. Gruber, J. M. Smith and R. Brockleman, "Ultrasound C Scans for Ceramic and Composite Materials", to be published, MATERIALS EVALUATION, 1987

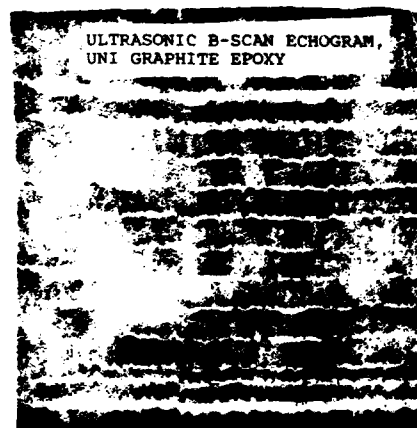
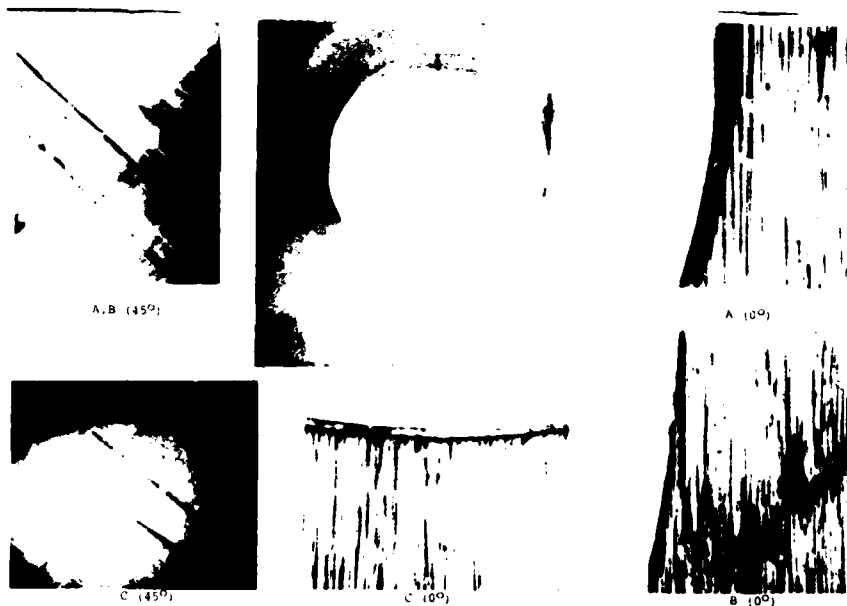
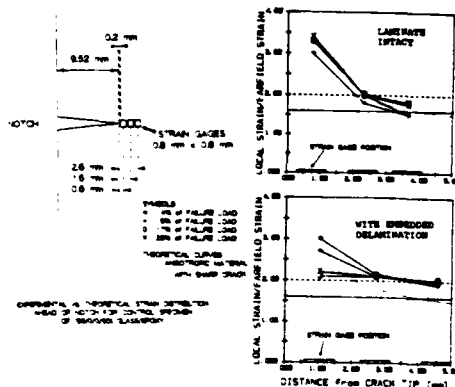


Fig. 10 DEVELOPMENT OF NDE METHODS
FOR COMPOSITES



DAMAGE ZONE MAPPING
BY DEPLOYING IN
0/+, -45/90 BOLTED
JOINT [24]



EMBEDDED STRAIN GAGE
STUDIES IN NOTCHED
LAMINATES (MANDELL &
ECHTERMEYER, MIT)

DAMAGE ZONE CONCEPTS FOR LAMINATES

- LINEAR ELASTIC FRACTURE MECHANICS INAPPROPRIATE FOR COMPOSITES
 - NO SELF SIMILAR CRACKS
 - COMPOSITES RELATIVELY TOUGH IN THE PRESENCE OF CRACK-LIKE NOTCHES
 - LOCAL DAMAGE AROUND STRESS CONCENTRATORS TEND TO BLUNT EFFECTS OF CRACKS
 - CONCEPTS OF "NOTCH SENSITIVITY" (STRENGTH OF NOTCHED LAMINATE/STRENGTH OF UNNOTCHED) PREFERABLE TO FRACTURE-MECHANICS CONCEPTS FOR LAMINATES
 - LAMINATES WITH CRACK-LIKE SLOTS MAY BE LESS NOTCH SENSITIVE THAN LAMINATES WITH CIRCULAR HOLES
- LOCAL DAMAGE AROUND NOTCHES TENDS TO DECOUPLE FIBERS, MAKE SHEAR TRANSFER ABSENT. STRESS CONCENTRATIONS THEREBY MARKEDLY REDUCED
- OBJECTIVE - DEVELOP REPRESENTATION OF PARTIALLY DAMAGED MATERIAL AS A "PLASTIC" ZONE WITH SPECIALLY DEVELOPED CONSTITUTIVE EQUATIONS
- MATERIAL IN THE DAMAGE ZONE MAY BEHAVE LIKE CABLES -- STIFFNESS CHARACTERISTICS SENSITIVE TO LOCAL LARGE ROTATION EFFECTS ("GEOMETRIC STIFFNESS" MATRIX OF A FINITE ELEMENT SYSTEM: SEE F. K. CHANG AND K. Y. CHANG "A PROGRESSIVE DAMAGE MODEL FOR LAMINATED COMPOSITE" JCM 1987)

Fig.11 DAMAGE ZONE STUDIES IN COMPOSITES

FAILURE OF ANGLE PLY LAMINATES [25]

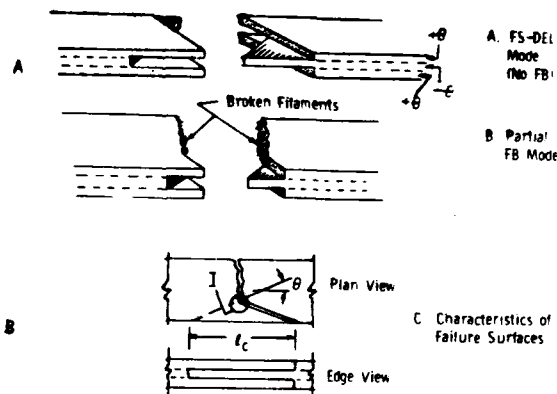


MOD 11/5206 (+45/-45)_S

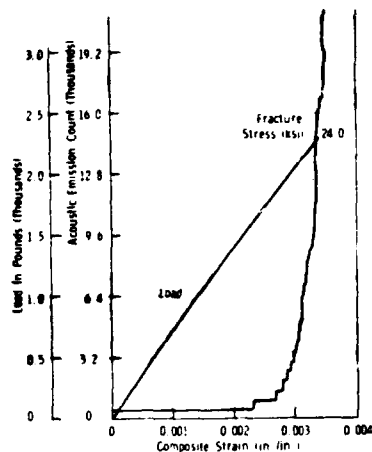


Boron/5505 (+20/-20)_S

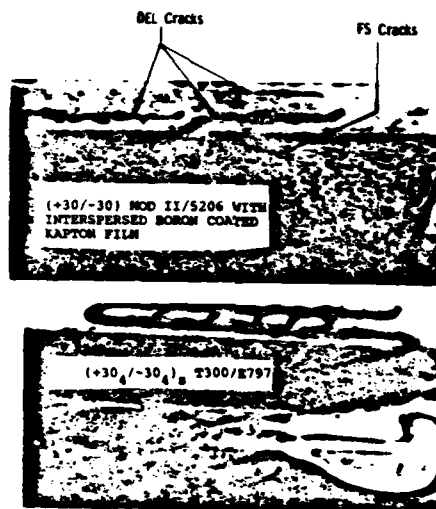
Typical Angle Ply Failures



Characteristic Features of
Failures in Angle Ply Laminates



ACOUSTIC EMISSION COUNT VS. LOAD IN (+30/-30)_s MOD II/5206



DAMAGE IN (+/-)30 GRAPHITE EPOXY LAMINATES AT LOAD SELECTED FROM ACOUSTIC EMISSION TRACE

FAILURE OF ANGLE PLY LAMINATES(cont)

Frame No.

0-148



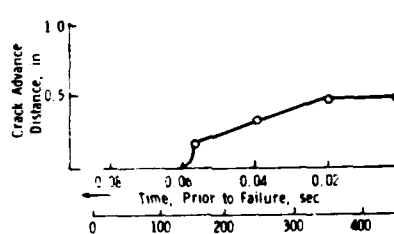
+149



+241



347-460



USE OF MOIRE AT 5000 FRAMES/SEC TO FOLLOW PROGRESSION OF SURFACE CRACK PARALLEL TO FIBERS (+30/-30)_s MOD II/5206

REFERENCES

- [23] P. Steiner, "Damage Zone of Notched Graphite Epoxy Plate" MS Thesis, Ocean Eng. Dept. MIT, 1980
 - [24] T. H. Tsiang and J. F. Mandell "Damage Development in Bolt Bearing in Composite Laminates", AIAA J. v. 23, p. 1570, 1985
 - [25] D. W. Oplinger, B. S. Parker and A. Grenis, AMMRC Solid Mechanics Symposium 1976, AMMRC-MS-76-2, pp. 263-286. 1976
- Notched Graphite Epoxy Plate" MS Thesis, Ocean Eng. Dept. MIT, 1980

PROPOSED DAMAGE DEVELOPMENT MODEL

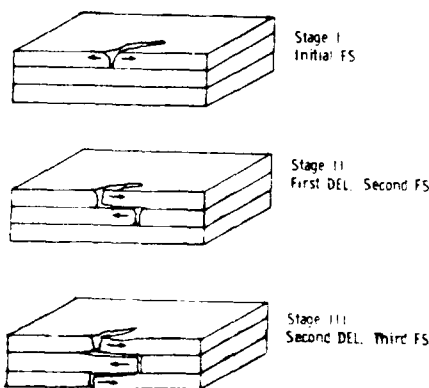


Figure 18 Proposed Model for Development of FS-DEL Damage Zone

CONCEPT OF EFFECTIVE EDGE NOTCH

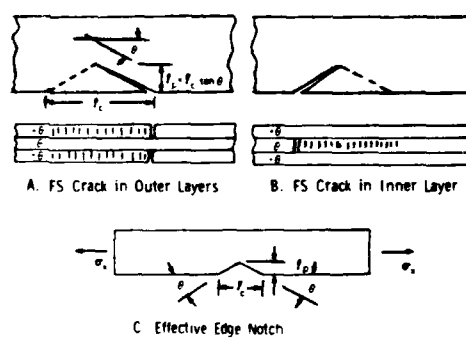


Fig. 11 DAMAGE ZONE STUDIES IN COMPOSITES (cont.)

THREE-DIMENSIONAL ANALYSIS OF A POSTBUCKLED EMBEDDED DELAMINATION

J. D. Whitcomb
NASA Langley Research Center
Hampton, Virginia 23665-5225

ABSTRACT

In recent years there has been increased interest in developing a method for predicting when instability-related delamination growth will occur. The first figure shows the two predominant configurations which have been examined: a laminate with either a through-width delamination or an embedded delamination.

Since the stresses at the delamination front are singular (at least mathematically), calculated stresses there have little meaning. Strain-energy release rates are finite parameters which characterize the intensity of the stresses near the singularity. Hence, most of the efforts to predict instability-related delamination growth are based on strain-energy release rates. For the through-width delamination, both detailed 2-D finite-element and approximate Raleigh-Ritz beam solutions for strain-energy release rate have been obtained. To date, only plate analysis has been applied to the embedded delamination. Plate analysis only yields the total strain-energy release rate (i.e. $G_I + G_{II} + G_{III}$). Ideally, one would like to obtain the magnitude of the individual components. To do so requires geometrically nonlinear three-dimensional finite-element analysis (or some other numerical stress analysis). Three-dimensional finite-element analysis tends to be quite expensive. Since nonlinear analysis requires iteration, nonlinear analysis is even more expensive. It is critical that only the minimum number of elements be used. This is in stark contrast to 2-D or quasi-3-D analysis wherein it is not unusual to inelegantly clobber a problem with many more elements than needed "just to be safe." Since there are no three-dimensional solutions for the postbuckled embedded delamination, there are presently no guidelines as to how detailed a model must be to give reasonable accuracy. Also, once there are reference solutions available, it is possible that reasonably accurate approximate (and less expensive!) analyses will be developed. At present there is no way to determine the accuracy of an approximate analysis.

This paper has several objectives. The first objective is to describe the theoretical aspects of a three-dimensional geometrically nonlinear finite-element program which was developed for this study. The program is named NONLIN3D. Another objective is to document a convergence study. The final objective is to present strain-energy release rate results from a limited parametric study of laminates with a postbuckled delaminated region. Only "homogeneous" quasi-isotropic laminates were considered. The parameters varied were delamination shape, delamination size, depth of the delamination, and modulus.

AD-A197 815

PROCEEDINGS OF THE ANNUAL MECHANICS OF COMPOSITES

2/2

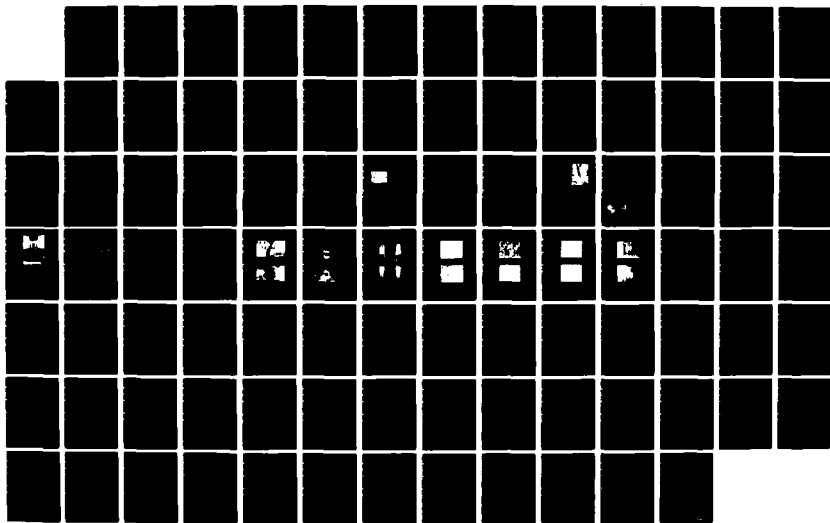
REVIEW (12TH) HELD IN M (U) AIR FORCE WRIGHT
AERONAUTICAL LABS WRIGHT-PATTERSON AFB OH MA

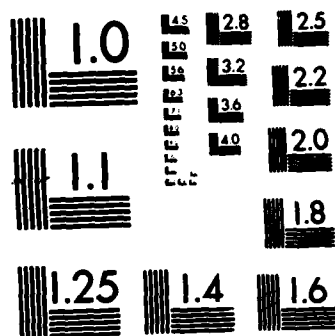
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F/G 11/4

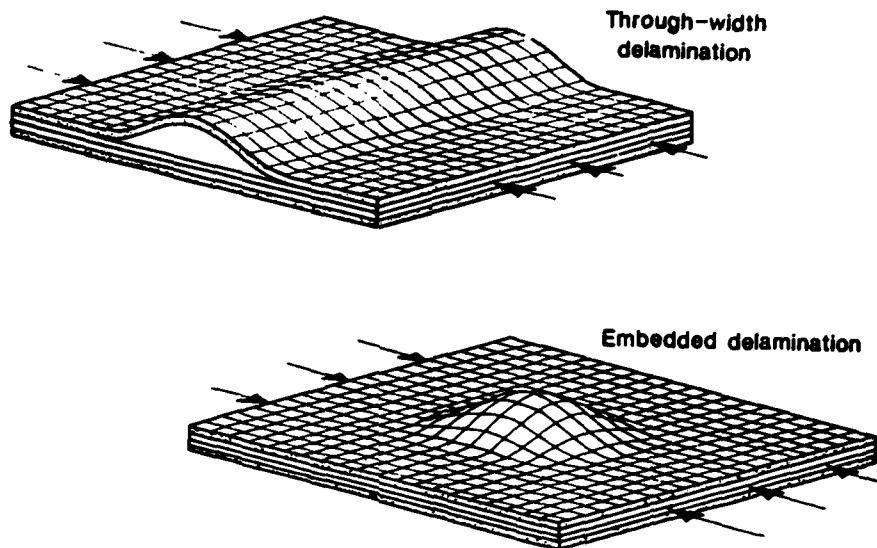
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

INSTABILITY-RELATED DELAMINATION GROWTH



REVIEW OF STATUS

THROUGH-WIDTH DELAMINATION

- * nonlinear beam-column ... G_T
- * nonlinear 2-D finite element ... G_I , G_{II}
- * hybrid superposition ... G_I , G_{II}

EMBEDDED DELAMINATION

- * Rayleigh-Ritz plate analysis (average)
- * finite element plate analysis (distribution)
- * no separation into modes

SCOPE

- * Description of analysis (NONLIN3D)
- * Verification of analysis
- * Analysis of embedded delamination
 - * homogeneous QI laminate
 - * circular and elliptical shapes
 - * G_I , G_{II} , G_{III} , G_T

GOVERNING NONLINEAR EQUATIONS

Total potential energy: $\Pi = \int C_{ij} \epsilon_i \epsilon_j dV - F^\alpha q^\alpha$
 $i, j = 1, 6$
 $\alpha = 1, \# \text{ of DOF}$

Forces: $F^\alpha = \frac{\partial \Pi}{\partial q^\alpha} = \int C_{ij} \epsilon_i \frac{\partial \epsilon_j}{\partial q^\alpha} dV$

Stiffness matrix: $K^{\alpha\beta} = \frac{\partial^2 \Pi}{\partial q^\alpha \partial q^\beta} = \int C_{ij} \frac{\partial \epsilon_i}{\partial q^\alpha} \frac{\partial \epsilon_j}{\partial q^\beta} dV$
 $+ \int C_{ij} \epsilon_j \frac{\partial^2 \epsilon_i}{\partial q^\alpha \partial q^\beta} dV$

NONLINEAR STRAIN - DISPLACEMENT RELATIONS

$$\epsilon_1 = u_x + 1/2 (u_x u_x + v_x v_x + w_x w_x)$$

$$\epsilon_2 = v_y + 1/2 (u_y u_y + v_y v_y + w_y w_y)$$

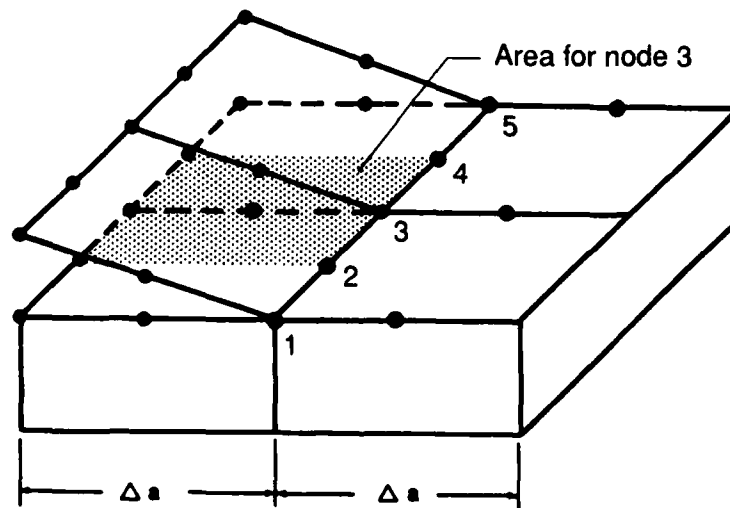
$$\epsilon_3 = w_z + 1/2 (u_z u_z + v_z v_z + w_z w_z)$$

$$\epsilon_4 = u_y + v_x + u_x u_y + v_x v_y + w_x w_y$$

$$\epsilon_5 = v_z + w_y + u_z u_y + v_z v_y + w_z w_y$$

$$\epsilon_6 = u_z + w_x + u_z u_x + v_z v_x + w_z w_x$$

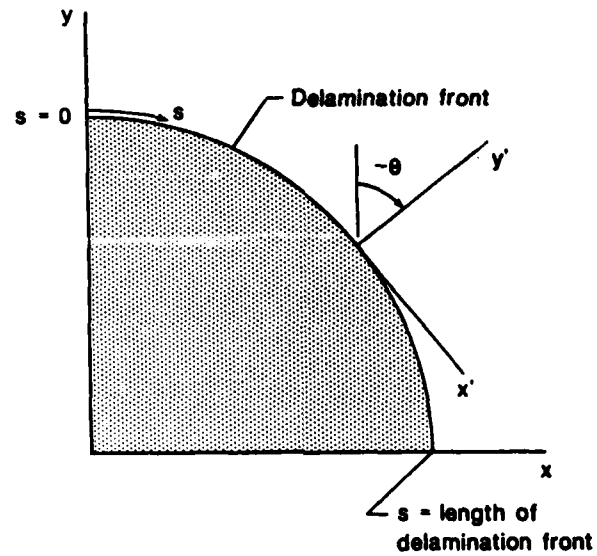
STRAIN-ENERGY RELEASE RATE CALCULATION



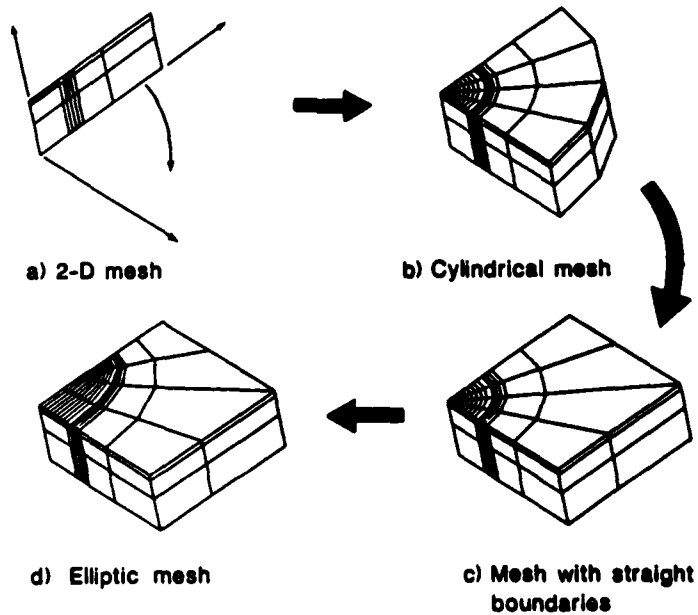
Energy = 1/2 (force) x (relative displacement)

For node 3: $G = [U_3 + 1/2 (U_2 + U_4)] / \text{area}$

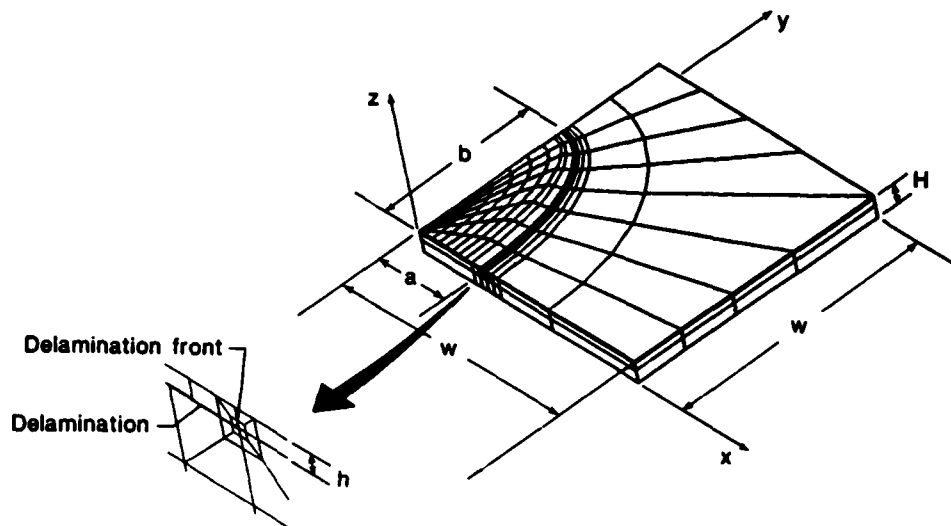
LOCAL COORDINATE SYSTEM



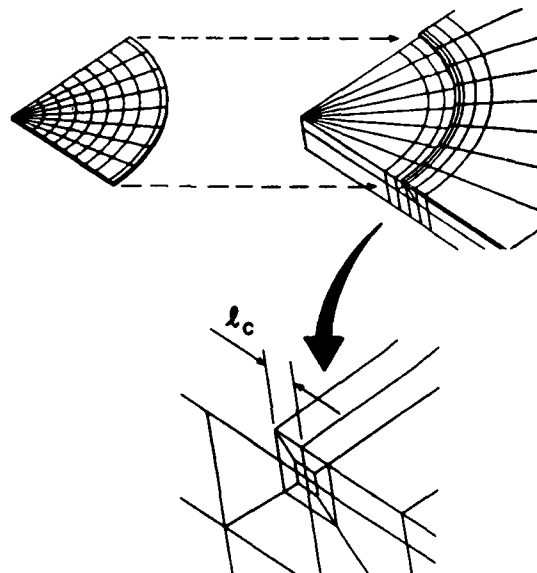
MESH GENERATION



TYPICAL MODEL



SUBSTRUCTURING



MATERIAL PROPERTIES

- Chosen to isolate geometric effects
- "Homogeneous quasi-isotropic laminate"

$$\sigma_i = C_{ij} \epsilon_j$$

$$\overline{C}_{ij} = \frac{1}{n} \sum_{l=1}^n (C_{ij})^l$$

$$E_{11} = 134 \text{ GPa}$$

$$G_{12} = G_{13} = 5.52 \text{ GPa}$$

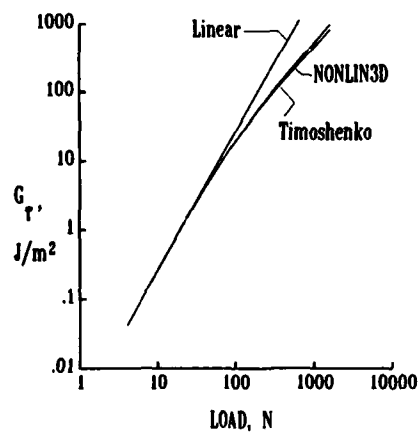
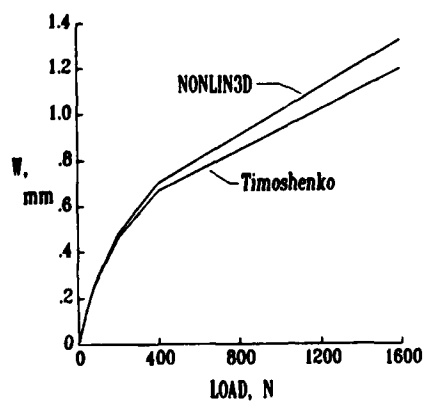
$$E_{22} = E_{33} = 10.2 \text{ GPa}$$

$$G_{23} = 3.43 \text{ GPa}$$

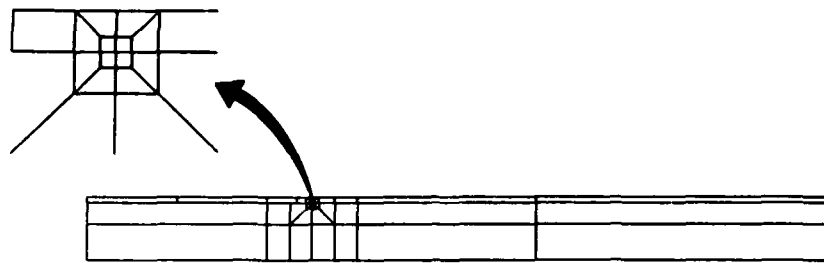
$$\nu_{12} = \nu_{13} = .3$$

$$\nu_{23} = .49$$

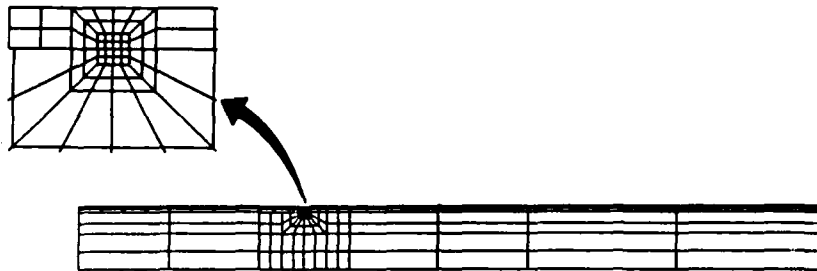
TRANSVERSELY LOADED CIRCULAR PLATE



2-D MESHES FOR CONVERGENCE STUDY

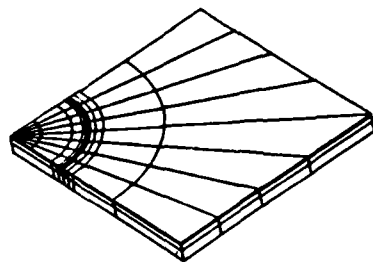


a) Coarse 2-D model (NN = 143)

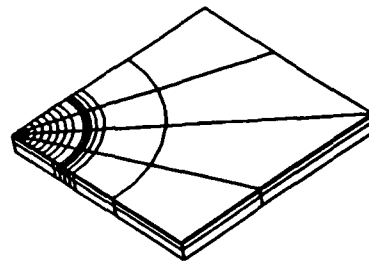


b) Refined 2-D model (NN = 533)

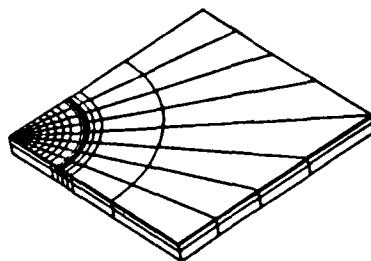
3-D MESHES FOR CONVERGENCE STUDY



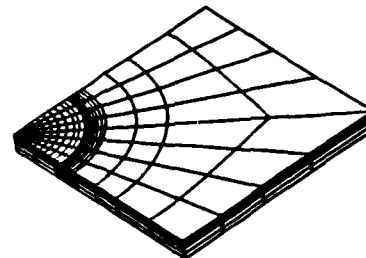
a) Model 1



b) Model 3

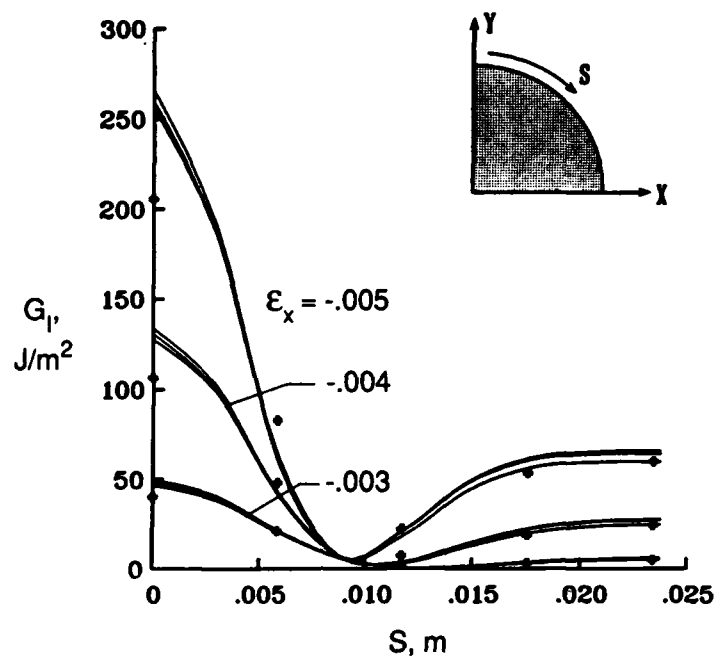


c) Model 4

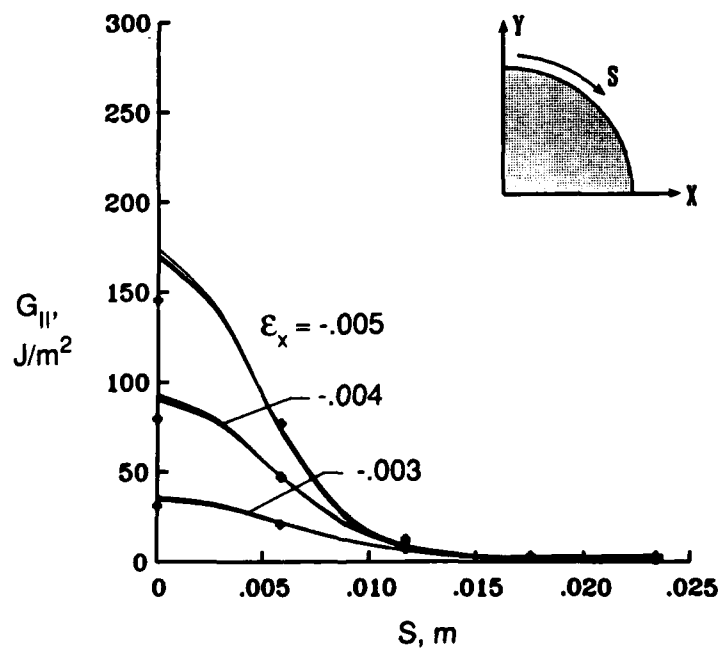


d) Model 6

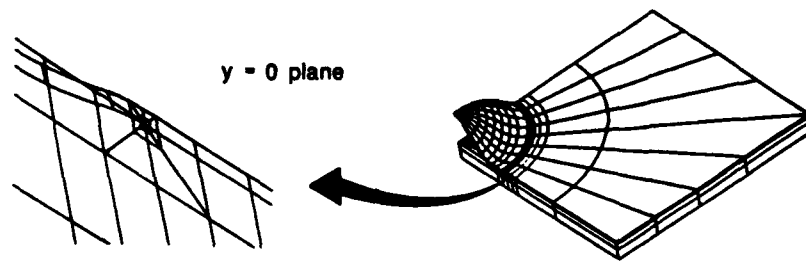
MODE I STRAIN-ENERGY RELEASE RATE



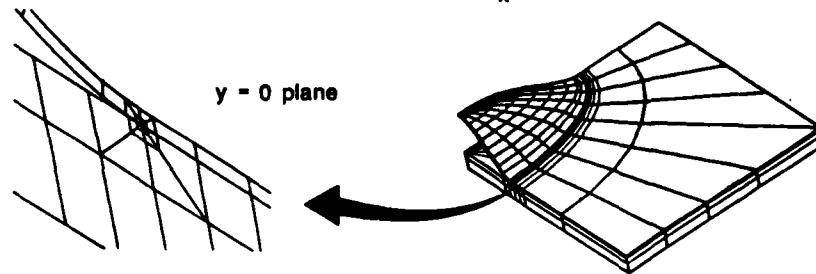
MODE II STRAIN-ENERGY RELEASE RATE



DEFORMED FINITE ELEMENT MODELS



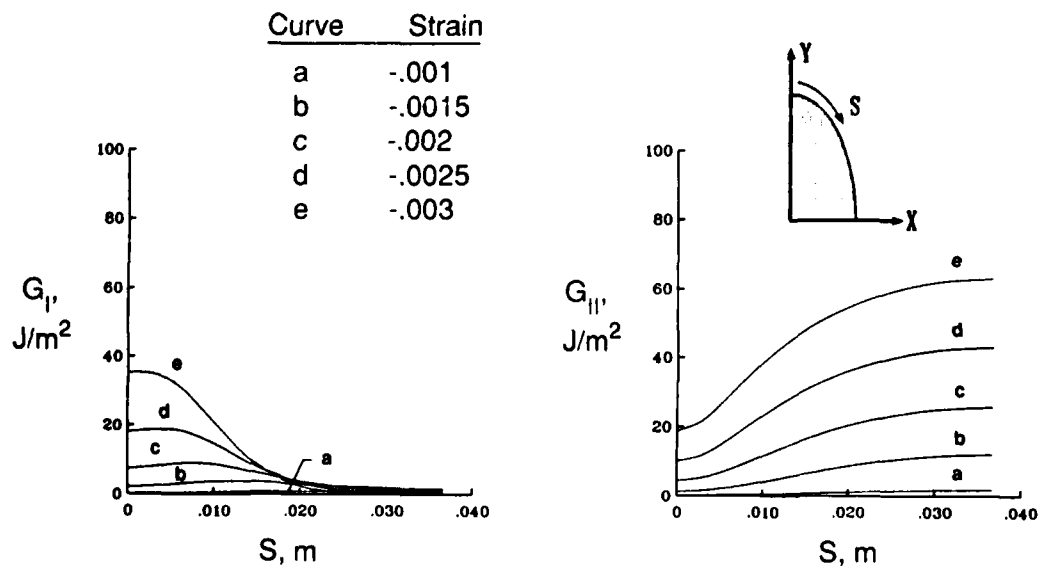
a) Circular delamination ($\epsilon_x = -.005$)



b) Elliptical delamination ($\epsilon_x = -.0015$)

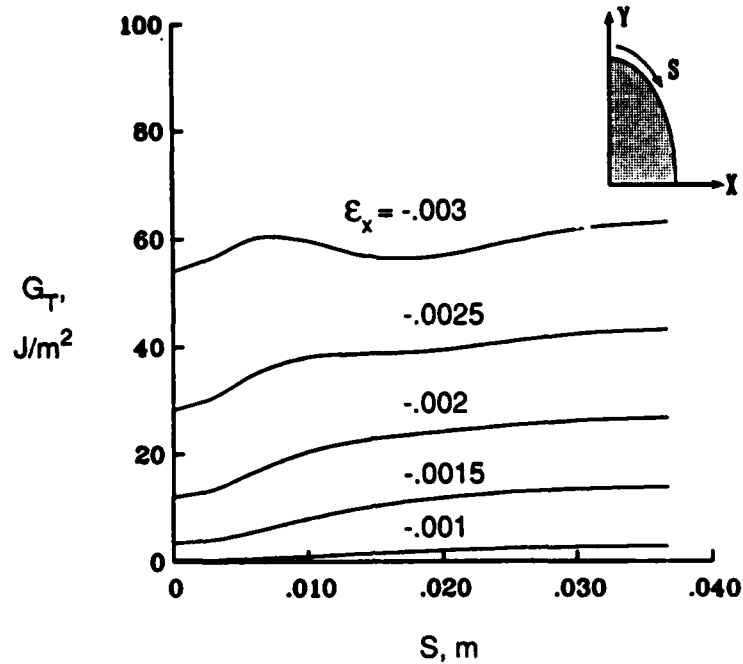
STRAIN-ENERGY RELEASE RATE DISTRIBUTION

($2A \times 2B = 30 \times 60 \text{ mm}$)



STRAIN-ENERGY RELEASE RATE DISTRIBUTION

($2A \times 2B = 30 \times 60 \text{ mm}$)



SUMMARY

- NONLIN3D : nonlinear, substructuring, G-calculation, vectorized
- Parametric analysis of postbuckled delamination
 - Large gradient of G_I and G_{II}
 - Significantly mixed mode
 - Mode mix varies with position along front
 - G_I and G_{II} sensitive to delamination shape
 - G_{III} is negligible
 - Contact analysis needed

POSTBUCKLING ANALYSIS OF COMPOSITE PLATES

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Structures and Dynamics Division
 NASA Langley Research Center
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ABSTRACT

One of the basic elements in a structures is the rectangular flat plate supported at its edges. An orthotropic plate may be constructed to have various extensional and bending properties. Design methods need to be established for orthotropic plates for a variety of structural configurations and loadings. Buckling is an important measure of loading, and it may be advantageous to determine if a plate can carry considerable load beyond buckling.

For linear problems, classical plate theory predicts inplane stresses and deformations which are comparable to those given by three-dimensional elasticity for thin plates of homogenous material. Transverse stresses are generally small compared to the largest inplane stress; however, they can be important when the plate is relatively weak in the transverse direction (through-the-thickness) and when the plate response is sensitive to the transverse stiffness as in buckling and the higher modes of vibration. One of the purposes of the present study is to determine if the plate postbuckling response is sensitive to transverse stiffness.

Results are presented for the postbuckling in compression and in shear for long rectangular plates made of aluminum and $\pm 45^\circ$ graphite epoxy, respectively. Curves were obtained from both classical and conventional transverse shearing theory for simply supported plates with four different inplane boundary conditions. The inplane conditions are that the average normal displacement or force is zero and the edges are either held straight or are unrestrained. The aluminum plate results were based on plates with thickness $h = .1$ inches, width $b = 10$ inches, with Young's modulus $E = 10.7 \times 10^6$ psi and Poisson's ratio $\mu = .33$. The $\pm 45^\circ$ graphite-epoxy laminate considered has the thickness $h = .1$ inches and width $b = 10$ inches and the following properties: (The units of the bending stiffnesses D 's are inch-pounds/inch and the units of the extensional stiffnesses A 's are pounds/inch.)

$$\begin{aligned}
 D_{11} = D_{22} &= .5186 \times 10^3 & A_{11} = A_{22} &= .62034 \times 10^6 \\
 D_{12} &= .37291 \times 10^3 & A_{12} &= .44606 \times 10^6 \\
 D_{66} &= .40423 \times 10^3 & A_{66} &= .48352 \times 10^6 \\
 & & A_{44} = A_{55} &= .59 \times 10^5
 \end{aligned}$$

The derivation of the equations to be solved using classical (Kirchhoff) theory has been presented in references 1 and 2. The derivation of equations using conventional transverse shearing theory follows similarly. Using both theories allows one to decide which approximation is needed for the range of variables considered. To get to classical theory from conventional transverse shearing theory requires that the rotations u^a/h , v^a/h be replaced by the slopes $-w^o_{,x}$, $-w^o_{,y}$, respectively, so that the transverse shearing strains vanish. In the analysis it is assumed that the deformations are sinusoidally periodic with half-wavelength $\lambda/2$ and for compressive loading the longitudinal displacement u has an extra linear-in- x term associated with the constant U which is the specified applied displacement. For shear loading the applied displacements are specified through boundary conditions on u . The equations give exact values at buckling. The value of λ of interest for the infinitely long plates considered here is the one that corresponds to minimum load and the solution of interest beyond buckling is on the equilibrium path that gives nonzero deflections.

Numerical postbuckling results are presented based on classical theory and conventional transverse shearing theory for long, simply-supported, aluminum and $\pm 45^\circ$ graphite-epoxy composite plates loaded in longitudinal compression or in inplane shear with 4 different inplane boundary conditions. Characteristic curves are given which indicate the average load corresponding to applied displacement. The slopes of these

curves at any point represent the stiffness at this loading. The maximum stress resultants N_x , N_y , N_{xy} and the maximum deflection are plotted for the range of loading considered. For compression loading, the effective width ratio b_{eff}/b which is equal to the ratio of N_{xav} from the characteristic curve to N_{xmax} from the maximum N_x stress curve is also presented. For compression loading essentially identical results were obtained from classical theory and conventional transverse shearing theory. For shear loading there are some differences using the two theories, the maximum differences occurred for the boundary condition denoted 3 where the average stress resultant N_y is zero and the edges are held straight and the differences even for this case is small as indicated by the curves (see reference 3, also).

REFERENCES

1. Stein, M.: Postbuckling of Long Orthotropic Plates in Combined Shear and Compression. AIAA Journal, Vol. 23, No. 5, May 1985, pp. 788-794.
2. Stein, M.: Analytical Results for Post-Buckling Behaviour of Plates in Compression and in Shear. Aspects of the Analysis of Plate Structures. Edited by D. L. Dawe, et. al., Clarendon Press, Oxford, 1985, pp. 205-233.
3. Stein, M.: Effects of Transverse Shearing Flexibility on the Postbuckling of Plates Loaded by Inplane Shear. AIAA Paper No. 87-0866-CP, April 1987.

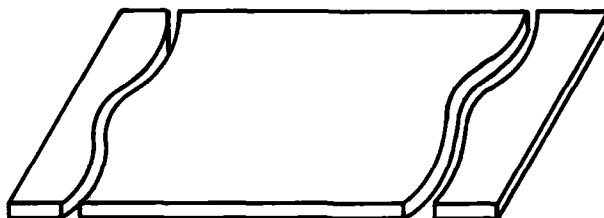
POSTBUCKLING ANALYSIS OF COMPOSITE PLATES

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POSTBUCKLING OF LONG RECTANGULAR PLATES



Two-dimensional problem is reduced to one dimension by assuming sinusoidal deformations in the long direction and by varying energy, to obtain a set of nonlinear ordinary differential equations for each theory considered

The equations subject to the boundary conditions are solved by Newton's method and then finite differences

The wave length of the assumed deformations is chosen to minimize the energy (or the average load) for each given applied deformation

SUMMARY

Postbuckling results are presented based on classical theory and conventional transverse shearing theory for long, simply-supported aluminum and $\pm 45^\circ$ graphite-epoxy composite plates loaded in longitudinal compression or in inplane shear with 4 different inplane boundary conditions

Transverse shearing theory is not needed for the thin plates ($b/h \geq 100$) and the range of loading considered

The stiffness of plates in compression is insensitive to the inplane boundary conditions while N_y and N_{xy} stresses and the deflection are sensitive

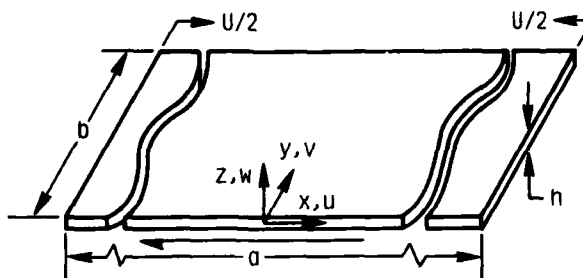
The stiffness of plates in shear is sensitive to the inplane boundary conditions while N_x and N_y stresses and the deflection are a little less sensitive

SINUSOIDAL DISPLACEMENTS AND BOUNDARY CONDITIONS CONSIDERED FOR COMPRESSION LOADING

$$u = u^0 + \frac{z}{h} u^a$$

$$v = v^0 + \frac{z}{h} v^a$$

$$w = w^0$$



where

$$u^0 = -U \frac{x}{a} + u_S^0(y) \sin \frac{2\pi x}{\lambda}$$

$$u^a = u_C^a(y) \cos \frac{\pi x}{\lambda}$$

$$v^0 = v_O^0(y) + v_C^0(y) \cos \frac{2\pi x}{\lambda}$$

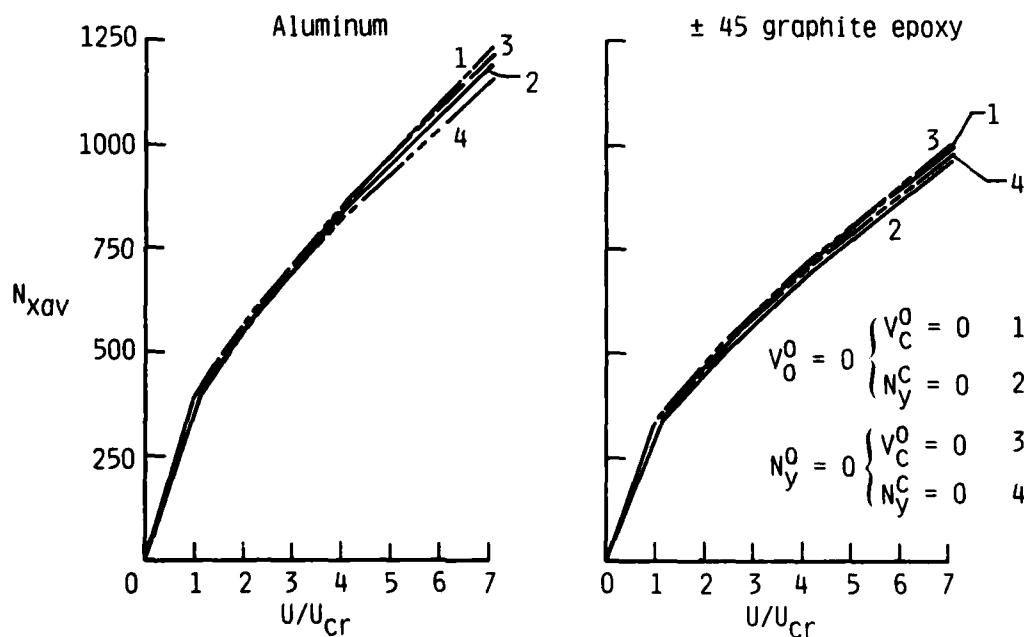
$$v^a = v_S^a(y) \sin \frac{\pi x}{\lambda}$$

$$w^0 = w_S^0(y) \sin \frac{\pi x}{\lambda}$$

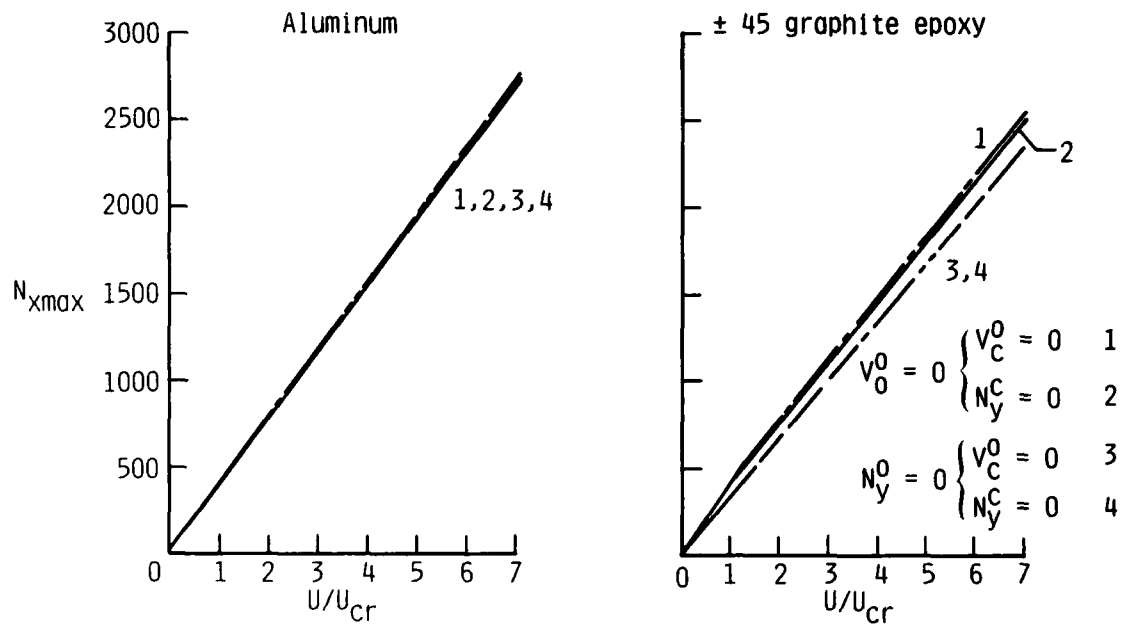
and at $y = 0, b$

$$u_S^0 = u_C^a = w_S^0 = M_y^S = \begin{cases} v_O^0 \\ \text{or} \\ N_y^0 \end{cases} = \begin{cases} v_C^0 \\ \text{or} \\ N_y^C \end{cases} = 0$$

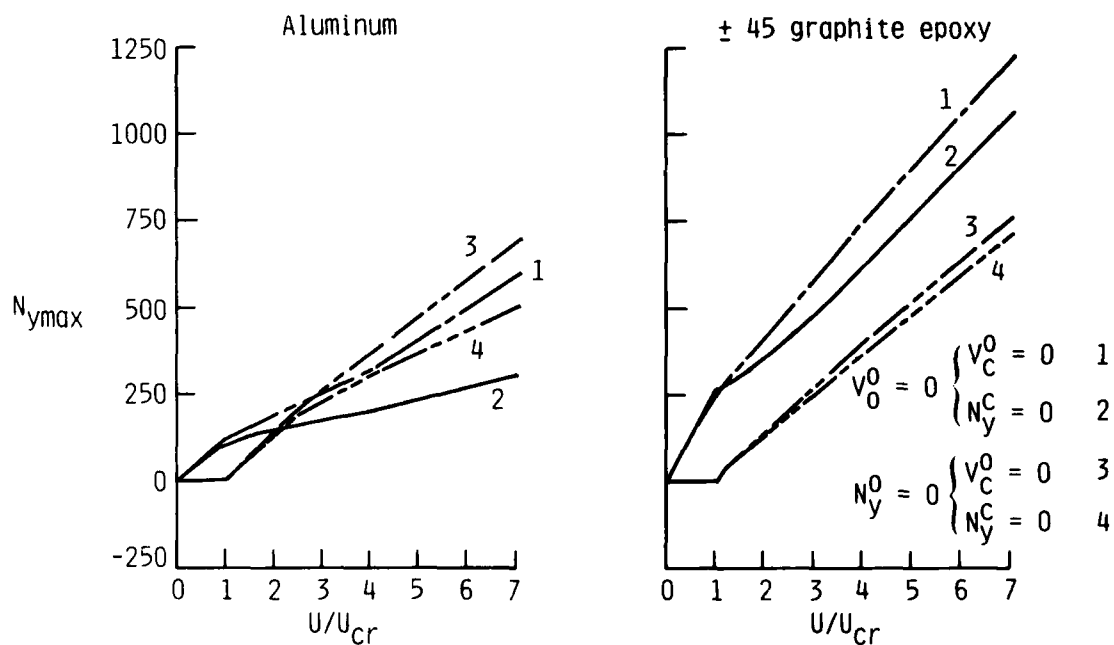
CHARACTERISTIC CURVES FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN COMPRESSION



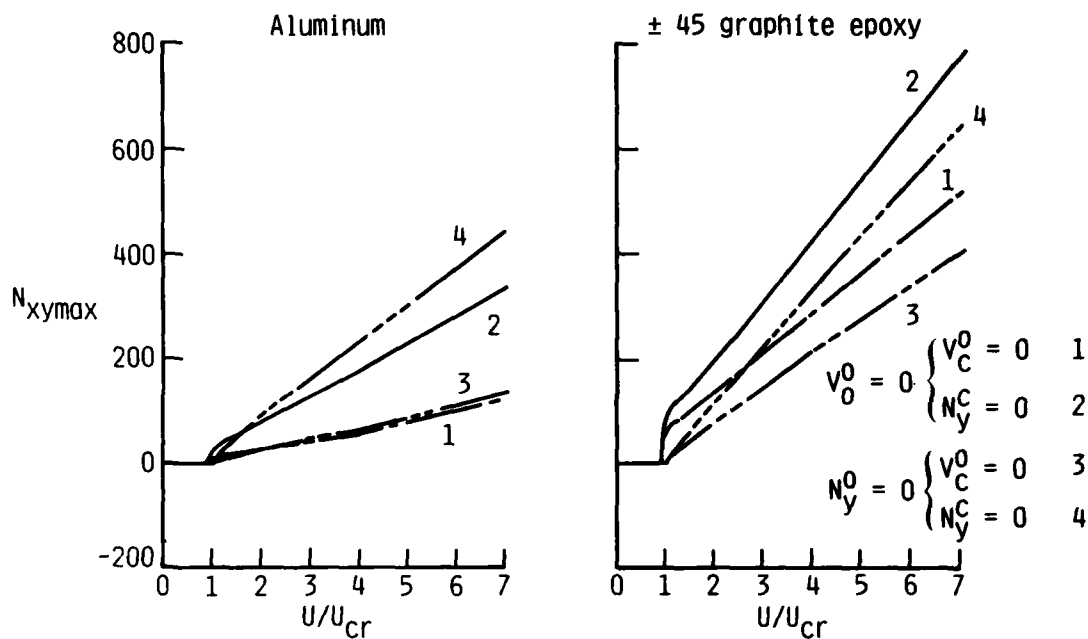
MAXIMUM N_x STRESS FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN COMPRESSION



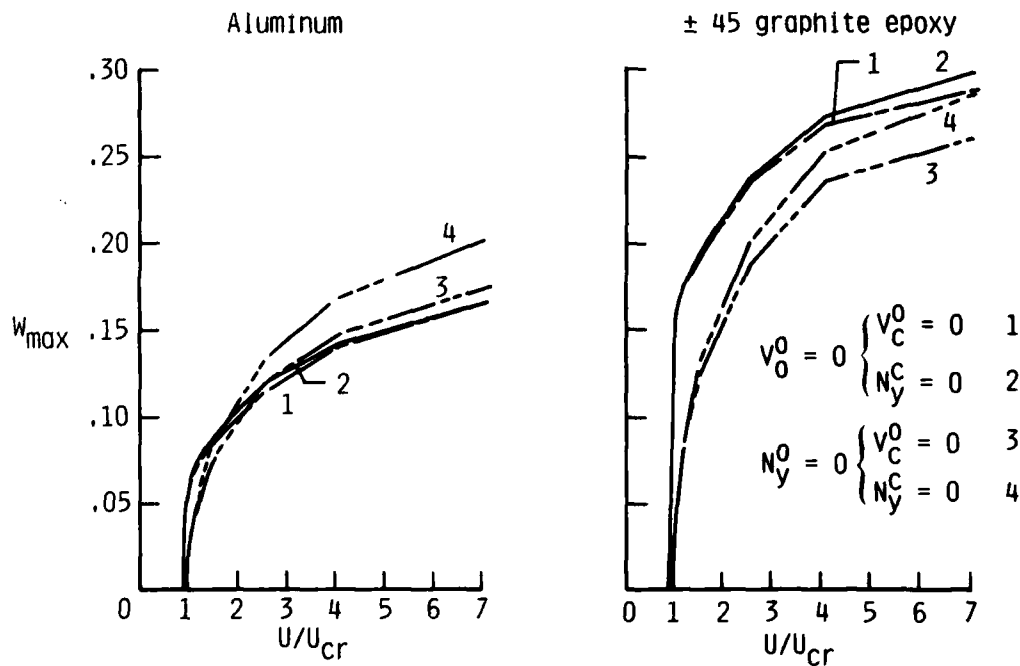
MAXIMUM N_y STRESS FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN COMPRESSION



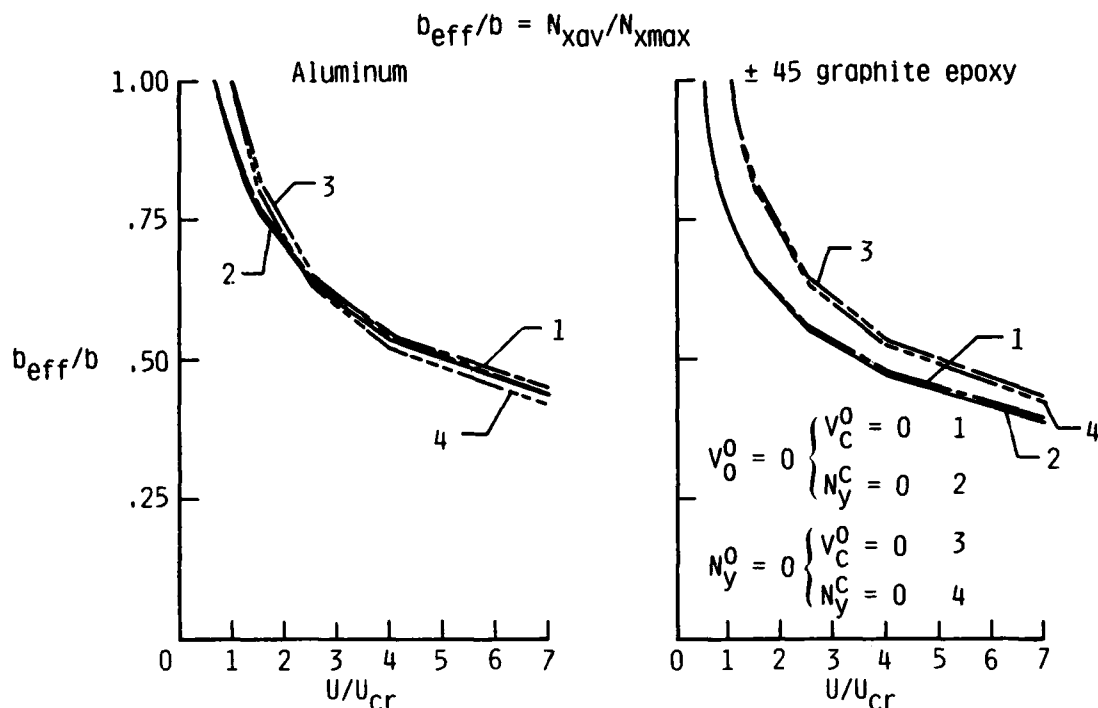
MAXIMUM N_{xy} STRESS FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN COMPRESSION



MAXIMUM DEFLECTION FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN COMPRESSION



EFFECTIVE WIDTH FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN COMPRESSION

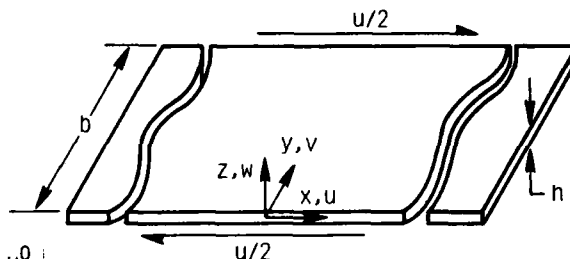


SINUSOIDAL DISPLACEMENTS AND BOUNDARY CONDITIONS CONSIDERED FOR SHEAR LOADING

$$u = u^0 + \frac{z}{h} u^a$$

$$v = v^0 + \frac{z}{h} v^a$$

$$w = w^0$$



where

$$\begin{Bmatrix} u^0 \\ v^0 \end{Bmatrix} = \begin{Bmatrix} u_0^0 \\ v_0^0 \end{Bmatrix} + \begin{Bmatrix} u_S^0 \\ v_S^0 \end{Bmatrix} \sin \frac{2\pi x}{\lambda} + \begin{Bmatrix} u_C^0 \\ v_C^0 \end{Bmatrix} \cos \frac{2\pi x}{\lambda}$$

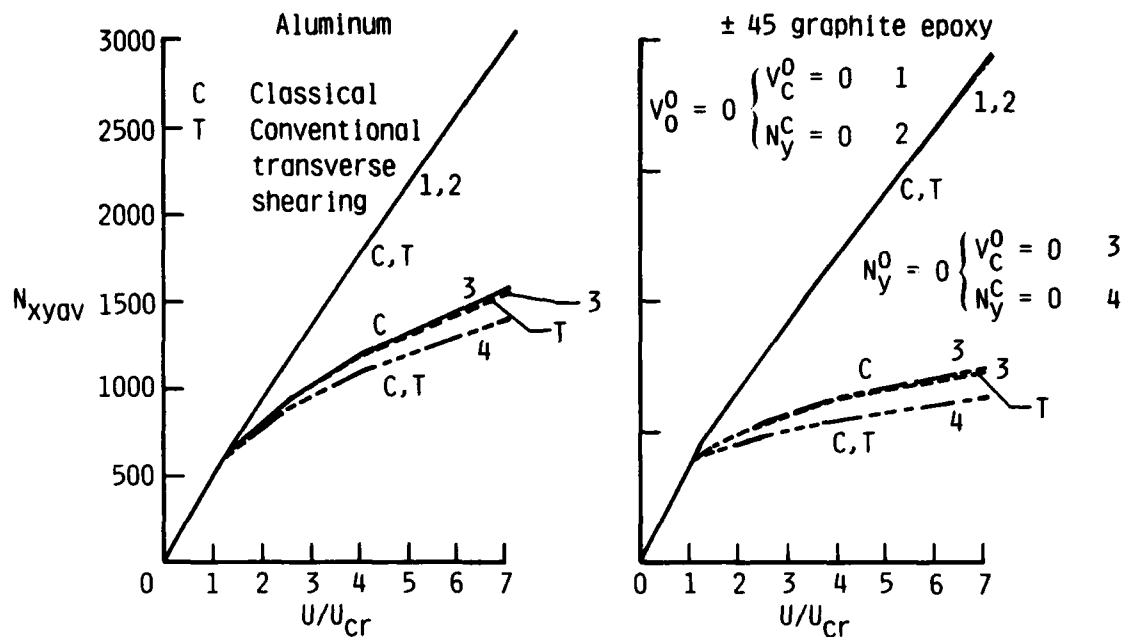
$$\begin{Bmatrix} u^a \\ v^a \\ w^0 \end{Bmatrix} = \begin{Bmatrix} u_S^a \\ v_S^a \\ w_0^0 \end{Bmatrix} \sin \frac{\pi x}{\lambda} + \begin{Bmatrix} u_C^a \\ v_C^a \\ w_0^0 \end{Bmatrix} \cos \frac{\pi x}{\lambda}$$

and at $y = 0, b$

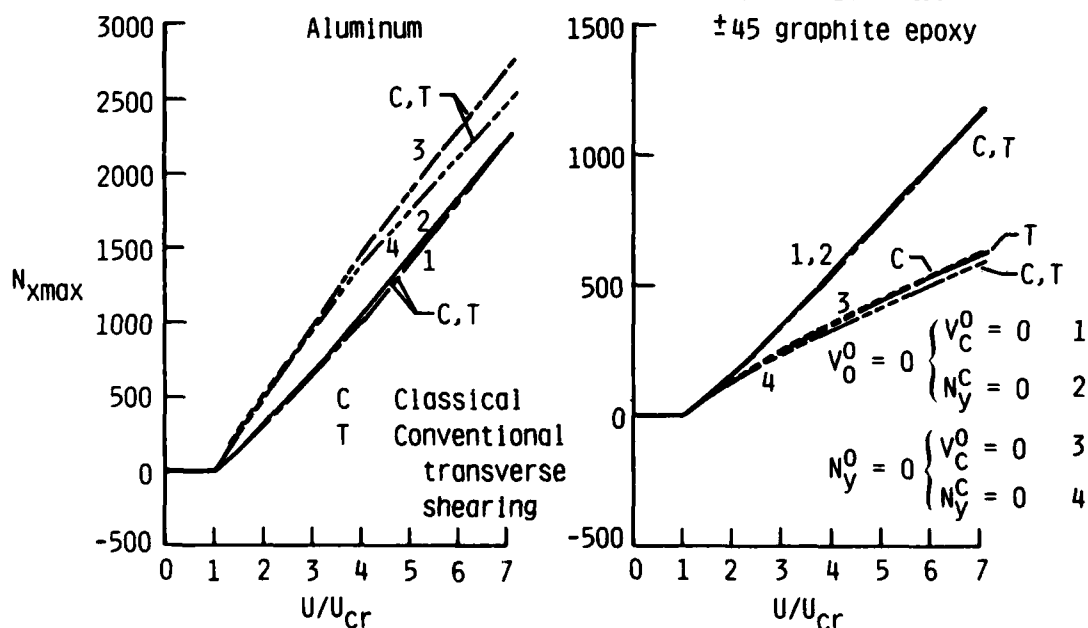
$$u_0^0 = \pm U/2; u_S^0 = u_C^0 = u_S^a = u_C^a = w_0^0 = w_C^0 = M_y^S = M_y^C = 0$$

$$\begin{Bmatrix} v_0^0 \\ \text{or} \\ N_y^0 \end{Bmatrix} = 0 \quad \begin{Bmatrix} v_S^0 = v_C^0 \\ \text{or} \\ N_y^S = N_y^C \end{Bmatrix} = 0$$

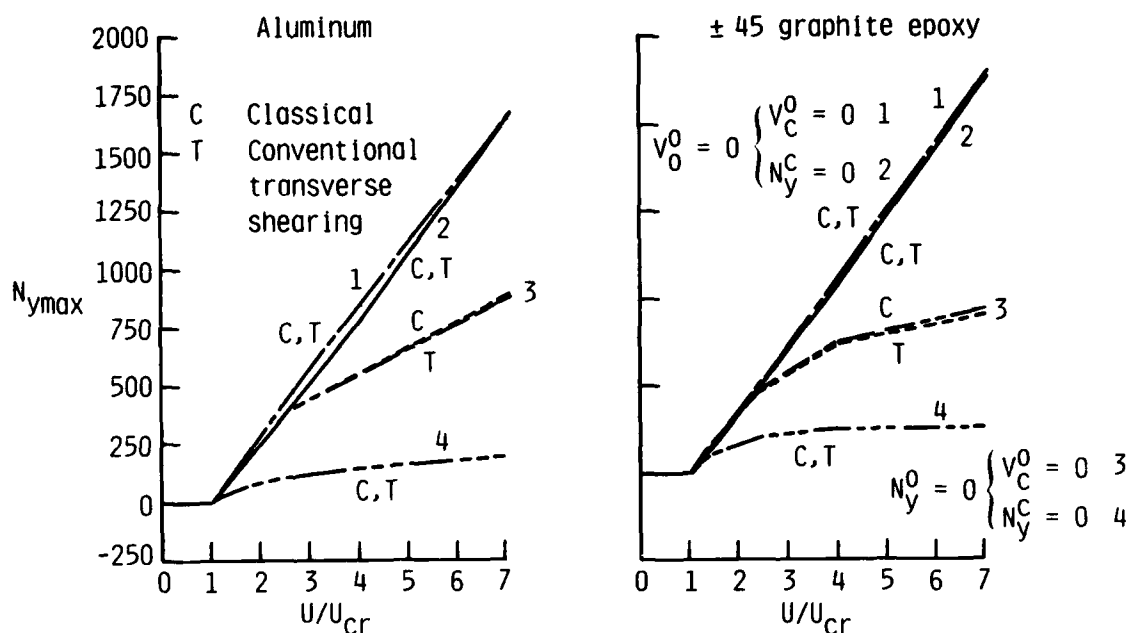
CHARACTERISTIC CURVES FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN SHEAR



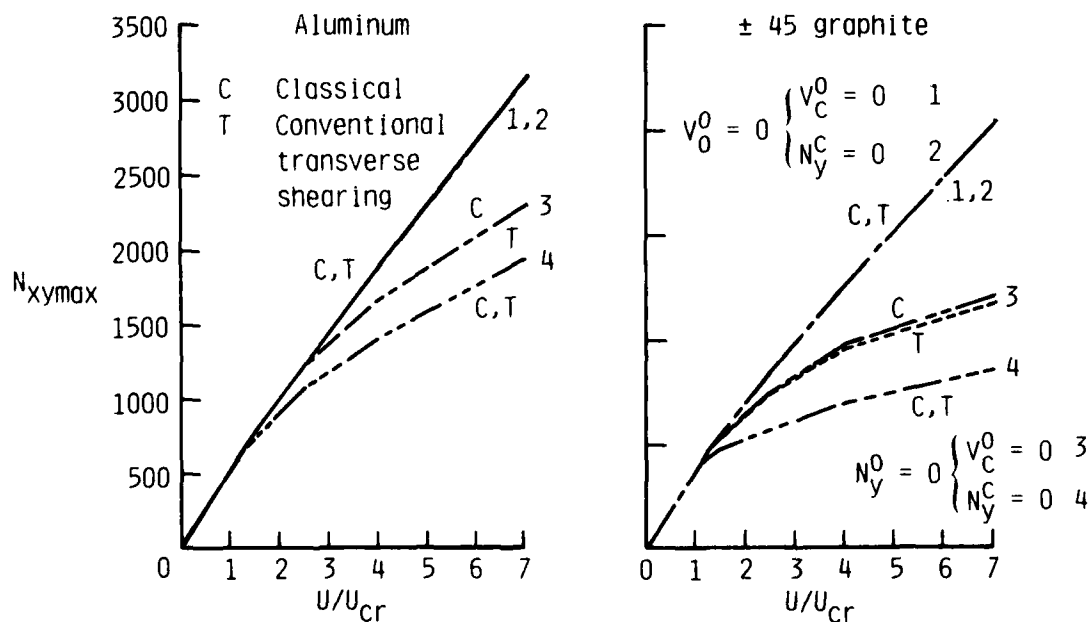
MAXIMUM N_x STRESS FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN SHEAR



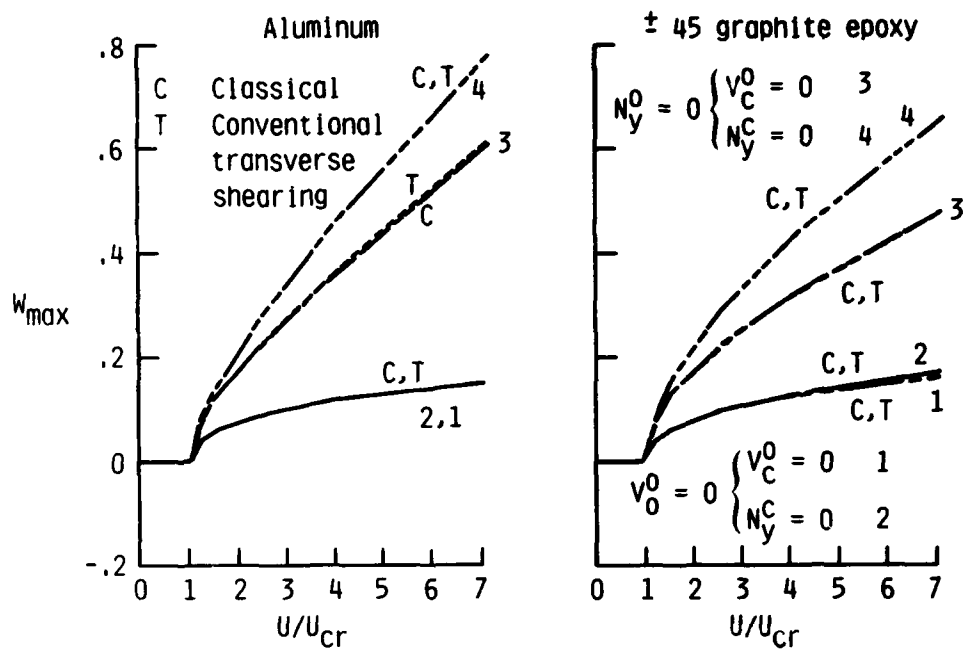
MAXIMUM N_y STRESS FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN SHEAR



MAXIMUM N_{xy} STRESS FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN SHEAR



MAXIMUM DEFLECTION FOR POSTBUCKLING OF LONG RECTANGULAR PLATES IN SHEAR



CERTIFICATION OF COMPOSITE STRUCTURES
USING THE LOAD ENHANCEMENT FACTOR APPROACH

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ABSTRACT

The use of fatigue scatter factors of 2-4 for metallic structures has historically been related to a reliability of approximately 699 in 700. Use of these scatter factors for composites cannot be justified because the scatter observed for composite fatigue life is extremely large. An extensive statistical data scatter analysis was conducted in Reference 1. The spectrum fatigue life Weibull shape parameter for composites ($\alpha = 2.17$) is significantly lower than for aluminum ($\alpha = 7.70$). This indicates that composite fatigue life data exhibits significantly more scatter than aluminum data. The reliability obtained from a two lifetime composite fatigue test will, therefore, be significantly lower than for aluminum. For $\alpha = 1.25$, the reliability demonstrated at one lifetime for a single article fatigue test to two test lifetimes is approximately 0.3. This is an unacceptably low value. The fatigue test lifetimes required to demonstrate B-basis reliability at one lifetime for $\alpha = 1.25$ is approximately 14 for a single test article. The use of such large life factors in certification programs is not economically feasible. An alternative load enhancement factor approach is discussed below which can demonstrate adequate reliability with significantly reduced test times.

The objective of the load enhancement factor (LEF) approach for fatigue life certification is to increase the applied loads in the fatigue test so that the same level of reliability can be achieved with a shorter test duration. If the maximum applied load in the fatigue test (P_T) is increased to a mean residual strength at one lifetime (P_R), then the B-basis residual strength of the structure would be equivalent to the design maximum fatigue stress. Thus, a successful fatigue test to one lifetime at applied stress P_T or a fatigue test to failure at applied stress P_R would both demonstrate B-basis reliability. In addition, combinations of the load enhancement and fatigue life factors could also be used to demonstrate B-basis life. In order to use this approach with confidence in a certification methodology, a formal relationship between the load enhancement factor and the life factor is required. The rigorous mathematical formulation of the load enhancement factor was presented in Reference 1.

There are three ways to demonstrate B-Basis reliability:

- (a) Load enhancement
- (b) Life factor
- (c) Combined load enhancement and life factors

The relationships between load enhancement factors and life factor have been determined for various combinations of α_L , α_R and n . These relationships can be used to specify test or design life requirements for composite structures.

The Sendekyj fatigue data analysis method can also be used to calculate load enhancement factors from experimental fatigue data. The Sendekyj analysis is described in Reference 2. This method of analysis was used in Reference 3 to obtain load enhancement factors from experimental data. The mathematical relationship for LEF's developed here was also used to check the accuracy of LEF's calculated by the Sendekyj analysis. Excellent agreement between the two methods was demonstrated. It can, therefore, be concluded that the Sendekyj analysis provides good estimates of LEF's from experimental data. This indicates that the assumptions made in the Sendekyj fatigue analysis method are valid.

REFERENCES

1. Whitehead, R.S., Kan, H. P., Cordero, R. and Saether, E. S., "Certification Testing Methodology for Composite Structures," Vol. I and II. Final Report, NADC Contract No. N62269-84-C-0243, October 1986.
2. Sendekyj, G. P., "Fitting Models to Composite Materials Fatigue Data," ASTM STP 734, 1981, pp. 245-260.
3. Whitehead, R. S., and Schwartz, M. G., "The Role of Fatigue Scatter in the Certification of Composite Structures," presented at the ASTM Symposium on the Long Term Behavior of Composites, Williamsburg, Virginia, March 1982.

ACKNOWLEDGEMENT

The work reported here was performed under NADC Contract No. N62269-84-C-0243. Mr. Ed Kautz was the Navy project engineer.

CERTIFICATION OF COMPOSITE STRUCTURES USING THE LOAD ENHANCEMENT FACTOR APPROACH

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DR. ROBIN S. WHITEHEAD**

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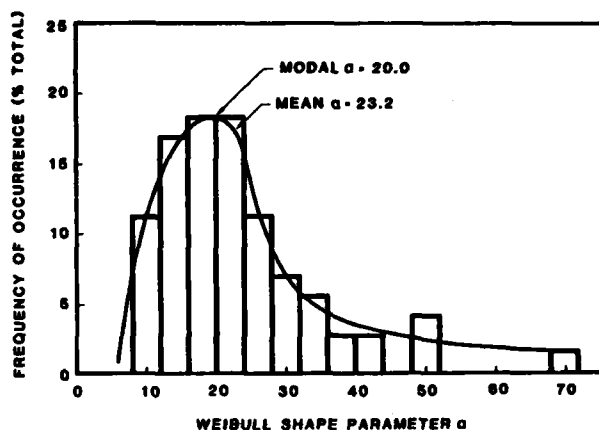
OBJECTIVE

**INCREASE THE APPLIED LOADS IN FATIGUE
CERTIFICATION TESTS SO THAT THE SAME
LEVEL OF RELIABILITY CAN BE ACHIEVED
WITH A SHORTER TEST DURATION**

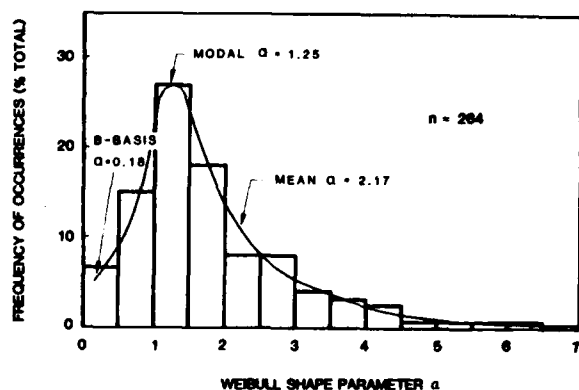
APPROACH

- DETERMINE WEIBULL DISTRIBUTIONS FOR BOTH FATIGUE LIFE AND RESIDUAL STATIC STRENGTH DATA
- RELATE THE STRENGTH AND LIFE DISTRIBUTIONS SO THAT THE RELIABILITY ACHIEVED FROM THE LOAD ENHANCEMENT FACTOR APPROACH WITH A SHORTER TEST DURATION IS THE SAME AS THE LIFE FACTOR APPROACH

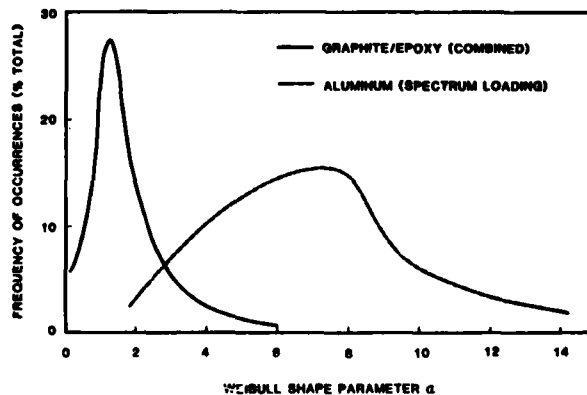
STATIC STRENGTH SCATTER DISTRIBUTION



FATIGUE LIFE SCATTER DISTRIBUTION



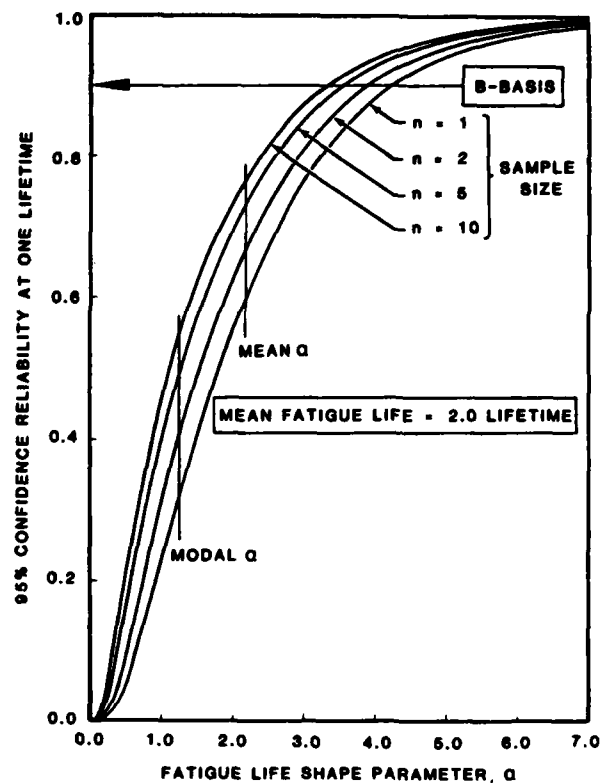
FATIGUE LIFE SCATTER DISTRIBUTION



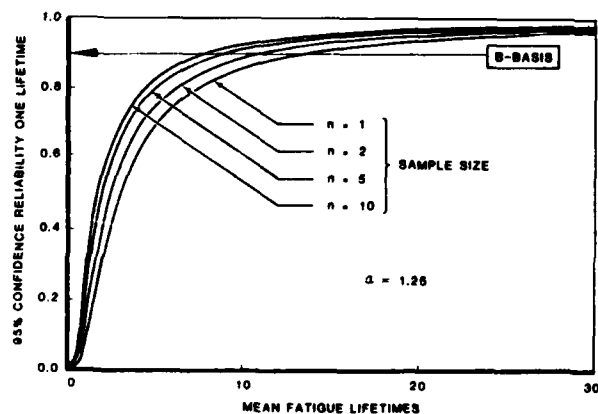
DATA SCATTER SUMMARY

MATERIAL	WEIBULL SHAPE PARAMETER			
	STATIC STRENGTH		SPECTRUM FATIGUE LIFE	
	MEAN	MODAL	MEAN	MODAL
GRAPHITE/EPOXY	23.2	20.0	2.17	1.25
ALUMINUM	35		7.70	7.50

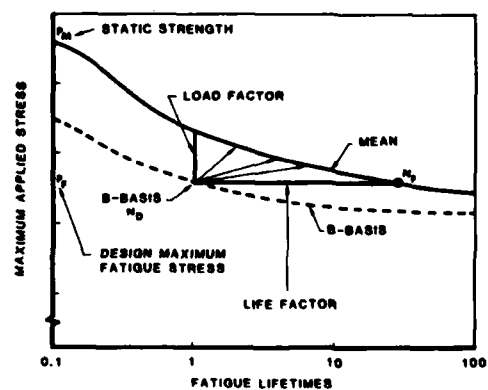
FATIGUE RELIABILITY vs FATIGUE SCATTER



FATIGUE REALIABILITY vs TEST LIFE



LOAD ENHANCEMENT FACTOR APPROACH



FORMULATION

- DETERMINE B-BASIS (OR A-BASIS) LIFE FACTOR FROM LIFE DISTRIBUTION
- DETERMINE B-BASIS (OR A-BASIS) AND MEAN RESIDUAL STATIC STRENGTH AFTER A SPECIFIED TEST DURATION (N)
- LOAD ENHANCEMENT FACTOR

$$F = \frac{P_T}{P_F} = \frac{\mu P_T}{N_R}$$

P_T IS THE MEAN RESIDUAL STRENGTH

P_F IS THE MAXIMUM FATIGUE STRESS

N_R IS THE B (OR A)-BASIS RESIDUAL STRENGTH

μ IS A COEFFICIENT SO THAT $F = 1.0$ AS $N = N_F$

FORMULATION (Continued)

- DETERMINE THE COEFFICIENT USING THE END CONDITION
 $F = 1.0$ AS $N = N_F$

$$\mu = \frac{[\Gamma(1 + 1/\alpha_L)]^{\alpha_L/\alpha_R}}{\Gamma(1 + 1/\alpha_R)}$$

α_L, α_R ARE THE WEIBULL SHAPE PARAMETERS FOR LIFE AND RESIDUAL STRENGTH, RESPECTIVELY

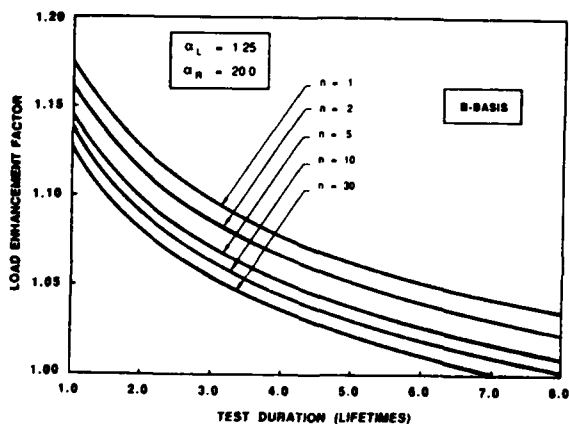
- DETERMINE THE LOAD ENHANCEMENT FACTOR

$$F = \frac{\mu \Gamma(1 + 1/\alpha_R)}{\left[\frac{-\ln(p)}{\chi^2_{(2n)} / (2n)} \right]^{1/R}}$$

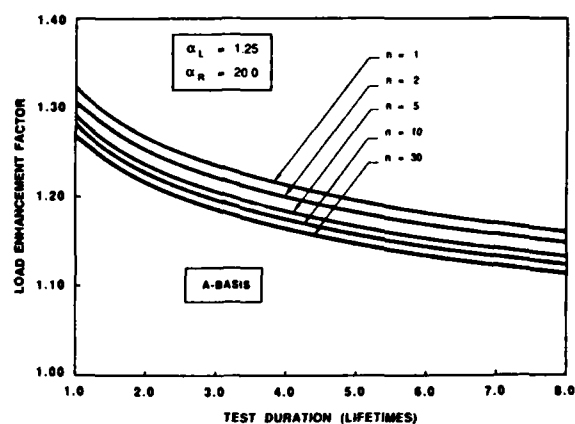
WITH $p = \text{EXP}[\ln(R)N^{\alpha_L}]$

R IS THE REQUIRED RELIABILITY

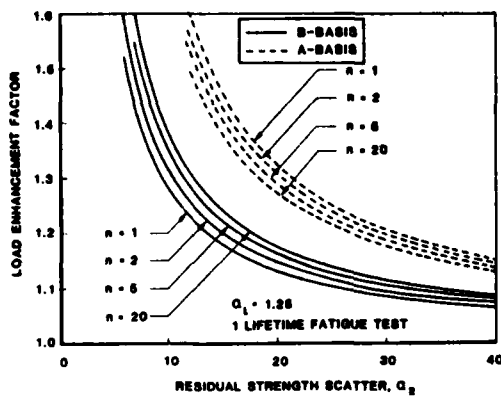
B-BASIS LOAD ENHANCEMENT FACTORS



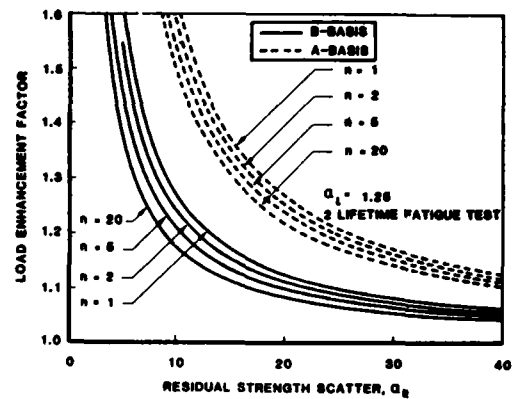
A-BASIS LOAD ENHANCEMENT FACTORS



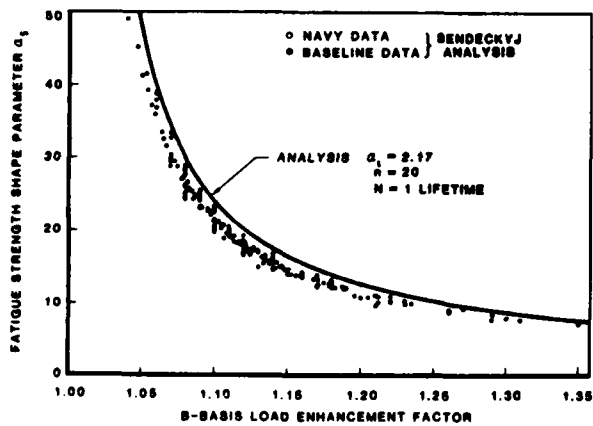
LEF VS α_R



LEF VS α_R



TEST LEF vs ANALYTICAL LEF



SUMMARY

- A LOAD ENHANCEMENT FACTOR APPROACH WAS DEVELOPED FOR FATIGUE LIFE CERTIFICATION OF COMPOSITE STRUCTURES
- THE ADVANTAGE OF THE LEF APPROACH REDUCED TEST DURATION FOR THE SAME LEVEL OF RELIABILITY
- THE METHOD DEVELOPED CAN BE USED FOR FATIGUE TEST PLANNING, AND CAN ALSO BE USED FOR COMBINED LIFE AND LOAD FACTOR TESTS
- THE METHOD CAN BE USED TO EVALUATE STRUCTURAL RELIABILITY BASED ON TEST DATA

COMPOSITE AIRCRAFT CERTIFICATION

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ABSTRACT

Over a period of many years, a reliable certification testing procedure for metal aircraft structures has evolved. The key requirements of this procedure are: 1) demonstrated strength of a full-scale static test article which equals or exceeds 150% design limit load and 2) demonstrated fatigue life of a full-scale fatigue test article equal to two times the design service life. These requirements are intended to account for uncertainties in usage and for scatter exhibited by metals. They were developed mainly through experience and are accepted methods of assuring structural integrity.

To make lighter, more maintainable and more durable aircraft, the aircraft industry has increased its use of resin matrix composites. The industry has adopted the certification philosophies that are used for metal structures, specifically the full-scale test requirements, and applied them to certification of composite structures. Changes and additions were made in the certification process to account for structural behavior inherent to composites.

In current aircraft designs, strain levels have been low (2000-4000 $\mu\text{in./in.}$ at limit load) such that composite structure is not fatigue critical, unlike metal structure. In comparison to metals, composites exhibit much greater static strength and fatigue life data scatter. Due to poor interlaminar strength, they are susceptible to out-of-plane failures and are generally more sensitive to environment where strength is matrix controlled. These differences in behavior make certification difficult for mixed composite/metal structure.

The next generation of fighter aircraft is expected to make even greater use of composites than current designs. Emerging higher modulus material systems, higher design strain levels, and damage tolerance requirements will make certification even more demanding. A testing methodology has been developed for the certification of all-composite and mixed composite/metal structures.

The test methodology was developed through analytic correlation with results of 8,000 composite unloaded and loaded-hole specimen tests. The effects of various parameters on scatter in strength, and constant amplitude and spectrum fatigue life were quantified using normal distribution statistical analyses. Major observations concerning scatter were:

- o Scatter in strength is 1 1/2 to 2 times greater for composites than for metals.
- o Coefficient of variance, C_v (standard deviation/mean), in strength is independent of loading direction, environment, and material system.
- o Specimens with holes exhibit less strength scatter than unnotched specimens.
- o Scatter in fatigue life is significantly greater for composites than for metals.
- o Fatigue scatter is dependent upon stress level, amount of load transfer, and stress ratio.
- o Scatter in fatigue life of specimens with load-transfer through the fastener is greater than for specimens without load-transfer.
- o Fatigue scatter is not affected by environment.

The sensitivity of resin matrix composites to environment and their large fatigue scatter precludes direct certification using only full-scale static and fatigue tests. This sensitivity necessitates the use of static coupon tests to evaluate the combined effects of temperature and moisture when certifying airframe strength, and "end-of-life" fatigue tests to determine life scatter. Thus, the developed methodology embraces a test scheme that coordinates the use of coupon, element, component and full-scale tests.

Four static strength and five fatigue certification test approaches were analytically evaluated through application to a Navy production fighter aircraft, the F/A-18, and its composite development database. The F/A-18 was studied since its design configuration represents state-of-the-art use of composite and metal materials, and the difficulties found in certification of mixed composite/metal structure.

The developed approach for composite static strength and fatigue certification involves correlation of full-scale structure measured strains to environmental static and fatigue element data. The traditional full-scale fatigue test to two times the design service life validates the metal structure.

In the certification methodology, the development test program and the calculation of composite design allowables is orchestrated to support certification of the full-scale structure.

REFERENCES

1. Sanger, K. B., "Certification Testing Methodology For Composite Structures," NADC Report 86032-60, January 1986.

CERTIFICATION TESTING METHODOLOGY FOR COMPOSITE STRUCTURES

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E.F. KAUTZ
NAVAL AIR DEVELOPMENT CENTER
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CERTIFICATION ISSUES

- SENSITIVITY TO ENVIRONMENT
- LARGE DATA SCATTER
- MIXED COMPOSITE/METAL STRUCTURE
- OUT-OF-PLANE LOADS

PROGRAM TASKS

- SCATTER ANALYSIS
- CERTIFICATION APPROACH
DEVELOPMENT/EVALUATION
- METHODOLOGY DEVELOPMENT
- METHODOLOGY DEMONSTRATION

DATA SUMMARY

STATIC STRENGTH (>7,000)

- MATERIAL SYSTEM
 - AS/3501-6
 - T300/5208
 - OTHER
- SPECIMEN TYPE
 - UNNOTCHED
 - UNLOADED HOLE
 - LOADED HOLE
- ENVIRONMENT
 - RTD
 - RTW
 - ETD
 - ETW
 - CTD
 - CTW

FATIGUE (>700)

- MATERIAL SYSTEM
 - AS/3501-6
 - T300/5208
- SPECIMEN TYPE
 - UNNOTCHED
 - NOTCHED-DOGBONE
 - OPEN HOLE
 - UNLOADED HOLE
 - COMPLEX
- ENVIRONMENT
 - RTD

SCATTER SUMMARY - STATIC STRENGTH

CONCLUSIONS

- STRENGTH SCATTER FOR COMPOSITES IS 1-1/2 TO 2 TIMES THAT FOR METALS
- COEFFICIENT OF VARIATION, C_v , IS INDEPENDENT OF:
 - LOADING DIRECTION (TENSION, COMPRESSION)
 - ENVIRONMENT
 - MATERIAL SYSTEM
- SPECIMENS WITH HOLES EXHIBIT 1/3 LESS SCATTER IN STRENGTH THAN UNNOTCHED SPECIMENS
- UNLOADED AND LOADED HOLES EXHIBIT THE SAME SCATTER (C_v)
- C_v IS INDEPENDENT OF t/d AND e/d RATIOS

SCATTER SUMMARY - FATIGUE LIFE

CONCLUSIONS

- FATIGUE LIFE SCATTER FOR COMPOSITES IS SIGNIFICANTLY GREATER THAN FOR METALS
- LOADED HOLE SPECIMENS EXHIBIT GREATER SCATTER THAN SPECIMENS WITH NO-LOAD-TRANSFER
- LIFE SCATTER OF NO-LOAD-TRANSFER SPECIMENS INCREASES WITH INCREASES IN STRESS LEVEL
- STRESS LEVEL HAS LITTLE EFFECT ON LIFE SCATTER FOR LOAD-TRANSFER SPECIMENS
- ENVIRONMENT HAS LITTLE EFFECT ON LIFE SCATTER

BUILDING BLOCK APPROACH

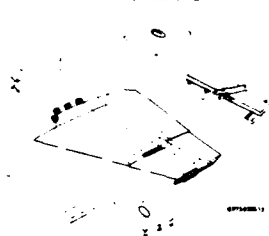
COUPONS AND ELEMENTS



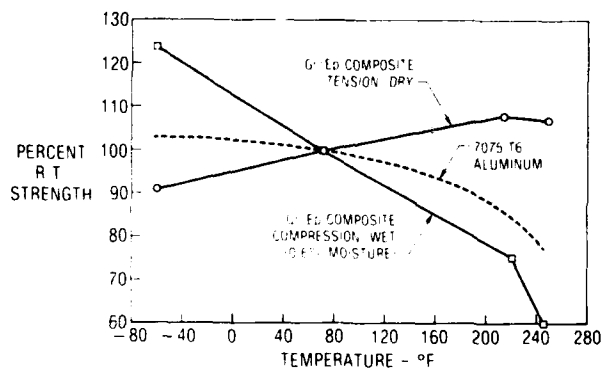
FULL-SCALE ARTICLES



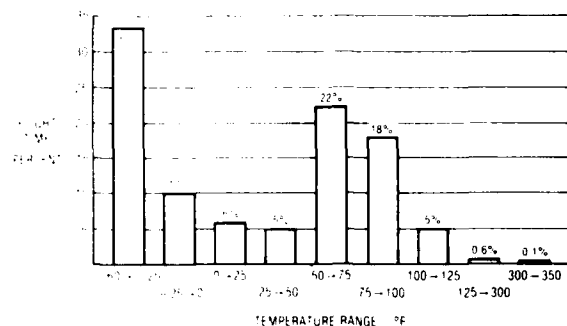
SUBCOMPONENTS AND COMPONENTS



ENVIRONMENTAL SENSITIVITY

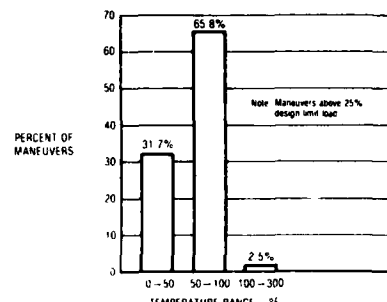


MULTIMISSION FIGHTER AIRCRAFT SPEND LITTLE TIME AT ELEVATED TEMPERATURE



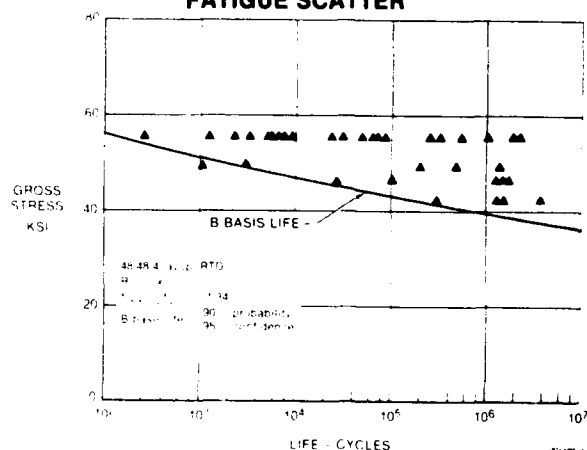
SEPTEMBER 1978

MULTIMISSION FIGHTER AIRCRAFT EXPERIENCE FEW MANEUVERS AT ELEVATED TEMPERATURES



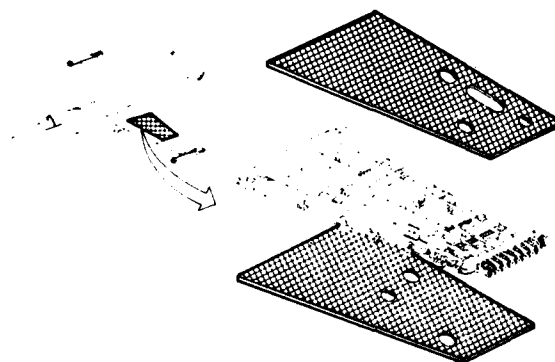
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FATIGUE SCATTER



SEPTEMBER 1978

MIXED COMPOSITE/METAL STRUCTURE



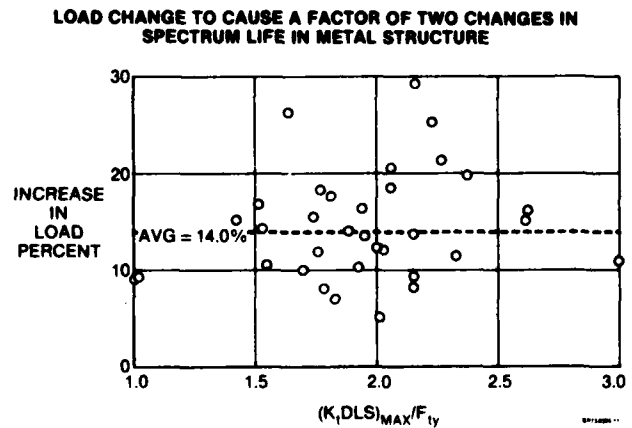
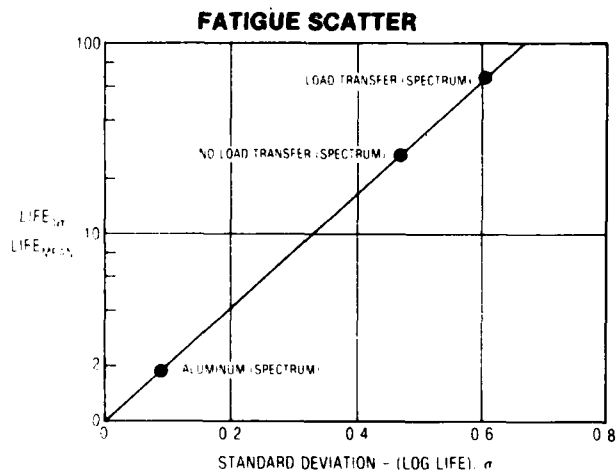
SEPTEMBER 1978

STATIC STRENGTH CERTIFICATION APPROACHES:

- CONDITION TEST ARTICLE
 - TEST CTD FOR TENSION LOADS
 - TEST ETW FOR COMPRESSION LOADS
- TEST UNDER RTD CONDITIONS
 - INCREASE LOADS TO COMPENSATE FOR ENVIRONMENT
 - CORRELATE MEASURED STRAINS WITH ENVIRONMENTAL ELEMENT DATA

FATIGUE CERTIFICATION APPROACHES

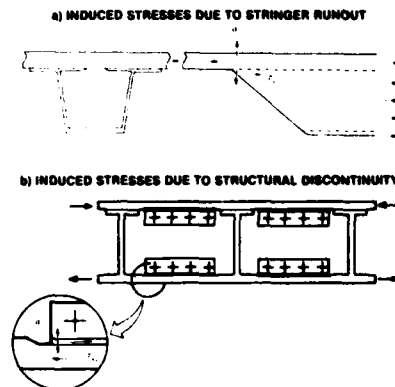
- APPLY A FACTOR TO FULL-SCALE ARTICLE TEST LIFE
- APPLY A FACTOR TO FULL-SCALE ARTICLE TEST LOADS
- INCREASE SEVERITY OF LOADS SPECTRUM
- CORRELATE STATIC STRAIN MEASUREMENTS WITH ELEMENT FATIGUE DATA/PERFORM $2 \times$ DESIGN LIFE FATIGUE TEST FOR METAL STRUCTURE



INDUCED CRIPPLING FAILURE DUE TO OUT-OF-PLANE LOADS



INDUCED OUT-OF-PLANE STRESSES DUE TO STRINGER RUNOUT AND STRUCTURAL DISCONTINUITY



SUMMARY

- ANALYSIS PERFORMED TO ESTABLISH STATIC STRENGTH AND FATIGUE LIFE SCATTERS FOR COMPOSITE BOLTED STRUCTURE
- APPROACHES TO STATIC STRENGTH AND FATIGUE CERTIFICATION WERE ANALYTICALLY EVALUATED
- CERTIFICATION TEST METHODOLOGY FOR EXISTING HYBRID FIGHTER STRUCTURE DEVELOPED, AND DEMONSTRATED

CONCLUSIONS

- TRADITIONAL METAL PROCEDURE BASED ON EXPERIENCE, RELIES ON FULL SCALE TESTS
- INHERENT COMPOSITE BEHAVIOR MAKE TRADITIONAL PROCEDURE INADEQUATE
 - SENSITIVITY TO ENVIRONMENT
 - DATA SCATTER
 - SUSCEPTIBILITY TO MORE FAILURE MODES, SOME UNPREDICTABLE
- COMPOSITES REQUIRE COORDINATED ELEMENT, SUBCOMPONENT AND FULL-SCALE TESTS, AND PROPER INTERPRETATION

INTERLAMINAR TEARING (MODE III) FRACTURE OF GRAPHITE/EPOXY COMPOSITES

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Air Force Wright Aeronautical Laboratories
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ABSTRACT

Existing analysis has shown that the driving modes for interlaminar cracks may consist of all three types (Modes I, II, and III). The ratio of each depends upon the material stiffness properties, the laminate stacking sequence, the nature of the applied global load, and the damage location and type. To predict interlaminar failure in composite materials, then, data for all three modes is required. However, the existing data concentrates only on the Mode I and II type of failure. Because of this, a research project was undertaken to measure interlaminar Mode III critical strain energy release rates in graphite fiber-reinforced epoxy and thermoplastic matrix composites.

The first method used was a split cantilever beam test, where a laminate, containing a starter crack, was bonded between two parallel aluminum bars. The bars were then loaded in opposite directions, parallel to the plane of the crack and normal to the length of the specimen to produce the out-of-plane tearing. Stable, self-similar crack growth was achieved. Toughness results on unidirectional graphite/epoxy material showed a G_{IIIc} in the range of 6.2-7.2 in-lb/in². This was roughly 2.5 times the reported G_{IIIc} value, and about 9 times the reported G_{Ic} value for the class of material. An implication of the higher Mode III toughness values in the brittle matrix system is that, if only the total strain energy release rate (and not the isolated modes) in a laminate is calculated, neglecting the Mode III effects could be highly conservative.

Sensitivity of the measured toughness values to the laminate thickness, beam depth, and data reduction method was ascertained to determine the generality and limitations of the test. This led to an increased confidence level in the data. The results from the 16 and 24-ply unidirectional specimens were in good agreement, however, the 8-ply specimen showed significant crack jumping. The 0.25 inch depth unidirectional specimen had considerable fiber bridging, hence only the initial data were consistent. The 0.5 inch depth specimen seemed optimum, with little fiber bridging and good agreement between the beam theory, compliance method, and area data reduction methods. In the 1.0 inch depth specimens, the beam theory was not applicable, most likely due to the violation of beam theory caused by transverse shear strain.

Multi-directional laminates of the type $[\theta_4//-\theta_8/\theta_4]_T$ were also tested, with $\theta = 15, 45$, and 75 degrees. The symbol $//$ indicates the crack plane. The 15 and 75 degree tests showed somewhat higher toughness than the unidirectional results and no fiber bridging. The 45 degree laminate results were significantly lower than the 15 and 75 degree laminate results. Thermal residual stress and possible edge effects due to the anisotropic mismatch between the specimen halves may have caused the differences.

Testing was attempted on unidirectional, off-axis laminates. In every specimen, regardless of the precrack method used, the crack deviated from the laminate centerline to the laminate edge, resulting in bondline failure. Testing was also conducted on a tough, ductile matrix thermoplastic. The laminate-to-aluminum bondline failed in all tests, so no data could be reported.

Edge delamination specimens were investigated as alternative Mode III tests. $[15_1/-15_1]_s$ angle-ply laminates were fabricated with four implanted starter cracks at the $+15/-15$ interfaces, adjacent to the laminate edges. The

results from the edge delamination tests were less concise than the beam results. There was good agreement between the tension and compression tests, indicating the negligible effects of the Mode I crack tip component. The calculated toughness values depended upon the initial assumption of the number of cracks which propagated. In addition, the toughness values were dependent upon the laminate thickness. If it was assumed that only one crack was critical, the different thickness laminate test results bounded the corresponding beam results.

OVERVIEW

- INTRODUCTION/BACKGROUND
- SPLIT CANTILEVER BEAM: EXPERIMENTAL PROCEDURE
- SPLIT CANTILEVER BEAM: RESULTS AND DISCUSSION
- EDGE DELAMINATION: EXPERIMENTAL PROCEDURE
- EDGE DELAMINATION: RESULTS AND DISCUSSION
- CONCLUSIONS

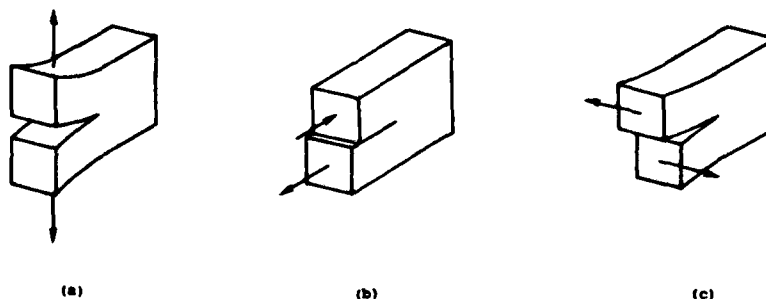


Figure 1. Three Classical Modes of Crack Propagation: (a) Mode I Peeling, (b) Mode II Forward Shearing, (c) Mode III Out-of-Plane Tearing

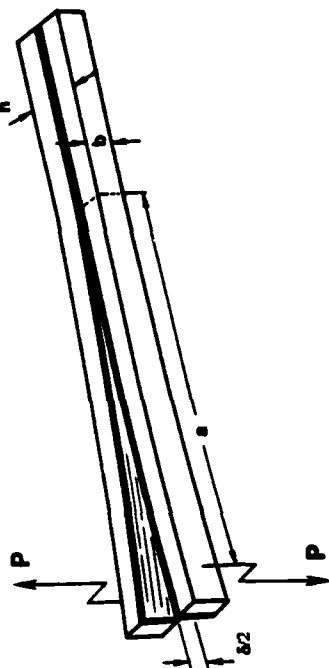


Figure 5. Split Cantilever Beam Test, Consisting of a Laminate Bonded Between Two Aluminum Bars

BACKGROUND

- DELAMINATION MAY LIMIT THE IN-PLANE LAMINATE STRENGTH
- MODE III STRESSES EXIST IN DELAMINATED LAMINATES, MAY DOMINATE
- MATERIALS MODE I, II, AND MIXED I-II WELL CHARACTERIZED
- MODE III MATERIAL TOUGHNESS: NO DATA

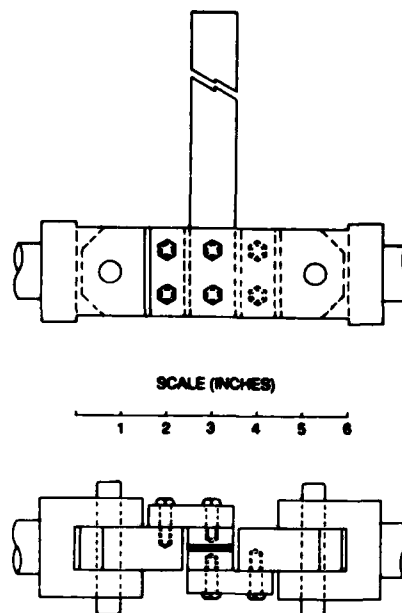
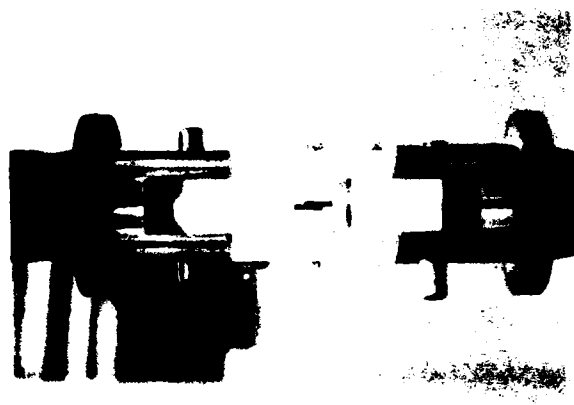


Figure 6. Diagram of the Split Cantilever Beam Specimen and Load Fixture. Beam Depth $b = 1.0$ inch Shown. Beam Lengths were 11.0 inches



SPLIT CANTILEVER BEAM

- LAMINATE BONDED BETWEEN ALUMINUM BARS
- LAMINATE PRE-CRACKED
- SPLICE PLATE & BLOCK: CENTERLINE
- PINNED ENDS

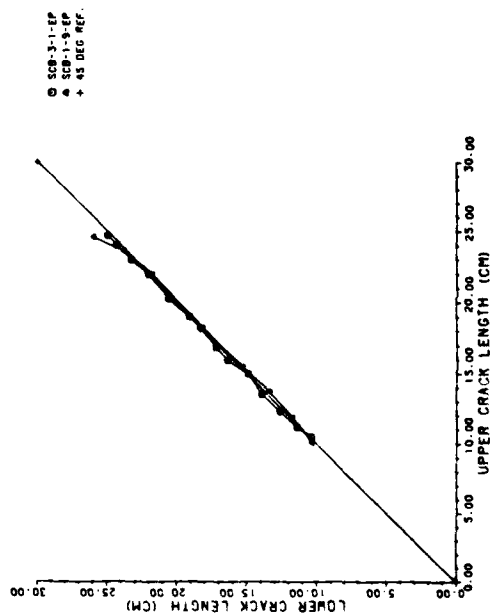


Figure 10. Lower vs Upper Crack Length, Showing No Significant Deviation Between the Two. AS4/3502

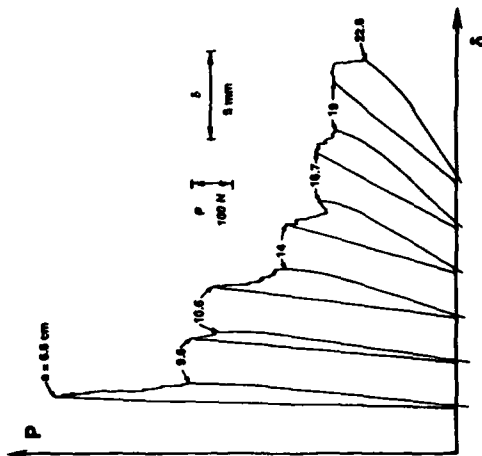


Figure 9. Load vs End Displacement for a Split Cantilever Beam Test with Increasing Crack Lengths Indicated, AS4/3502

SCB DATA REDUCTION

BEAM THEORY

$$\delta/2 = Pa^3 / (3EI); G_{IIIc,i} = (3\delta_i P_i) / (2ba_i)$$

COMPLIANCE METHOD

$$\delta/P = Ka^n; G_{IIIc,i} = (nP_i \delta_i) / (2ba_i)$$

AREA METHOD

$$G_{IIIc,i} = \{P_i (d\delta/da)_i - \delta_i (dP/da)_i\} / (2b)$$

SCB RESULTS

- G_{IIIc} vs data reduction method
- G_{IIIc} vs a (crack length)
- G_{IIIc} vs n (laminare thickness)
- G_{IIIc} vs b (beam depth)
- G_{IIIc} vs θ (angle-ply orientation)

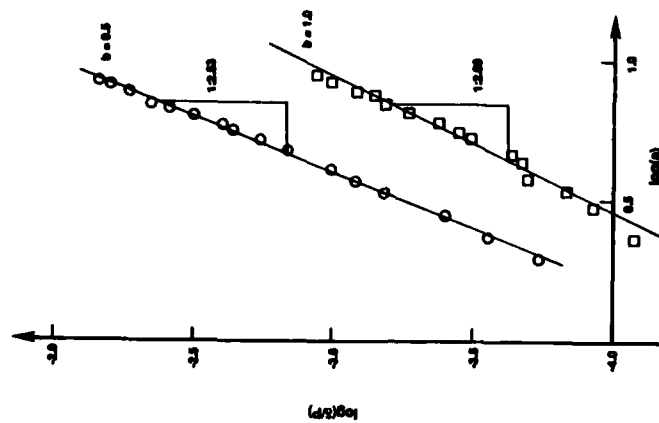


Figure 11. Compliance Curve Calibration for Two Different Depth Specimens. NS4/3502

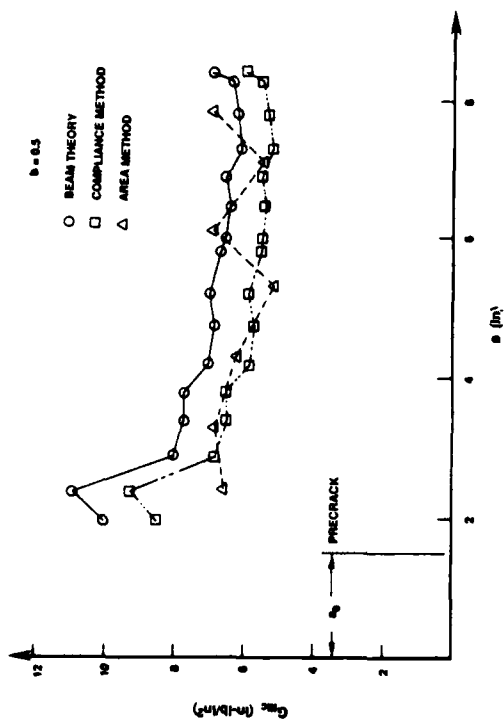


Figure 13. Measured Toughness as a Function of Crack Length. AS4/3502. (a) $b = 0.5$, (b) $b = 1.0$

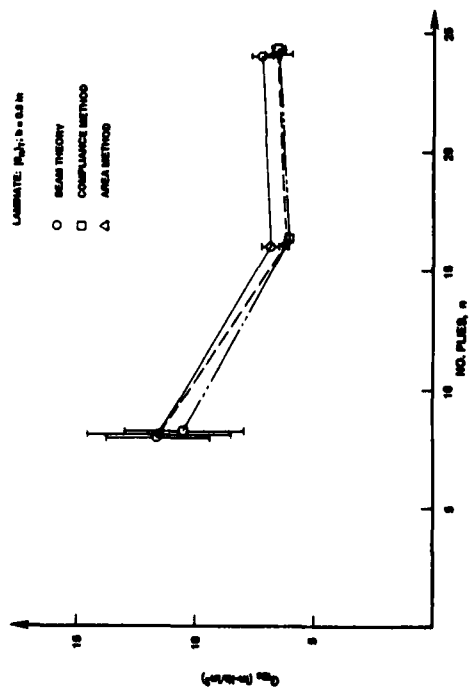


Figure 14. Toughness as a Function of Laminates Thickness. 8-Ply Specimens Showed Crack Jumping. AS4/3502

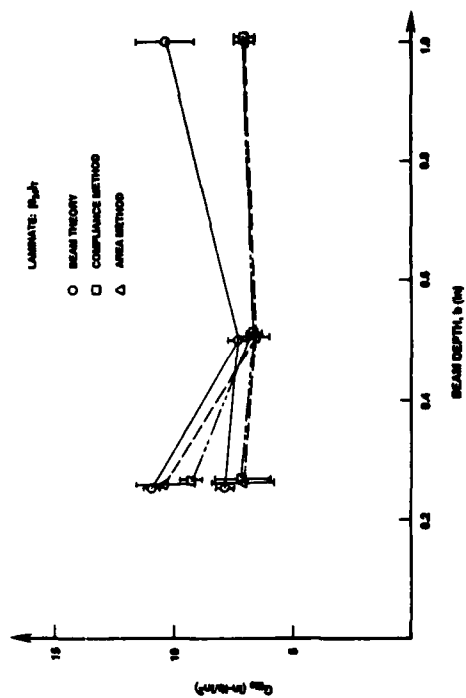
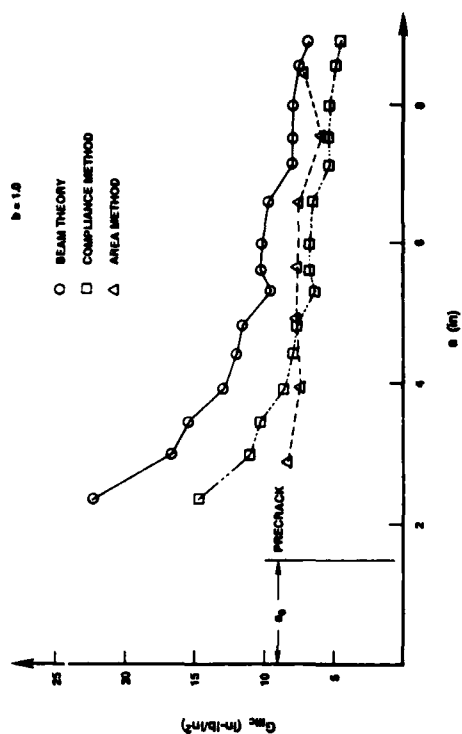


Figure 15. Toughness vs Beam Depth. 0.25 inch Specimens Showed Significant Fiber Bridging. Hence Average (upper data) and Initial (lower data) are Plotted

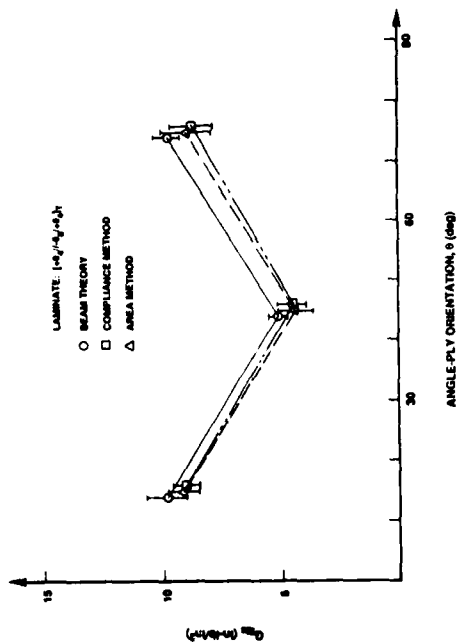


Figure 16. Toughness as a function of Ply Orientation in the Angle-Ply Multi-Directional Laminates

MODE I EFFECTS

- END OPENING MEASURED VS. CRACK LENGTH
- BEAM THEORY TO CALCULATE G
- $G_I/G_{III} < 3\%$
- $G_I/G_{Ic} < 22\%$

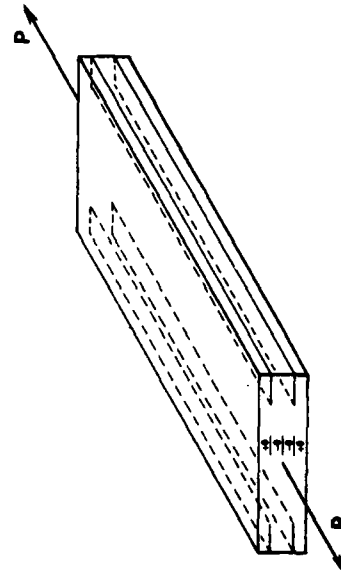


Figure 19. Schematic of Angle-Ply Edge Delamination Specimen. Note that Four Starter Cracks were Required per Specimen

OTHER SCB TESTS

$[\theta_{16}]_T; \theta = 15^\circ, 30^\circ, 90^\circ \rightarrow$ CRACK DEVIATION

$[0_{24}]_T$ AS4/PEEK APC-2 $\rightarrow$ BONDLINE FAILURE

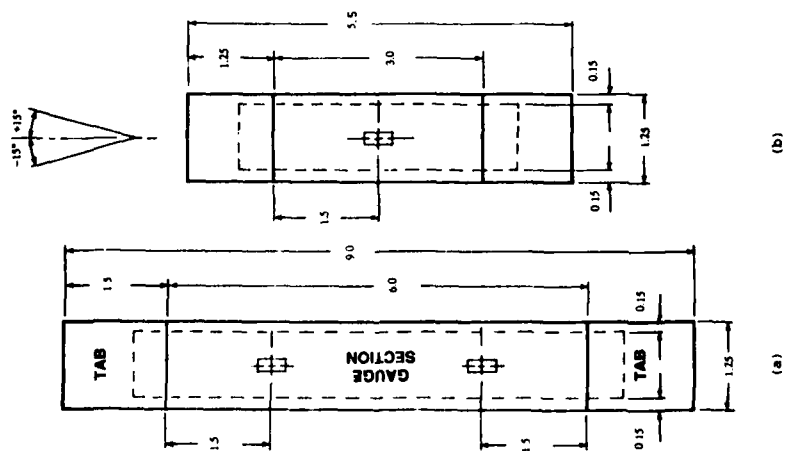


Figure 20. Lay-out of Edge Delamination Specimens Tested in (a) Tension, (b) Compression

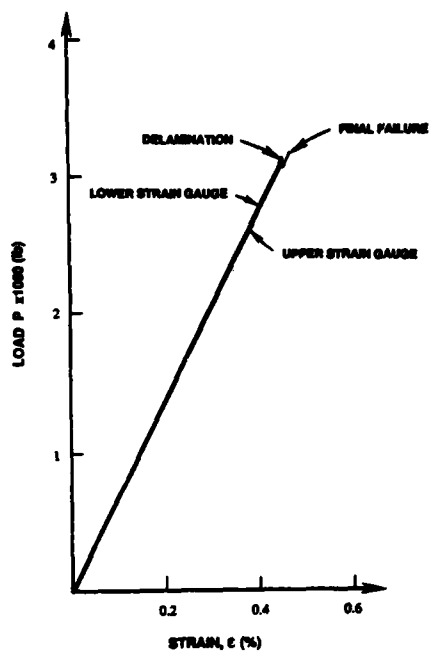


Figure 23. Load vs Strain for the Edge Delamination Specimen. Note Delamination Followed Almost Immediately by Final Failure



Figure 24. Penetrant Enhanced X-ray Views of Edge Delamination Specimens after (a) 50% of Ultimate Load, (b) Delamination Load, (c) Final Failure

EDGE DELAMINATION

- FOUR EDGE DELAM IMPLANTS PER SPECIMEN
- TENSION AND COMPRESSION LOADED
- TWO THICKNESSES
- STRAIN GAGES
- $[15_1/-15_1]_s$

EDGE DELAMINATION DATA REDUCTION

• O'BRIEN

$$G_c = t \epsilon_c^2 (E_{lam} - E^*) / N$$

• THERMAL EFFECTS

LAMINATE PLATE THEORY

EDGE DELAMINATION RESULTS

G_c vs i (laminate thickness)

G_c vs N (number of cracks)

G_c vs loading (tension/compression)

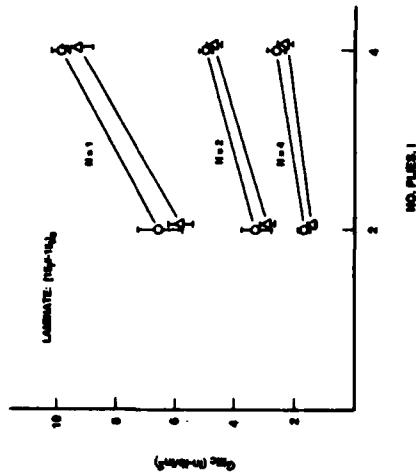


Figure 26. Toughness as Determined by the Edge Delamination Test versus the Laminate Thickness. A84/3502

CONCLUSIONS -- EDGE DELAMINATION

- SIMILAR TENSION AND COMPRESSION RESULTS
- RESULTS DEPEND ON LAMINATE THICKNESS
- NUMBER OF CRITICAL CRACKS UNRESOLVED

CONCLUSIONS -- SPLIT CANTILEVER BEAM

- SCB SUCCESSFUL IN MEASURING G_{IIIc} OF UNIDIRECTIONAL GR/EP:
 $6.2-7.2 \text{ in-lb/in}^2$ ($2.5x G_{IIc}$; $9x G_{IC}$)
- SCB DATA REDUCTION, LAMINATE THICKNESS, BEAM DEPTH, AND CRACK LENGTH EFFECTS CHARACTERIZED
- LAMINATE EFFECTS MORE COMPLEX
- OFF-AXIS AND APC-2 TESTS UNSUCCESSFUL

INFLUENCE OF LOAD FACTORS AND TEST METHODS ON
IN-SERVICE RESPONSE OF COMPOSITE MATERIALS AND STRUCTURES

C. Bakis, K. Razvan, W. Stinchcomb and K. Reifsnider

Materials Response Group
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061-4899

ABSTRACT

Many engineering components must perform a function over service lives of various lengths, from a few hours to several years. In many cases it is not feasible to generate data concerning that performance in sufficient detail to address issues of durability, reliability, remaining stiffness, or strength, safety, or expected life. Data generated under one set of conditions must, therefore, be related to other conditions in some cases. A common example is the practice of load scaling whereby performance under high amplitude cyclic loading (for short periods) is used to estimate performance under lower load amplitudes (common to service environments) for longer periods of time by some "load scaling" scheme. The present paper reports the results of an effort to establish a fundamental understanding of the micro-damage events associated with the fully reversed cyclic loading of edge-notched (EN) and center-notched (CN) laminated coupon specimens, and to use that understanding as the basis of an attempt to model the effect of load level on damage development in order to put such load scaling practice on a firmer technical footing.

At the global level, variations in cyclic load level can cause changes in failure modes. For $R=-1$ loading of "tough" matrix orthotropic graphite reinforced laminates, high amplitude loading may cause failure by the localized propagation of a single crack in tension, while for lower load amplitudes compressive failure by delamination and buckling may control failure. In general, damage modes become very much more dispersed (Fig. 2) for low loads, and more localized for high loads. This was true for all of the five material systems and several laminates investigated. Delamination played a distinctly greater role in low level loading (Fig. 3). For notched laminates under fully reversed loading, damage (especially delamination from edges) begins preferentially from the surface of the laminate and spreads to the interior plies. This spread is more rapid and more extensive at higher load levels (Fig. 4). However, the greatest (most important) difference in the damage development at high and low levels is associated with fiber fracture. Fiber fracture is much more localized at high load levels (Figs. 5,6,7). Since fibers control the remaining strength of these laminates, this feature is of special interest. Under high load levels, highly localized single crack growth through zero degree plies is more common, frequently along directions parallel to matrix cracks in neighboring plies (Figs. 5B,8B). At low levels, fiber damage is more dispersed, even at the tip and ahead of the tip of cracks growing across fibers (Figs. 6,7). Perhaps the most surprising finding is the relationship between fiber fracture and delamination under long-term low level loading (Fig. 5A).

Present efforts continue to generate a fundamental fiber fracture relationship as a function of cyclic load level using a carefully designed control experiment. Model formulation using the critical element concept is also underway. This approach will incorporate the understanding gained from the experimental program into a model that predicts remaining strength and life as a function of load history. Hence, load scaling will be represented by a model which allows users of composite materials to anticipate long-term behavior as a function of cyclic load level. A fundamental premise of the approach is that "critical elements" of material, such as the fibers in tensile loading of fibrous reinforced material, degrade under cyclic loading in a way that is controlled by the local stress state, according to a degradation relationship that can be determined from control tests. Then, as long as the failure mode is controlled by that critical element, the remaining strength and life of other laminates under other types of loading can be predicted by considering the local state of the critical element in those conditions.



$\sigma_a = 48$ ksi

1.5 cycles



$\sigma_a = 45.2$ ksi

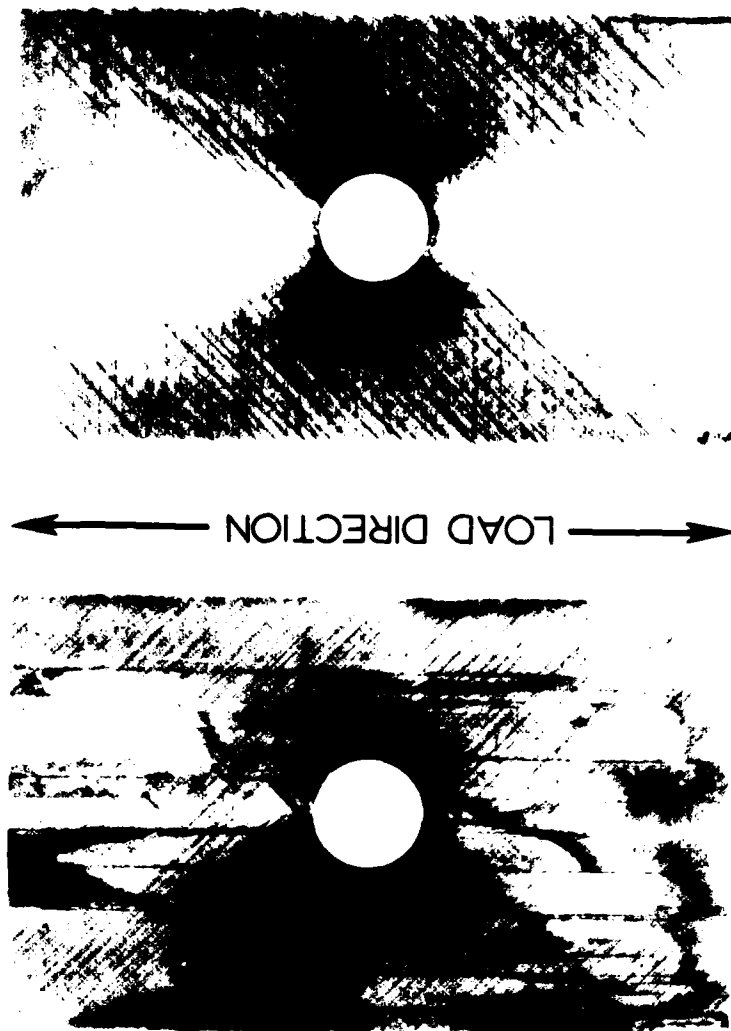
24320 cycles

AS4 / 1808 (0, 45, 0, -45)_{S4}

$S_T = 55.9$ ksi $S_C = -56.6$ ksi

Figure 2.

CN A54/3501-6 (0,45,90,-45)_{S4}



LOW LOAD
 $N_f = 2380K$

HIGH LOAD
 $N_f = 1.9K$

Figure 3.

CN AS4/ 3501-6 (0,45,90,-45)_{S4}



LOW LOAD
 $N_f = 2380K$

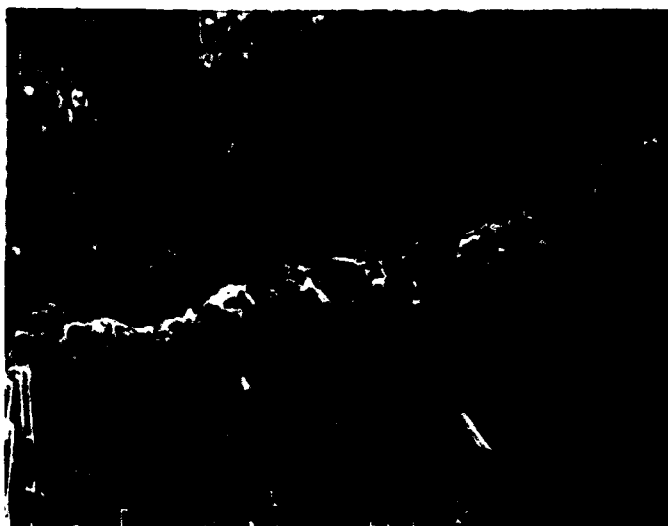


HIGH LOAD
 $N_f = 1.9K$

Figure 4.

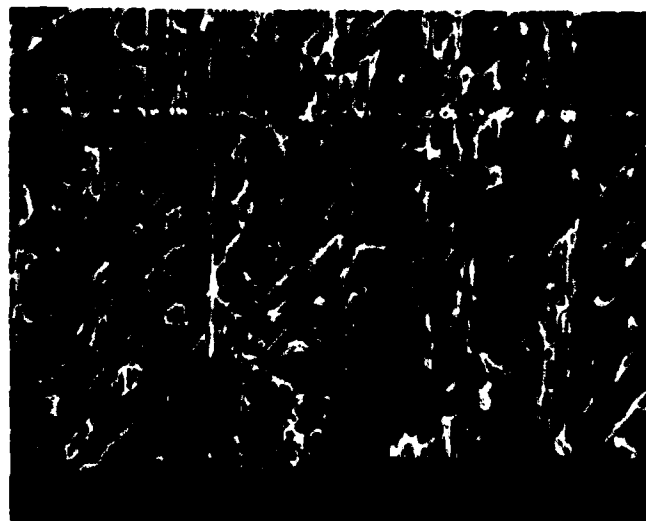


A



B

Scanning Electron micrographs of T300 5208 [0 45 90 - 45]_{s4} laminate under (A) low, (B) high amplitude loadings at late life.



A

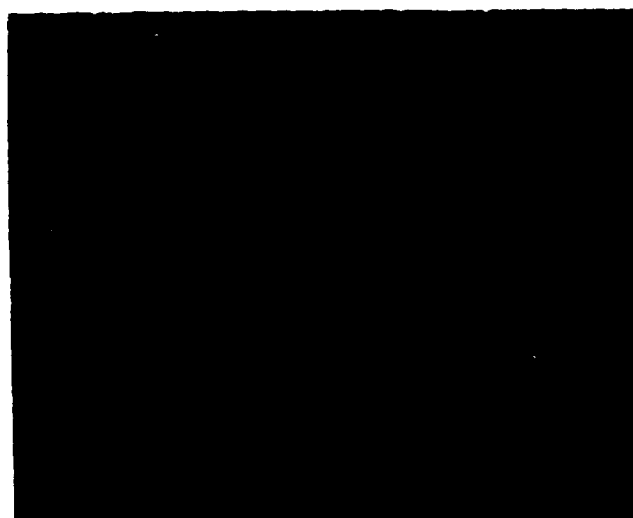


B

Crack tip fiber fractures in AS4/1808 [0/45/0/-45]_{s4} laminate under (A) low, (B) high amplitude loading at impending laminate failure.

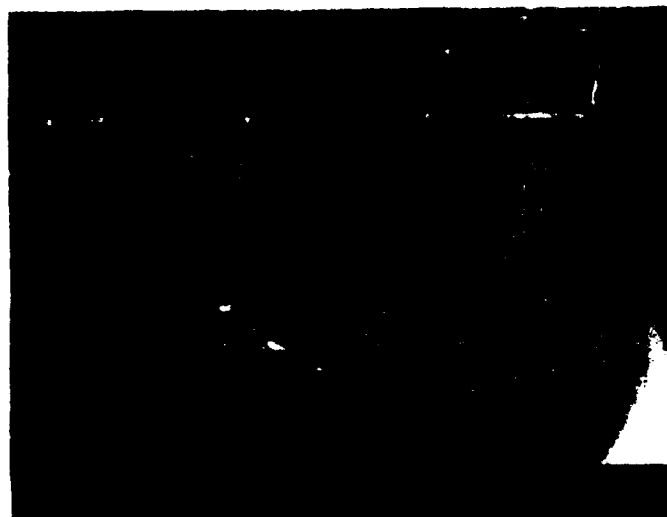


A

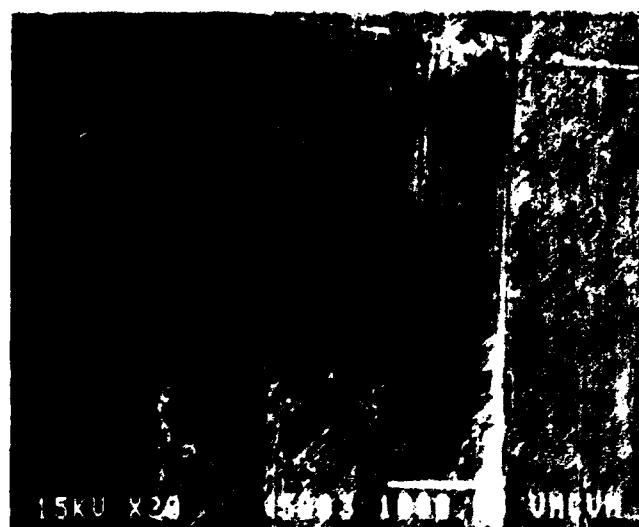


B

Fiber fracture ahead of the crack tip close to the end of life of $[0/45/0/-45]_{3/4}$ laminate under (A) low, (B) high amplitude loading.



A



B

Transverse cracks in the 0° ply of AS4/1808 [0/45/0/-45]_{s4} under (A) low, (B) high amplitude loading.

APPENDIX A: PROGRAM LISTINGS

**AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
MATERIALS LABORATORY**

IN-HOUSE

**ADVANCED COMPOSITES
WORK UNIT DIRECTIVE (WUD) NUMBER 45
86 October - 88 October**

**WUD Leader: Stephen W. Tsai
Materials Laboratory
Air Force Wright Aeronautical Laboratories
AFWAL/MLBM
Wright-Patterson AFB, OH 45433-6533
(513) 255-3068 Autovon: 785-3068**

Objective: The objective of the long term thrust is to develop understanding of deformation and failure process of composite laminates. The short term objectives include the following: (a) Development of design methodology of thick composites and their test methods. (b) Role of interface in emerging composite systems.

CONTRACTS

**IMPROVED DAMAGE RESISTANT COMPOSITE MATERIALS
F33615-84-C-5070
1 Sep 84 - 1 Feb 88**

**Project Engineer: Marvin Knight
Materials Laboratory
Air Force Wright Aeronautical Laboratories
AFWAL/MLBM
Wright-Patterson AFB, OH 45433-6533
(513) 255-7131 Autovon: 785-7131**

**Principal Investigator: Ron Servais
University of Dayton Research Institute
300 College Park Avenue
Dayton, OH 45469**

Objective: The objective of this program is to investigate from both an experimental and analytical standpoint the potential of new and/or modifications of existing polymeric materials and reinforcement forms for use in advanced composite materials, including processing/mechanical property relationships. Such materials are subsequent candidates for use in advanced aircraft and aerospace structural applications.

IMPROVED TECHNOLOGY FOR ADVANCED COMPOSITE MATERIALS

F33615-87-C-5239

15 Sep 87 - 01 Feb 92

Project Engineer: Marvin Knight
Materials Laboratory
Air Force Wright Aeronautical Laboratories
AFWAL/MLBM
Wright-Patterson AFB, OH 45433-6533
(513) 255-7131 Autovon: 785-7131

Principal Investigator: David P. Anderson
University of Dayton Research Institute
300 College Park Avenue

Objective: The objective of this program is to investigate from both an experimental and an analytical standpoint the potential of new and/or modifications of existing matrix materials and reinforcements/product forms for use in advanced composite materials, including processing/mechanical property relationships. Such materials are subsequent candidates for use in advanced aircraft and aerospace structural applications.

3-DIMENSIONAL RESPONSE OF COMPOSITES

F33615-85-C-5034

01 Jun 85 - 01 Sep 88

Project Engineer: Nicholas J. Pagano
Materials Laboratory
Air Force Wright Aeronautical Laboratories
AFWAL/MLBM
Wright-Patterson AFB, OH 45433-6533
(513) 255-6762 Autovon: 785-6762

Principal Investigator: Som R. Soni
Adtech Systems Research Inc.
211 N. Broad Street
Fairborn, OH 45324

Objective: The objective of this program is to develop 3-dimensional analytical models capable of predicting the mechanical response of thick laminated composites, including cracked layers and to provide efficient methods of solution for these problems.

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

INHOUSE

NONE

GRANTS AND CONTRACTS

DAMAGE MODELS FOR CONTINUOUS FIBER COMPOSITES

AFOSR-84-0067

01 April 87 - 31 March 88

Principal Investigators: Dr David Allen
Dr Charles E Harris
Department of Aerospace Engineering
Texas A+M University
College Station, TX 77843
(409) 845-7541

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop a damage model for predicting strength and stiffness of continuous fiber composite structure subjected to fatigue loading, and to verify this model with experimental results.

STUDIES IN THE DELAMINATION FRACTURE BEHAVIOR OF COMPOSITE MATERIALS

AFOSR-84-0064

01 August 87 - 31 July 89

Principal Investigator: Dr Walter L Bradley
Department of Mechanical Engineering
Texas A+M University
College Station, TX 77843
(409) 845-1259

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

To illucidate the micromechanisms underlying delamination failures in polymer composites which are subjected to mixed-mode loading.

ELEVATED TEMPERATURE PERFORMANCE OF CERAMIC AND GLASS MATRIX COMPOSITES

AFOSR-87-0383

15 July 87 - 14 October 91

Principal Investigator: Dr Tsu-Wei Chou
University of Delaware
Center for Composite Materials
Newark, DE 19716
(302) 451-2904

Program Manager: Major Joseph W Hager
AFOSR/NE
Bolling AFB DC 20332-6448
(202) 767-4933

Objective: The primary objectives of the proposed research are: (a) To provide a fundamental understanding of the high-temperature mechanical properties, environmental effects and failure mechanisms of glass and ceramic matrix composites through experimental characterization and theoretical modeling, and (b) To establish high-temperature mechanical testing and characterization methods for glass and ceramic matrix composites.

MICROCRACKING AND TOUGHNESS OF CERAMIC-FIBER/CERAMIC-MATRIX COMPOSITES UNDER HIGH TEMPERATURE

AFOSR-87-0288

01 August 87 - 30 July 89

Principal Investigators: Dr Feridun Delale
Dr Been-Ming Liaw
Department of Mechanical Engineering
The City College of
The City University of New York
New York, NY 10036
(212) 690-4252

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To study the mechanisms of microcracking at the fiber/matrix level in a ceramic-fiber/ceramic-matrix composite material subjected to thermomechanical loading.

DYNAMICS AND AEROELASTICITY OF COMPOSITE STRUCTURES

F49620-86-C-0066

01 July 86 - 30 June 87

Principal Investigator: Dr John Dugundji
Department of Aeronautics + Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139
(617) 253-3758

Program Manager: Dr Anthony K Amos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-4937

Objective: To pursue combined experimental and theoretical investigations of aeroelastic tailoring effects on flutter and divergence of aircraft wings.

ANALYTICAL AND EXPERIMENTAL CHARACTERIZATION OF DAMAGE PROCESSES IN COMPOSITE LAMINATES

AFOSR-84-0366

30 September 85 - 31 August 87

Principal Investigator: Dr George J Dvorak
Department of Civil Engineering
Rensselaer Polytechnic Institute
Troy, NY 12181
(518) 266-6943

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop distributed damage analysis applicable to high matrix crack densities, examine damage propagation across and along ply interfaces, model damage growth from intensely damaged regions, and analyze stability and compressive strength of laminated plates containing distributed and/or concentrated damage.

FAILURE OF LAMINATED PLATES CONTAINING HOLES

AFOSR-87-0204

01 April 87 - 31 March 89

Principal Investigator: Dr E S Folias
Department of Civil Engineering
The University of Utah
Salt Lake City, UT 84112
(801) 581-6931

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To analytically determine the three-dimensional stress field in a laminated plate containing a cylindrical hole through its entire thickness and loaded uniformly in the in-plane direction and to establish failure criteria.

PREDICTION AND CONTROL OF PROCESSING-INDUCED RESIDUAL STRESSES IN COMPOSITES

AFOSR-87-0242

01 June 87 - 31 May 89

Principal Investigator: Dr H Thomas Hahn
Department of Engineering Science and Mechanics
The Pennsylvania State University
University Park, PA 16802
(814) 863-0997

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To identify the mechanisms underlying the introduction of residual stresses during processing of polymer matrix composites, and to develop a prediction methodology as well as a procedure for controlling these stresses through optimization of the process cycle.

MODELING OF THE IMPACT RESPONSE OF FIBRE-REINFORCED COMPOSITES

AFOSR-87-0129

15 November 86 - 14 November 89

Principal Investigators: Dr John Harding
Dr C Ruiz
Department of Engineering Science
University of Oxford
Oxford, OX1 3PJ England

Program Manager: Dr Anthony K Amos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-4937

Objective: To characterize the mechanical behavior and failure mechanisms of carbon/epoxy, Kevlar/epoxy, and hybrid composites under tensile impact loading using specially designed split Hopkinson bar equipment.

STIFFNESS REDUCTION; FAILURE AND STRESS CONCENTRATION IN FIBER COMPOSITE LAMINATES

AFOSR-85-0342

30 September 85 - 29 December 87

Principal Investigator: Dr Zvi Hashin
Department of Materials Science and Engineering
University of Pennsylvania
Philadelphia, PA 19104
(215) 898-8337

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop variational methods for analysis of stiffness and failure of cracked laminates as well as for stress concentrations produced at free edges, holes, and other stress raisers.

CRAZING IN POLYMERIC AND COMPOSITE SYSTEMS
AFOSR-87-0143
01 April 87 - 31 March 90

Principal Investigator: Dr C C Hsiao
Department of Aerospace Engineering and Mechanics
University of Minnesota
Minneapolis, MN 55455
(612) 625-7363

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop time-dependent theories for the crazing behavior of polymeric and structural composite systems by understanding the microstructural behavior of the materials during crazing.

FRACTURE AND LONGEVITY OF COMPOSITE STRUCTURES
AFOSR-85-0206
15 June 86 - 14 June 87

Principal Investigator: Dr Paul A Lagace
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139
(617) 253-3628

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To gain understanding of the fundamental mechanisms and their interactions occurring in the failure of composite laminates and to generate the data base to support analytical models for representing these phenomena.

NONLINEAR DYNAMIC RESPONSE OF COMPOSITE ROTOR BLADES
01 December 85 - 30 November 87
F49620-86-K-0003

Principal Investigators: Dr Ozden Ochoa
Dr John J Engblom
Department of Mechanical Engineering
Texas A+M University
College Station, TX 77843
(409) 845-2022

Program Manager: Dr Anthony K Amos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-4937

Objective: To develop nonlinear finite element models suitable for predicting the structural dynamic response and resulting damage of composite rotor blades under impact and other transient excitations.

OPTIMUM AEROELASTIC CHARACTERISTICS FOR COMPOSITE SUPER-MANEUVERABLE AIRCRAFT

F49620-87-C-0046

01 June 87 - 31 May 88

Principal Investigator: Dr Gabriel Oyibo
Department of Mechanical + Aerospace Engineering
Polytechnic University
Farmingdale, NY 11735
(516) 454-5120

Program Manager: Dr Anthony K Amos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-4937

Objective: To identify, characterize, and model the effects of constrained warping on the dynamics and aeroelastic stability of aircraft composite wings

INVESTIGATION AND MODELING OF DAMAGE GROWTH IN COMPOSITE LAMINATES

AFOSR-85-0087

01 January 85 - 31 December 87

Principal Investigators: Dr Kenneth L Reifsnider
Dr Wayne W Stinchcomb
Department of Engineering Science and Mechanics
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
(703) 961-5316

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop a general damage-growth prediction methodology for damage in composite laminates under general tension/compression spectrum loading.

STUDIES ON DEFORMATION AND FRACTURE OF VISCOELASTIC COMPOSITE MATERIALS

AFOSR-87-0257

01 July 87 - 30 June 89

Principal Investigator: Dr Richard A Schapery
Department of Civil Engineering
Texas A+M University
College Station, TX 77843
(409) 845-2449

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop and verify mathematical models of deformation and delamination of viscoelastic composites with distributed micro-damages.

CONTROL AUGMENTED STRUCTURAL OPTIMIZATION OF AEROELASTICALLY TAILORED FIBER COMPOSITE WINGS

F49620-87-K-0003

01 November 86 - 31 October 89

Principal Investigators: Dr Lucien A Schmit
Dr Peretz Friedmann
Dept of Mechanical, Aerospace and Nuclear Engineering
University of California, Los Angeles
Los Angeles, CA 90024
(213) 825-7697

Program Manager: Dr Anthony K Amos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-4937

Objective: To develop a control-augmented optimization capability for the efficient aeroelastic tailoring of composite wings and lifting surfaces. The analytical methods to be developed should permit extension of formal optimization procedures in design applications beyond current capabilities.

PREPARATION AND CHARACTERIZATION OF CARBON AND SI(C) FILAMENTS
F49620-86-C-0083
15 November 87 - 14 October 89

Principal Investigator: Professor Ian L Spain
Department of Physics
Colorado State University
Fort Collins, CO 80523
(303) 491-6076

Program Manager: Major Joseph W Hager
AFOSR/NE
Bolling AFB DC 20332-6448
(202) 767-4933

Objective: The objectives of this research are to establish the principles governing the growth of carbon and silicon carbide filaments and to study the interrelationships of crystal structure, microstructure and electrical and mechanical properties of these microscale materials.

A STUDY OF THE CRITICAL FACTORS CONTROLLING THE SYNTHESIS OF CERAMIC MATRIX COMPOSITES FROM PRECERAMIC POLYMERS
F49620-87-C-0093
15 September 87 - 14 August 90

Principal Investigator: Professor James R Strife
United Technologies Research Center
East Hartford, CT 06108
(203) 727-7270

Program Manager: Major Joseph W Hager
AFOSR/NE
Bolling AFB DC 20332-6448
(202) 767-4933

Objective: The objective of this research is to investigate the critical factors which determine the mechanical properties of composites synthesized from a preceramic polymer matrix and carbon or ceramic fibers.

A COMPREHENSIVE STUDY ON DAMAGE TOLERANCE PROPERTIES OF NOTCHED COMPOSITE LAMINATES
AFOSR-84-0334
30 September 85 - 29 September 87

Principal Investigator: Dr Albert S D Wang
Department of Mechanical Engineering and Mechanics
Drexel University
Philadelphia, PA 19104
(215) 895-2297

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To conduct a comprehensive analysis of the stress fields in notched laminates so as to develop a fundamental understanding of the damage mechanisms near the notch region.

INVESTIGATIONS OF THERMALLY-INDUCED DAMAGE IN COMPOSITES

AFOSR-87-0128

01 March 87 - 29 February 88

Principal Investigator: Dr Y Weitsman
Department of Civil Engineering
Texas A-M University
College Station, TX 77843
(409) 845-7512

Program Manager: Major George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop a constitutive model, generic to the response of composite materials under load, temperature, and moisture. Special emphasis is placed on the evolution of damage within the material under the influence of interacting drivers such as the diffusion of moisture and temperature.

NASA LANGLEY RESEARCH CENTER

IN-HOUSE

DELAMINATION MICROMECHANICS ANALYSIS

85 October 1 - 88 September 30

Project Engineer: Dr. John H. Crews, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23365-5225
(804) 865-3048 FTS 928-3048

Objective: To develop a fiber-resin stress analysis for region near a delamination front subjected to Mode I loading.

EFFECT OF IMPACT ON FWC FOR SPACE SHUTTLE'S SRBs

83 August - 88 September

Project Engineer: C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2338 FTS 928-2338

Objective: To determine the strength loss of filament wound cases (FWCs) due to low velocity impact.

DAMAGE TOLERANT COMPOSITE STRUCTURES

74 June 1 - 88 September 30

Project Engineer: C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2338 FTS 928-2338

Objective: To measure the ability of buffer strips and bonded stringers to increase the residual tension strength of damaged panels, and to develop an analysis to predict residual strength in terms of panel configuration and damage size.

PREDICTION OF INSTABILITY-RELATED DELAMINATION GROWTH

79 January 2 - 88 June 1

Project Engineer: John D. Whitcomb
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-3046 FTS 928-3046

Objective: To predict the rate of instability-related delamination growth. Rigorous and approximate techniques for calculating strain-energy release rates have been developed for two-dimensional configurations. The current effort is concentrating on three-dimensional configurations. Experiments are planned for evaluation of the analytical methodology.

CHARACTERIZATION OF MODE I AND MODE II DELAMINATION GROWTH AND THRESHOLDS IN GRAPHITE/PEEK COMPOSITES

87 June - 88 May

Project Engineer: Ms. Gretchen B. Murri
Aerostructures Directorate, USAARTA (AVSCOM)
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23365-5225
(804) 865-2093 FTS 928-2093

Objective: To characterize the Mode I and Mode II delamination failures of graphite/PEEK composite using the double cantilevered beam (DCB) and end-notched flexure (ENF) tests. A fatigue delamination growth criteria and threshold value for no-crack growth will be established.

INTERLAMINAR SHEAR FRACTURE TOUGHNESS

87 May - 87 December

Project Engineer: Ms. Gretchen B. Murri
Mail Stop 188E
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2093 FTS 928-2093

Objective: This program is part of a round robin of fracture toughness tests organized by ASTM Committee D30 on High Modulus Fibers and Their Composites. The end-notched flexure tests will be used to measure the Mode II strain energy release rate of two composite materials. Data reduction methods will be compared. Results will be compared with those of other test labs participating and will be used to develop ASTM test standards for interlaminar shear fracture toughness.

DELAMINATION GROWTH IN TAPERED COMPOSITE LAMINATES WITH INTERNAL PLY DROPS

86 June - 88 December

Project Engineer: Dr. T. Kevin O'Brien
Mail Stop 188E
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2093 FTS 928-2093

Objective: In tapered composites containing internal ply drops which undergo tension and bending loads, delamination failures are typically observed at the locations of the ply drops. The objective of this program is to develop analyses which accurately model this delamination failure mode.

INTERLAMINAR FRACTURE TOUGHNESS TESTING OF COMPOSITES

86 April - 88 April

Project Engineer: Dr. T. Kevin O'Brien
Mail Stop 188E
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2093 FTS 928-2093

Objective: In order to develop standard tests for measuring interlaminar fracture toughness of composites, ASTM Committee D30 on High Modulus Fibers and Their Composites has organized a round robin series of four test methods. The double cantilevered beam (DCB), edge delamination tension (EDT), cracked lap shear (CLS) and end-notched flexure (ENF) tests will be evaluated by a total of 32 laboratories using 3 different materials, ranging from very brittle to very tough.

ADVANCED COMPOSITES FOR PRECISION REFLECTORS IN SPACE
85 October 1 - 90 September 30

Project Engineer: Dr. Stephen S. Tompkins
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-4558 FTS 928-4558

Objective: To develop dimensionally stable, graphite reinforced polymer matrix and ceramic matrix composites for high precision, stable reflectors for space. Develop low expansion epoxy resin for composite materials.

DIMENSIONAL STABILITY OF METAL-MATRIX COMPOSITES IN THE SPACE ENVIRONMENT
82 October 1 - 89 September 30

Project Engineer: Dr. Stephen S. Tompkins
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-5225 FTS 928-4558

Objective: To develop dimensionally stable, graphite reinforced metal-matrix composite materials for space structures. Develop analytical methods to predict dimensional changes induced by thermal cycling and long-time exposure to the space environment.

EXPERIMENTAL EVALUATION OF ADVANCED COMPOSITE MATERIAL FORMS
84 June 1 - 89 June 1

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2869 FTS 928-2869

Objective: To determine mechanical properties and establish damage tolerance of 2-D- and 3-D woven, stitched, and braided composite materials.

FLIGHT SERVICE EVALUATION OF COMPOSITE COMPONENTS ON COMMERCIAL AND MILITARY AIRCRAFT
72 March 1 - 90 December 31

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2869 FTS 928-2869

Objective: To evaluate the long-term durability of composite components installed on commercial and military transport and helicopter aircraft. Over 300 components constructed of boron, graphite, and Kevlar composites will be evaluated after extended service. Components include graphite/epoxy rudders, spoilers, tail rotors, vertical stabilizers, Kevlar/epoxy fairings, doors and ramp skins, and boron/aluminum aft pylon skins. Note: Over 4.2 million total component flight hours have been accumulated since initiation of flight service in 1972. Composite components on L-1011, B-737, and DC-10 aircraft have accumulated over 39,000 flight hours each. Excellent in-service performance and maintenance experience has been achieved with the composite components.

THE ENERGY ABSORPTION OF COMPOSITES
80 August 1 - 88 July 31

Project Engineer: Mr. Gary L. Farley
Mail Stop 188B
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2850 FTS 928-2850

Objective: To develop an understanding of the energy absorption mechanisms of composite materials and how the constitutive properties and specimen architecture effect energy absorption capability. Develop subfloor structural concepts and the analytical ability to predict their energy absorption.

ADVANCED CONCEPTS FOR COMPOSITE HELICOPTER FUSELAGE STRUCTURES

83 April 1 - 92 January 1

Project Engineer: Mr. Donald J. Baker
Mail Stop 188B
Aerostructures Directorate, USAARTA (AYSCOM)
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2850 FTS 928-2850

Objective: To investigate new design concepts for composite materials on lightly loaded helicopter fuselage structures. Trade studies will be performed using the computer code PASC0. A 4-year task assignment contract will be awarded in Fiscal Year 1988 to fabricate selected designs that will be tested at NASA Langley.

POSTBUCKLING AND CRIPPLING OF COMPRESSION-LOADED COMPOSITE STRUCTURAL COMPONENTS
79 March 1 - 88 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Objective: To study the postbuckling and crippling of compression-loaded composite components and to determine the limitations of postbuckling design concepts in structural applications.

DESIGN TECHNOLOGY FOR STIFFENED CURVED COMPOSITE PANELS
79 October 1 - 88 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Objective: To develop verified design technology for generic advanced-composite stiffened curved panels.

POSTBUCKLING OF FLAT STIFFENED GRAPHITE/EPOXY SHEAR WEBS
81 July 1 - 88 September 30

Project Engineer: Mr. Marshall Rouse
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-4585 FTS 928-4585

Objective: To study the postbuckling response and failure characteristics of flat stiffened graphite/epoxy shear webs.

POSTBUCKLING ANALYSIS OF GRAPHITE/EPOXY LAMINATES
80 October 1 - 88 September 30

Project Engineer: Dr. Manuel Stein
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2813 FTS 928-2813

Objective: To develop accurate analyses for the postbuckling response of graphite/epoxy laminates and to determine the parameters that govern postbuckling behavior.

CRASH CHARACTERISTICS OF COMPOSITE FUSELAGE STRUCTURES
82 July 1 - 88 September 30

Project Engineer: Mr. Huey D. Carden
Mail Stop 495
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-3795 FTS 928-3795

Objective: To study the crash characteristics of composite transport fuselage structural components.

BUCKLING AND STRENGTH OF THICK-WALLED COMPOSITE CYLINDERS
86 October 1 - 88 September 30

Project Engineer: Ms. Dawn C. Jegley
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-4052 FTS 928-4052

Objective: To develop accurate analyses for the buckling and strength predictions of thick-walled composite cylinders.

ADVANCED COMPOSITE STRUCTURAL CONCEPTS
84 October 1 - 88 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Objective: To develop composite structural concepts and design technology needed to realize the improved performance, structural efficiency, and lower-cost advantage offered by new material systems and manufacturing methods for advanced aircraft structures.

COMPRESSION STRENGTH OF COMPOSITE LAMINATES WITH DAMAGE AND LOCAL DISCONTINUITIES
76 October 1 - 88 September 30

Project Engineer: Dr. Mark J. Stuart
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23365-5225
(804) 865-2813 FTS 928-2813

Objective: To study the effects of impact damage and local discontinuities on the compression strength of composite structural components, to identify the failure modes that govern the behavior of compression loaded components subjected to low-velocity impact damage, and to analytically predict failure and structural response.

MECHANICS OF ANISOTROPIC COMPOSITE STRUCTURES
86 October 1 - 88 September 30

Project Engineer: Dr. Michael P. Nemeth
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-4052 FTS 928-4052

Objective: To develop analytical procedures for anisotropic structural components that accurately predict the response of tailored structures.

MICROMECHANICS MODELING OF COMPOSITE THERMOELASTIC BEHAVIOR
86 October 1 - 88 October 1

Project Engineer: Mr. David E. Bowles
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804)865-4558 FTS 928-4558

Objective: Develop analytical methods to investigate thermally induced deformations and stresses in continuous fiber reinforced composites at the micromechanics level, and predict how these deformations and stresses affect the dimensional stability of the composite.

CONTRACTS

CRACK PROBLEMS IN ORTHOROPIC PLATES AND NONHOMOGENEOUS MATERIALS
NAG-1-713
86 November 1 - 87 October 31

Project Engineer: Dr. C. A. Bigelow
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-3047 FTS 928-3048

Principal Investigator: Dr. Fazil Erdogan
Department of Mechanical Engineering and Mechanics
Lehigh University
Bethlehem, PA 18015
(215) 758-3000

Objective: The objective of this program is the study of plate and shell structures containing surface cracks under mixed mode loading conditions, the consideration of crack closure on the compression side of plate with a through crack under bending, the determination of the profile of a subcritically growing crack in a plate under bending and membrane loading, and the modeling of the interface region in bonded materials.

THE INFLUENCE OF WAVY LAYERS ON LAMINATE STRENGTH
NAG-1-711
86 October 15 - 87 December 15

Project Engineer: Clarence C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2338 FTS: 928-2338

Principal Investigator: Dr. Charles E. Harris
Department of Aerospace Engineering/Texas Engineering
Experiment Station
Texas A&M University System
College Station, TX 77843

Objective: Determine the influence of wavy layers on the tensile strength of laminated composites using an analysis based on variational principles. Experiments with Moire interferometry will be used to verify the analysis.

FRACTURE OF THICK COMPOSITE LAMINATES DUE TO COMBINED TENSILE AND BENDING LOADS

NAG-1-264

87 January 1 - 87 December 31

Project Engineer: Clarence C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665-5225
Hampton, Virginia 23665-5225
(804) 865-2338 FTS: 928-2338

Principal Investigators: Dr. D. H. Morris and Dr. R. A. Simonds
Department of Engineering Science and Mechanics
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Objective: Compare linear elastic fracture mechanics with the fracture behavior of a thick, quasi-isotropic graphite/epoxy laminate with surface cuts subjected to simultaneous tensile and bending loads.

COMPRESSION CREEP OF FILAMENTARY COMPOSITES

NAG-1-621

85 October 1 - 87 December 31

Project Engineer: John D. Whitcomb
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-3046 FTS 928-3046
Mail Stop 188E

Principal Investigators: Dr. K. Y. Lin
Department of Aeronautics and Astronautics Engineering
FS-10
University of Washington
Seattle, WA 98195
(206) 543-6334

Dr. Mark Tuttle
Department of Mechanical Engineering
FU-10
University of Washington
Seattle, WA 98195
(206) 543-0299

Objective: The objectives of this program are to measure strain redistribution in a notched laminate subjected to sustained compression loads and to predict this redistribution using visco-elastic finite-element analysis. The primary challenges were to develop a Moire measurement procedure and an efficient stress analysis.

MICROMECHANICS OF COMPOSITE LAMINATE COMPRESSIVE FAILURE

NAG-1-659

86 February 1 - 88 June 30

Project Engineer: John D. Whitcomb
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-3046 FTS 928-3046

Principal Investigator: Dr. Walter Bradley
Department of Mechanical Engineering
Texas A&M University
College Station, TX 77843

Objective: The objective of this program is to characterize the compressive failure behavior of notched laminates under static and sustained loads. Both room temperature and elevated temperature conditions are being examined.

ANALYSIS OF DELAMINATION RELATED FRACTURE PROCESSES IN COMPOSITES

NAG-1-637

87 February 12 - 88 February 11

Project Engineer: Dr. T. Kevin O'Brien
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Mail Stop 188E
Hampton, Virginia 23665-5225
(804) 865-2093 FTS 928-2093

Principal Investigator: Dr. Lawrence W. Rehfield
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

Objective: The objective of this program is to extend an existing sublamine analysis method to model tapered ply-drop configurations and delaminations initiating from internal ply cracks. The analyses are intended for use on personal class computers.

THERMAL AND SPECTRUM LOADING EFFECTS ON STRAIN ENERGY RELEASE RATES DURING TENSILE FATIGUE TESTING UTILIZING THE EDGE DELAMINATION TEST

NAG-1-674

86 June 1 - 87 October 31

Project Engineer: Dr. T. Kevin O'Brien
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Mail Stop 188E
Hampton, Virginia 23665-5225
(804) 865-2093 FTS 928-2093

Principal Investigator: Dr. Richard S. Zimmerman
Department of Mechanical Engineering
University of Wyoming
Laramie, WY 82071

Objective: The objective of this program is to study the thermal and spectrum loading effects in fatigue on strain energy release rates of carbon fiber reinforced composite laminates using the edge delamination test.

INTERFACE DAMAGE GROWTH IN COMPOSITE LAMINATES WITH INTERLEAVES

NAG-1-629

87 January 1 - 87 August 15

Project Engineer: Dr. T. Kevin O'Brien
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Mail Stop 188E
Hampton, Virginia 23665-5225
(804) 865-2093 FTS 928-2093

Principal Investigator: Dr. James G. Goree
Department of Mechanical Engineering
Clemson University
Clemson, SC 29634-0921

Objective: The objective of this program is to extend an existing two-dimensional shear lag model to a popular class of laminated composites containing adhesive layers and to optimize the interleaf thickness to prevent splitting. By rotating the analysis to model the thickness, delamination growth from matrix cracks in off-axis plies can be modeled, and strain energy release rates and stress intensity factors can be determined.

RESIDUAL THERMAL STRESSES IN METAL MATRIX COMPOSITES

L-24457C

87 July - 88 January

Project Engineer: Dr. W. S. Johnson
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2715 FTS 928-2715

Principal Investigator: Dr. Yehia A. Bahei-El-Din
Department of Civil Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180-3590
(518) 276-8043

Objective: This contract is to develop an analytical method for estimating residual thermal stresses in continuous fiber-reinforced metal matrix composites due to fabrication and/or subsequent thermal cycling.

FRACTOGRAPHY OF COMPOSITE MATERIALS

NAG-1-705

86 October 1 - 88 September 30

Project Engineer: Dr. John H. Crews, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23365-5225
(804) 865-3048 FTS 928-3048

Principal Investigator: Dr. W. D. Bascom
Department of Materials Science and Engineering
University of Utah
Salt Lake City, Utah 84112

Objective: To analyze the laminate microdamage that accompanies delamination.

ANALYSIS OF A DELAMINATION FRONT

NAG-1-474

84 May 1 - 88 April 30

Project Engineer: Dr. John H. Crews, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23365-5225
(804) 865-3048 FTS 928-3048

Principal Investigator: Dr. W. G. Knauss
Aeronautics and Applied Mechanics Department
California Institute of Technology
Pasadena, California 91125
(213) 356-4524

Objective: To evaluate toughening mechanisms at a delamination front in a DCB specimen.

THERMALLY INDUCED INTERFACIAL STRESS-STRAIN BEHAVIOR IN RESIN MATRIX COMPOSITES

NAS1-18231

87 August 1 - 88 July 31

Project Engineer: Mr. David E. Bowles
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-4558 FTS 928-4558

Principal Investigator: Dr. W. L. Morris
Rockwell Science Center
P. O. Box 1085
Thousand Oaks, CA 91360
(805) 373-4287

Objective: Experimentally and analytically investigate the thermally induced interfacial stress-strain behavior in aerospace resin matrix composites.

IN-SITU STUDY OF DELAMINATION TOUGHENING MECHANISMS

NAG-1-443

84 February 1 - 88 December 31

Project Engineer: Dr. John H. Crews, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-3048 FTS 928-3048

Principal Investigator: Dr. W. L. Bradley
Department of Mechanical Engineering
Texas Engineering Experiment Station
Texas A&M University
College Station, Texas 77843
(409) 845-1259

Objective: To identify the toughening (deformation) mechanisms associated with delamination in tough composites.

EFFECTS OF STRESS CONCENTRATIONS IN COMPOSITE STRUCTURES

NSG-1483

78 January 15 - 88 January 14

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Principal Investigator: Dr. Wolfgang G. Knauss
California Institute of Technology
Pasadena, California 91125
(213) 356-4524/4528

Objective: To study the effects of low-speed impact damage in composite structural components using high-speed motion pictures and to develop an analytical procedure for the propagation of the resulting impact damage.

ADVANCED COMPOSITE STRUCTURAL DESIGN TECHNOLOGY FOR COMMERCIAL TRANSPORT AIRCRAFT

NAS1-15949

79 September 24 - 88 September 23

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Principal Investigator: Mr. John N. Dickson
Lockheed-Georgia Company
86 South Cobb Drive
Marietta, Georgia 30063
(404) 425-6718

Objective: To design, analyze, fabricate, and test generic advanced-composite structural components for transport aircraft applications in order to develop verified design technology.

STRUCTURAL OPTIMIZATION FOR IMPROVED DAMAGE TOLERANCE

NAG-1-168

81 September 1 - 88 October 15

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Principal Investigator: Dr. Raphael T. Haftka
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061
(703) 961-4860

Objective: To develop a structural optimization procedure for composite wing boxes that includes the influence of damage-tolerance considerations in the design process.

EFFECTS OF STRESS CONCENTRATIONS IN COMPOSITE STRUCTURES

MSG-1483

78 January 15 - 88 January 14

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Principal Investigator: Dr. Wolfgang G. Knauss
California Institute of Technology
Pasadena, California 91125
(213) 356-4524/4528

Objective: To study the effects of low-speed impact damage in composite structural components using high-speed motion pictures and to develop an analytical procedure for the propagation of the resulting impact damage.

ADVANCED COMPOSITE STRUCTURAL DESIGN TECHNOLOGY FOR COMMERCIAL TRANSPORT AIRCRAFT

NAS1-15949

79 September 24 - 88 September 23

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Principal Investigator: Mr. John N. Dickson
Lockheed-Georgia Company
86 South Cobb Drive
Marietta, Georgia 30063
(404) 425-6718

Objective: To design, analyze, fabricate, and test generic advanced-composite structural components for transport aircraft applications in order to develop verified design technology.

STRUCTURAL OPTIMIZATION FOR IMPROVED DAMAGE TOLERANCE

NAG-1-168

81 September 1 - 88 October 15

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Principal Investigator: Dr. Raphael T. Haftka
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061
(703) 961-4860

Objective: To develop a structural optimization procedure for composite wing boxes that includes the influence of damage-tolerance considerations in the design process.

FAILURE ANALYSIS AND DAMAGE TOLERANCE OF COMPOSITE AIRCRAFT STRUCTURES

NAS1-17925

85 February 23 - 88 February 22

Project Engineer: Dr. Mark J. Shuart
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2813 FTS 928-2813

Principal Investigator: Dr. Sherrill B. Biggers
Lockheed-Georgia Company
86 South Cobb Drive
Marietta, Georgia 30063
(404) 424-5854

Objective: To develop advanced structural concepts and to advance the analytical capability to predict composite structure failure.

USING CONEJENT RADIATION IN FIBER OPTICS AS AN NDE TOOL

NAG-1-68

85 October 1 - 86 September 30

Project Engineer: Dr. Joseph S. Heyman
Mail Stop 231
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-3036 FTS 928-3036

Principal Investigator: Dr. Richard O. Claus
Department of Electrical Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061
(703) 961-6646

Objective: The objective is to study the use of fiber optics that are implanted in composites for the continuous monitoring of stress and damage in the composites.

ANISOTROPIC SHELL ANALYSIS

NAG-1-665

86 October 1 - 88 September 30

Project Engineer: Dr. Michael P. Nemeth
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-4052 FTS 918-4052

Principal Investigator: Dr. Michael W. Myer
University of Maryland
College Park, Maryland 20742
(202) 454-8878

Objective: To develop accurate analyses for the response of anisotropic composite shell structures.

THICKNESS DISCONTINUITY EFFECTS

NAG-1-537

85 October 1 - 88 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Principal Investigator: Dr. Eric R. Johnson
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061
(703) 961-6699

Objective: To develop verified analytical models of compression loaded laminates with thickness discontinuities and dropped plies.

DESIGN OF ANISOTROPIC PLATES FOR IMPROVED DAMAGE TOLERANCE

NAG-1-643

85 October 1 - 88 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2552 FTS 928-2552

Principal Investigator: Dr. Zafer Gurdal
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061
(703) 961-5905

Objective: To develop structural optimization procedures and failure analyses for anisotropic panels with discontinuities and geodesic stiffness.

ANISOTROPIC PLATE ANALYSIS
NAG-1-749
86 October 1 - 88 September 30

Project Engineer: Dr. Manuel Stein
Mail Stop 190
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2813 FTS 928-2813

Principal Investigator: Dr. Liviu Librescu
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 20461
(703) 961-5916

Objective: To develop analytical models for the behavior of elastic anisotropic laminated composite flat structures subjected to deterministic and random loadings.

DEVELOPMENT OF AN IN-PLANE SHEAR MATERIAL PROPERTY TEST FOR COMPOSITE LAMINATES
NCC-1-93
85 November 1 - 88 August 31

Project Engineer: Mr. Gary L. Farley
Mail Stop 188B
Aerstructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2850 FTS 928-2850

Principal Investigator: Dr. John M. Kennedy
Department of Mechanical Engineering
Clemson University
Clemson, SC
(803) 656-5632

Objective: To develop an improved in-plane shear test method for determining the in-plane shear stiffness and strength of metallic and composite materials. Develop methods of introducing the load into the specimen in a uniform manner and experimentally validate the test method.

INFLUENCE OF CONSTITUENT PROPERTIES AND GEOMETRIC FORM ON COMPOSITE PROPERTIES
83 June 1 - 87 October 1

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2869 FTS 928-2869

Principal Investigator: Dr. Dale Wilson
Center for Composite Materials
University of Delaware
201 Spencer Laboratory
Newark, Delaware 19711
(303) 451-8960

Objective: To correlate predicted and measured response of 3-D orthogonal composite materials. Included will be 3-D finite-element modeling and graphite/thermoplastic composites.

DEVELOPMENT OF ADVANCED WOVEN COMPOSITE MATERIALS AND STRUCTURAL FORMS

NAS1-18358

86 August 29 - 90 August 29

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2869 FTS 928-2869

Principal Investigator: Ms. Janice Maiden
Textile Technologies, Inc.
2800 Turnpike Drive
Hatboro, Pennsylvania 19040
(215) 443-5325

Objective: To develop textile technology to produce 2-D and 3-D woven preforms and structural elements with integral stiffening, multilayers, and multidirectional reinforcement.

ANALYSIS OF 2-D AND 3-D REINFORCED COMPOSITES

NAS1-18000

87 March 1 - 90 March 1

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-2869 FTS 928-2869

Principal Investigator: Mr. Raymond L. Foye
PRC Kentron, Inc.
Hampton, Virginia 23665-5225
(804) 865-2850 FTS 928-2850

Objective: To develop analytical methods to understand and predict the elastic and strength response of 2-D and 3-D reinforced composite materials. Emphasis is on improved fracture toughness and impact resistance for woven, stitched, and braided material forms.

ENVIRONMENTAL EXPOSURE EFFECT ON COMPOSITE MATERIALS FOR COMMERCIAL AIRCRAFT

NAS1-15148

77 November 1 - 88 November 30

Project Engineer: Dr. Ronald K. Clark
Mail Stop 193
NASA Langley Research Center
Hampton, Virginia 23665-5225
(804) 865-4557 FTS 928-4557

Principal Investigator: Mr. Randy Coggeshall
Boeing Commercial Airplane Company
P. O. Box 3707
Seattle, Washington 98124
(206) 251-2705

Objective: To provide technology in the area of environmental effects on graphite/epoxy composite materials, including long-term performance of advanced resin-matrix composite materials in ground and flight environments.

COMPOSITES CHARACTERIZATION WORK BREAKDOWN STRUCTURE WBS-79
Active Program 1975 - Present

Program Leader: Joseph S. Heyman
IRD, Materials Characterization Instrumentation Section
NASA Langley Research Center
Mail Stop 231
Hampton, VA 23665-5225
(804) 865-3036 FTS 928-3036

Objective: Develop quantitative measurement and technology to characterize properties of composites nondestructively and link physical properties thus measured to engineering properties needed for materials and structures certification.

QUANTITATIVE PREDICTIONS OF STRENGTH USING NDE ON IMPACT DAMAGED COMPOSITES
January 1985 - September 1989

Research Scientist: Eric I. Madaras
IRD, Materials Characterization Instrumentation Section
NASA Langley Research Center
Mail Stop 231
Hampton, VA 23665-5225
(804) 865-3036 FTS 928-3036

Objective: The objective of this work is to develop advanced measurement systems for improved non-destructive characterization of composite materials. Recent work has included quantitative evaluations of impact damage, porosity, and other material defects in composites and efforts are being made to relate these measurements to materials strength.

IMAGE ENHANCEMENT TECHNIQUES FOR QUANTITATIVE EVALUATION STUDIES OF COMPOSITE MATERIALS
June 1986 - September 1989

Research Scientist: Patrick H. Johnston
IRD, Materials Characterization Instrumentation Section
NASA Langley Research Center
Mail Stop 231
Hampton, VA 23665-5225
(804) 865-3036 FTS 928-3036

Objective: To combine quantitative techniques of measurement science with methods of image production, enhancement, and display to aid in the nondestructive characterization and evaluation of composite structures.

DEVELOP NDE MEASUREMENT TECHNIQUES TO DETERMINE ENGINEERING PARAMETERS FOR METAL MATRIX
September 1985 - September 1989

Research Scientist: William T. Yost
IRD, Materials Characterization Instrumentation Section
NASA Langley Research Center
Mail Stop 231
Hampton, VA 23665-5225
(804) 865-3036 FTS 928-3036

Objective: To compare engineering based measurements with other physical measurements in metal matrix composites. This is done through cooperation of and with our Materials Division.

INVESTIGATION OF METHODS FOR MONITORING CURE PROCESSING OF COMPOSITES USING OPTICAL FIBER SENSORS

September 1986 - September 1989

Research Scientist: Robert S. Rogowski
IRD, Materials Characterization Instrumentation Section
NASA Langley Research Center
Mail Stop 231
Hampton, VA 23665-5225
(804) 865-3036 FTS 928-3036

Objective: Investigate fiber-optic sensors as potential internal sensors for composite materials. The embedded sensors are intended to monitor cure processing and subsequently serve as sensors for strain temperature, physical and chemical damage and other parameters important to the function of the material during use.

USE OF ULTRASONIC TECHNIQUES FOR COMPOSITE CURE MONITORING AND CHARACTERIZATION OF RESIN SYSTEM DURING PROCESSING

September 1983 - September 1989

Research Scientist: William P. Winfree
IRD, Materials Characterization Instrumentation Section
NASA Langley Research Center
Mail Stop 231
Hampton, VA 23665-5225
(804) 865-3036 FTS 928-3036

Objective: The objective of this program is to develop techniques for determining the material properties of composites during their cure. These material properties can be used as inputs to a process controller which can tailor a process to maximize the integrity of a composite. The research has concentrated on using ultrasonic techniques, with both conventional transducers and acoustic wave guides as sensors.

GRANTS

Project Engineer: Eric I. Madaras
IRD, Materials Characterization Instrumentation Section
NASA Langley Research Center
Mail Stop 231
Hampton, VA 23665-5225
(804) 865-3036 FTS 928-3036

QUANTITATIVE NON-DESTRUCTIVE EVALUATION OF COMPOSITE MATERIALS BASED ON ULTRASONIC WAVE PROPAGATION

NSG-1-601

September 1981 - September 1989

Principal Investigator: James G. Miller
Department of Physics
Washington University
St. Louis, MO 63130

Objective: The overall goal of our research program is the development and application of quantitative ultrasonic techniques to problems of non-destructive evaluation of composite materials. One goal of this work is to demonstrate the potential application of approaches based on the relationship between frequency dependent attenuation and dispersion to non-destructive evaluation of porosity. A second goal is the use of quantitative polar backscatter and attenuation measurements to characterize material properties.

INVESTIGATION OF ACOUSTIC PROPERTIES OF COMPOSITE MATERIALS

NAG-1-431

September 1983 - September 1989

Principal Investigator: **Barry T. Smith**
Department of Physics
Christopher Newport College
Newport News, VA 23606

Objective: The research involves an investigation of the ultrasonic acoustic properties of composite materials. The objective is to characterize the material as well as develop means of assessing any damage. Research to date has included quantitative measurement of impact damage in thin graphite/epoxy composites, evaluation of porosity and determination of fundamental ultrasonic properties to elucidate the propagation of ultrasonic waves in these materials.

DEVELOPING AN ACOUSTIC EMISSION TECHNIQUE FOR TESTING SOLID ROCKET MOTOR O-RING SEALS

NGT 50214

June 1987 - June 1990

Principal Investigator: **Michael Gorman**
Department of Engineering Mechanics
The University of Nebraska - Lincoln
Lincoln, NE 68588

Objective: Measuring spectral content of acoustic emission from single and multiple fiber brakes under various load sharing arrangements. Also, measuring spectral content and carrying out parametric studies of acoustic emission from breaking adhesive bonds.

FIBER WAVEGUIDE SENSORS FOR INTELLIGENT MATERIALS

NAG-1-7801

September 1983 - September 1989

Project Engineer: **Robert S. Rogowski**
IRD, Materials Characterization Instrumentation Section
NASA Langley Research Center
Mail Stop 231
Hampton, VA 23665-5225
(804) 865-3036 FTS 928-3036

Principal Investigator: **Richard O. Claus**
Department of Electrical Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Objective: Program Objective - Development of fiber-optic based opto-electronic sensing instrumentation for the characteristic of materials and materials structures.

Current Research Goals:

1. Design and implementation of embedded optical-fiber sensors for the nondestructive monitoring of material cure, in service structural dynamics and material integrity.
2. Basic research of the operation of discrete fiber sensors and sensor systems.
3. Applied research of multi-parameter and distributed fiber sensor networks.
4. Improvement of such sensors via specialized fiber materials, geometries, codings and opto-electronic processing.

OFFICE OF NAVAL RESEARCH
ARLINGTON, VA 22217-5000

NATIONAL CENTER FOR COMPOSITE MATERIALS RESEARCH

p400013f101

September 86 September 91

Scientific Officer: Dr. Alan S. Kushner
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4305, Autocon 226-4305

Principal Investigator: Prof. S. S. Wang
University of Illinois
Department of Theoretical and Applied Mechanics
Urbana, IL 61801
(217) 333-1835

Objective: Under ONR-URI sponsorship, a National Center for Composite Materials Research will be established to conduct a well structured, multidisciplinary research program in composites spanning the disciplines of solid mechanics, materials science, chemistry and surface physics. Initial emphasis will be on critical research issues associated with the use of thick composites for ship structures.

FLAW GROWTH AND FRACTURE OF COMPOSITE MATERIALS AND ADHESIVE JOINTS

N00014-85-K-0654

July 83 - November 89

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autocon 226-4405

Principal Investigator: Prof. S. S. Wang
University of Illinois
Department of Theoretical and Applied Mechanics
Urbana, IL 61801
(217) 333-1835

Objective: Analytical and numerical studies will be conducted of flaw growth and fracture in fiber reinforced composite laminates and adhesively bonded joints. The interactions between local material instability and global structural instability will be investigated.

NONDESTRUCTIVE EVALUATION AND DAMAGE ACCUMULATION OF COMPOSITES

N00014-87-K-0159

April 87 - March 89

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autocon 226-4405

Principal Investigator: Prof. I. M. Daniel
Northwestern University
Department of Civil Engineering
Evanston, IL 60201
(312) 491-5649

Objective: Research will be conducted to understand the process of damage growth in composite laminates subjected to complex loading states and fatigue.

Nondestructive techniques will be developed to detect and assess damage.

ENVIRONMENTAL EFFECTS AND ENVIRONMENTAL DAMAGE IN COMPOSITES

N00014-82-K-0562

October 84 - September 90

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof. Y. Weitman
Texas A&M University
Department of Civil Engineering
College Station, TX 77843
(713) 845-7512

Objective: Research will be conducted into the effects of stress, temperature and moisture on the mechanical response of polymer composites. Environmentally induced damage growth and its effect on composite response will be investigated.

INVESTIGATION OF IMPACT DAMAGE IN COMPOSITES

N00014-84-K-0460

June 84 - January 88

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof. J. Awerbuch
Drexel University
Department of Mechanical Engineering
Philadelphia, PA 19104
(215) 895-2291

Objective: Investigations of damage in graphite-epoxy laminates due to normal and oblique impact will be conducted using a variety of experimental techniques. The use of acoustic emission for damage assessment will be explored.

DYNAMIC MATRIX CRACKING AND DELAMINATION IN COMPOSITE LAMINATES SUBJECTED TO IMPACT LOADING

N00013-84-K-0554

July 84 - May 89

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof. C. T. Sun
Purdue University
School of Aeronautics and Astronautics
West Lafayette, IN 47907
(317) 494-5130

Objective: The propagation of damage in composite laminates due to impact loading conditions will be investigated using theoretical and experimental techniques. Dynamic delamination models will be established. Concepts for controlling impact damage will be explored.

NONLINEAR MODELS FOR BINARY METAL-MATRIX COMPOSITES

N00014-87-K-0176

February 87 - January 89

Scientific Officer: Dr. A. S. Kushner
Office of Naval Research

Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4305, Autovon 226-4305

Principal Investigator: Prof. H. Murakami
University of California, San Diego
Department of Theoretical and Applied Mechanics
La Jolla, CA 92093
(619) 452-3821

Objective: A nonlinear theory for metal-matrix composites will be developed, based on variational principles and multi-variable asymptotic expansion techniques, and accounting for the effects of fiber breakage, fiber-matrix debonding and slip, matrix plasticity and delaminations.

FRACTURE OF METAL-MATRIX COMPOSITES
N00014-85-K-0247
March 85 - May 89

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof. G. J. Dvorak
Rensselaer Polytechnic Institute
Department of Civil Engineering
Troy, N.Y. 12181
(518) 276-6943

Objective: Investigations of damage growth and fracture in metal-matrix composites will be conducted using experimental and analytical techniques. The bimodal plasticity theory will be extended to account for matrix hardening and for general mechanical loading states.

MECHANICAL PROPERTIES OF COMPOSITES AT ELEVATED TEMPERATURES
N00014-85-K-0480
July 85 - June 88

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof. G. S. Springer
Stanford University
Department of Aeronautics and Astronautics
Stanford, CA 94305
(415) 497-4135

Objective: Mechanics-based models for the temperature dependence of the mechanical properties and failure characteristics of composites will be established.

QUANTITATIVE ULTRANSONIC MEASUREMENTS IN COMPOSITES
N00014-85-K-0460
July 85 - September 89

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof. W. Sachse
Cornell University
Department of Theoretical and Applied Mechanics
Ithaca, N.Y. 14853
(607) 255-5065

Objective: Research will be conducted to establish quantitative active and passive

ultrasonic measurement techniques for characterizing the microstructure and mechanical properties as well as the dynamics of deformation processes in a variety of composite materials.

DAMAGE ASSESSMENT IN COMPOSITES USING ACOUSTO-ULTRASONIC TECHNIQUES

N00014-87-K-0143

February 87 - February 89

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof. H. T. Hahn
Pennsylvania State University
Department of Engineering Science and Mechanics
University Park, PA 16802
(814) 863-0997

Objective: Theoretical and experimental studies will be conducted for the application of the acousto-ultrasonic technique for damage assessment in composites.

DYNAMIC BEHAVIOR OF FIBER AND PARTICLE REINFORCED COMPOSITES

N00014-86-K-0280

October 86 - April 88

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof. S.K. Datta
University of Colorado
Department of Mechanical Engineering
Boulder, CO 80309
(303) 492-7750

Objective: Research will be conducted into the diffraction of elastic waves by cracks and other inhomogeneities in laminated fiber reinforced composites. Investigations of dynamic material properties of fiber and particle reinforced metal-matrix composites will be conducted.

IMPACT RESPONSE AND QNDE OF LAYERED COMPOSITES

N00014-87-K-0351

April 87 - March 89

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington, VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof. A.K. Mal
University of California, Los Angeles
Department of Mechanical, Aerospace and Nuclear Engineering
Los Angeles, CA 90024
(213) 825-5481

Objective: Research will be conducted into wave propagation in composite laminates, with the focus on dynamic loading conditions and theoretical aspects of quantitative acoustic microscopy.

NAVAL RESEARCH LABORATORY
WASHINGTON, DC 20375-5000

STRUCTURAL RESPONSE OF DAMAGED COMPOSITES

October 79 - September 88

Project Engineer: Dr. P.W. Mast

Naval Research Laboratory
Washington, DC 20375-5000
(202) 767-2165 Autovon 297-2165

Objective: Develop a capability for predicting the structural response of composite structures containing a defect or damage.

CONTRACTS

DYNAMIC BEHAVIOR OF COMPOSITES
N00014-86-C-2580
October 86 - September 89

Project Engineer: Dr. Irvin Wolock
Naval Research Laboratory, Code 6383
Washington, DC 20375-5000
(202) 767-2567 Autovon 297-2567

Principal Engineer: Longin B. Greszczuk
McDonnell Douglas Astronautics Company
5301 Bolsa Avenue
Huntington Beach, CA 92647
(714) 896-3810

Objective: Determine the effect of large area dynamic loading on the mechanical response of composite materials.

NAVAL AIR DEVELOPMENT CENTER
WARMINSTER, PA 18974-5000
IN-HOUSE

IMPROVED MATRIX DOMINATED PROPERTIES
October 82 - September 87

Project Engineer: Dr. J.M. Alper
Naval Air Development Center
AVCSTD/6043
Warminster, PA 18974-5000
(215) 441-1134 Autovon 441-1134

Objective: Investigate methods to improve composite performance by reinforcing the matrix with silicon carbide whiskers.

HYBRID COMPOSITE FRACTURE CHARACTERIZATION
September 85 - October 88

Project Engineer: Lee W. Gause
Naval Air Development Center
AVCSTD/6043
Warminster, PA 18974-5000
(215) 441-1330 Autovon 441-1330

Objective: Characterize the strength, mechanical properties, and damage tolerance of woven and hybrid composite structures.

METAL MATRIX CRACK INITIATION/PROPAGATION
September 85 - October 88

Project Engineer: Dr. H.C. Tsai
Naval Air Development Center
AVCSTD/6043
Warminster, PA 18974-5000
(215) 441-2871 Autovon 441-2871

Objective: Characterize the crack initiation/propagation mechanics of silicon carbide/titanium metal matrix composites as applied to landing gear and arrestor hooks in the naval shipboard environment.

CONTRACTS

INFLUENCE OF LOAD FACTORS AND TEST METHODS ON IN-SERVICE RESPONSE OF COMPOSITE MATERIALS AND STRUCTURES

N62269-85-C-0234
June 85 - June 88

Project Engineer: Lee W. Gause
Naval Air Development Center
AVCSTD/6043
Warminster, PA 18974-5000
(215) 441-1330 Autovon 441-1330

Principal Investigator: Prof. K.L. Reifsnider
Virginia Polytechnic and State University
Department of Engineering Science and Mechanics
Blacksburg, VA 24061
(703) 561-5316

Objective: Develop an understanding of the relationship between composite laminate response to high load levels for short time periods and response to low load levels long time periods. Develop an understanding of the relationship between test methods and laminate response. Establish the manner in which these relationships are associated with strength and life. Formulate a mechanistic model which can be used to anticipate long-term behavior.

OUT-OF-PLANE ANALYSIS FOR COMPOSITE STRUCTURES
September 87 - March 89

Project Engineer: E. Kautz
Naval Air Development Center
AVCSTD/6043
Warminster, PA 18974-5000
(215) 441-1561 Autovon 441-1561

Principal Investigator: TBD

Objective: In develop and verify an analysis methodology that provides an up-front capability to identify potential out-of-plane loading situations in composite structures and determine strength and failure mode without resorting to expensive three dimensional finite element analysis.

CERTIFICATION OF COMPOSITE STRUCTURES
September 87 - March 89

Project Engineer: E. Kautz
Naval Air Development Center
AVCSTD/6043
Warminster, PA 18974-5000
(215) 441-1561 Autovon 441-1561

Principal Investigator: TBD

Objective: To expand the certification methodology for composite structures to address adhesively bonded and co-cured construction and the effects of in-service impact damage on static strength and fatigue life of composite structures.

DAVID TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
CARDEROCK, MD 20084
IN-HOUSE

COMPRESSIVE FAILURE OF THICK SECTION COMPOSITE PRESSURE HULL STRUCTURES

PE 61152N
October 86 - Present

Project Engineer: Erik Rasmussen
Code 1720.2
David Taylor Naval Ship R&D Center
Bethesda, MD 20084-5000
(301) 227-1656, Autovon 287-1656

Objective: The objectives of this program are to determine compressive failure mechanisms, identify methods to increase the compressive strength,

and develop analytical methodologies for determining compressive failure strength for thick section fiber reinforced composite structures which are under consideration for submarine pressure hulls.

DYNAMIC FAILURE OF THICK SECTION COMPOSITE PRESSURE HULL STRUCTURES

PE 61152N

October 86 - Present

Project Engineer: Erik Rasmussen
Code 1720.2
David Taylor Naval Ship R&D Center
Bethesda, MD 20084-5000
(301) 227-1656 Autovon 287-1656

Objective: The objective of this program is to develop the experimental and analytical techniques required to assess the dynamic capabilities of proposed composite submarine pressure hull structural and material concepts. Currently, the techniques are available for metallic submarine hull materials but these techniques are not directly applicable to composite materials.

**U.S. ARMY
ARMY RESEARCH OFFICE**

CONTRACTS

TITLE: Optimal Design of Fibered Structures

RESPONSIBLE INDIVIDUAL: J. Chandra
Army Research Office
ATTN: DRXRO-MA
P.O. Box 12211
Research Triangle Park, NC 27709
(919) 544-8213

PRINCIPAL INVESTIGATOR: W.G. Strang
Massachusetts Institute of Technology,
Department of Mathematics, Cambridge, MA 02139

OBJECTIVE: Methods for optimal design of structures with special emphasis on the optimal placement of fibers in order to achieve maximum strength for least weight. The mathematical analysis will provide guidance in designing of new composite materials with desirable material properties. The approach will be based on application of convex analysis to variational principles with inequality constraints.

TITLE: Nature of Fracture Failure in Composite Materials

RESPONSIBLE INDIVIDUAL: R.E. Singleton
Army Research Office
ATTN: DRXRO-EG
P.O. Box 12211
Research Triangle Park, NC 27709
(919) 544-8213

PRINCIPAL INVESTIGATORS: R.N.S. Rad, H.Y. Yeh, C.T. Luke
Prairie View A&M University,
Department of Civil Engineering
Prairie View, TX 77445

OBJECTIVE: To investigate fatigue strength characteristics of boron fiber-aluminum matrix composite materials. Information concerning the fatigue behavior of metal composites is important in the design and analysis of Army structures and material. Fatigue tests will be conducted on an Instron push-pull machine and fractured specimens will be examined on an electron microscope to determine the nature of fracture. The experiments will be carried out over a variety of stresses and a range of boron-aluminum ratios.

TITLE: On the Dynamic Mechanical Behavior of 3-D Integrated Fabric-Reinforced Composites

RESPONSIBLE INDIVIDUAL: G. Mayer
Army Research Office
ATTN: DRXRO-MS
P.O. Box 12211
Research Triangle Park, NC 27709
(919) 544-8213

PRINCIPAL INVESTIGATORS: F.K. Ko, H. Rogers
Drexel University
Department of Materials
Philadelphia, PA 19104

OBJECTIVE: To investigate the dynamic impact resistance of 3-D braided composites. The research is of great importance to the Army, since it could lead to composites that have an added impact resistance. Such new materials may be useful for missile and aircraft applications where complex stresses come into play. A drop-weight impact test and a compressed air gun will be used to determine the dynamic impact resistance. These composites will be compared to other 3-D fabrics. The 3-D braided fabric preform will be designed and manufactured in the Textile Structural Laboratory at Drexel University. Full microstructural analysis will be conducted.

TITLE: Deformation & Fracture Behavior of Metal Matrix Composites

RESPONSIBLE INDIVIDUAL: G. Mayer

Army Research Office
ATTN: DRXRO-MS
P.O. Box 12211
Research Triangle Park, NC 27709
(919) 544-8213

PRINCIPAL INVESTIGATOR: H.J. Rack

Clemson University
Department of Mechanical Engineering
Clemson, SC 29631

OBJECTIVE: To establish a fundamental understanding between microstructure, processing and dynamic mechanical properties in metal-matrix composite systems. Metal matrix composites are of significant relevance to the Army mission, since they are candidate materials for bridges, antenna masts, launchers, etc. Discontinuously reinforced AL composites based on model AL-MG and AL-CU systems will be studied. The high temperature deformation and fracture behavior of these composites will be investigated. The validity of applying linear elastic fracture mechanics as a failure criterion to these composites will be examined.

TITLE: Vibrothermography: Investigation, Development and Application of New
Nondestructive Evaluation Technique

RESPONSIBLE INDIVIDUAL: G. Mayer

Army Research Office
ATTN: DRXRO-MS
P.O. Box 12211
Research Triangle Park, NC 27709
(919) 544-8213

PRINCIPAL INVESTIGATORS: K.L. Reifsnider, E.G. Henneke, and W.W. Stinchcomb

Virginia Polytechnic Institute
Blacksburg, VA 24061

OBJECTIVE: To develop an understanding of the mechanisms of heat generation associated with defects in composite materials and how they relate to strength, stiffness and residual life. The program will include: 1. The development of a model that describes the mechanisms of heat generation by internal flaw surface-to-surface interference; 2. The identification of those materials properties that determine the quantitative suitability of different materials for application of vibrothermography for defect detection, defect monitoring and defect interpretation; 3. The development of an automated procedure for that pattern analysis; and 4. The development of an understanding of that pattern generated by distributions of defects especially as they relate to strength, stiffness and residual life.

TITLE: Manufacturing Science, Reliability, and Maintainability Technology

RESPONSIBLE INDIVIDUALS: A. Crowson

Army Research Office
ATTN: DRXRO-MS
P.O. Box 12211
Research Triangle Park, NC 27709
(919) 544-8213

PRINCIPAL INVESTIGATORS: T.-W. Chou and R.L. McCullough

Center for Composite Materials
University of Delaware
Newark, Delaware 19716

OBJECTIVE: This University Research Initiative Program consists of eight research elements, each led by different primary investigators. The eight elements include cure characterization and monitoring; on-line intelligent nondestructive evaluation for in-process control of composites manufacturing; process simulation, computer-aided manufacturing for filament winding and fiber placement; structure-property relationships of textile structural composites; mechanics of thick section composite laminates; structural performance and durability; and integrated engineering for durable structures. The primary investigators are: R.L. McCullough and M.T. Klein; R.A. Blake; S.I. Gucer; R.B. Pipes; T.-W. Chou; J.W. Gillespie, Jr.; A.P. Majidi; and D.J. Wilkens, respectively. The objective of the program is to address the fundamental issues involved in the manufacturing science, reliability and maintainability of composite structures for future Army systems, with emphasis on thick composite sections.

**U.S. ARMY AVIATION SYSTEMS COMMAND
U.S. ARMY AVIATION RESEARCH AND TECHNOLOGY ACTIVITY**

IN-HOUSE EFFORTS

TITLE: Structural Scaling Methods

RESPONSIBLE INDIVIDUAL: F. Bartlett
U.S. ARMY ARTA
Aerostructures Directorate
Mail Stop 266
Langley Research Center
Hampton, VA 23665-5225
(804) 865-2866

PRINCIPAL INVESTIGATOR: R. Boynott, K. Jackson

OBJECTIVE: The goal of this project is to determine the effectiveness of scale model tests to predict crashworthiness of full-scale graphite/epoxy composite components which are typical of helicopter substructure. Currently, large finite element analyses and full-scale drop tests are used to determine the impact response. Analyses and experimental programs will be conducted to determine the impact response of beams of quarter, half and full scale which are to be loaded to produce dynamic buckling. The beams are to be fabricated in-house and will be constructed of graphite/epoxy composite material. A variety of layups will be tested including unidirectional, cross ply, and angle ply laminates. A fully instrumented drop tower with supporting apparatus is available at the Impact Dynamics Research Facility of NASA Langley Research Center for performing the tests. Measurements of tip deflection, strain, incident velocity, and support reactions will be made during impact. Comparisons of the test results between the scale models and full scale components would verify the model analysis and indicate whether full-scale composite beam behavior can be determined through inexpensive scale-model testing.

TITLE: Structures Technology

RESPONSIBLE INDIVIDUAL: F. Bartlett
U.S. Army ARTA
Aerostructures Directorate
Mail Stop 266
Langley Research Center
Hampton, VA 23665-5225
(804) 865-2866

PRINCIPAL INVESTIGATOR: M. Nixon

OBJECTIVE: To demonstrate new structural concepts and investigate helicopter rotor aeroelastic effects, and to develop accurate techniques for predicting and controlling vibration levels in existing and future Army aircraft. A thrust, where appropriate, will be to integrate recent materials, dynamics, and aerodynamic advances into new concepts. This technology will lead to lightweight, cost effective helicopter structural design methods which will preclude the occurrence of high vibration levels and instabilities to enhance the safety, survivability and mission effectiveness. To this end, the following will be developed: low cost structural concepts for next generation helicopter fuselage structures; new blade and hub concepts that take advantage of improved composite material systems; passive and active vibration control devices; and passive vibration reduction methods based on use of composite materials. Design criteria and techniques will be established for application in the development of helicopters tailored to the Army's mission. These are to be accomplished through systematic jointly-sponsored (with NASA) investigations with wind tunnel tests of the aeroelastic structures and the application of analytical and empirical design methods.

TITLE: Research in Structures

RESPONSIBLE INDIVIDUAL: F. Bartlett
U.S. Army ARTA
Aerostructures Directorate
Mail Stop 266
Langley Research Center
Hampton, VA 23665-5225
(804) 865-2866

PRINCIPAL INVESTIGATORS: K. O'Brien, G. Farley

OBJECTIVE: To provide, in conjunction with NASA-Langley, the fundamental structures and materials application technology necessary for subsequent demonstration of the significant improvements possible in helicopter safety, survivability, and mission effectiveness. Research will be directed to the increase in reliability of composite materials under cyclic and crushing loads through the development of failure-process-related predictive criteria for the myriad of continually changing material systems. Materials application efforts will focus on developing material systems for low-cost composite components, evaluating effectiveness of thin-gage composite and bonded systems, and methods to improve the resistance of composites to low-velocity impacts. These efforts will look toward formulating design and material concepts for crashworthy helicopter fuselage structures.

CONTRACTS

TITLE: Investigation of Fatigue Methodology

RESPONSIBLE INDIVIDUAL: B.S. Spigel
U.S. Army ARTA
Aviation Applied Technology Directorate
Ft. Eustis, VA 23604-5577
(804) 878-5732

PRINCIPAL INVESTIGATOR: D.A. Tice
Kaman Aerospace Corp
Bloomfield, CT 06002

OBJECTIVE: Develop an improved methodology for predicting the structural life of metallic and composite helicopter components. This methodology will provide the certification agencies with an equitable basis for evaluation of proposals, reduce the review burden, and minimize incidental differences between contractor's life predictions. The methodology will also provide helicopter manufacturers with a foundation to enhance their fatigue life determination techniques. Current methods of determining the fatigue lives of helicopter components with emphasis on load prediction techniques, spectrum fatigue, and reliability statistics will be evaluated.

TITLE: Investigation of Fatigue Methodology

RESPONSIBLE INDIVIDUAL: B.S. Spigel
U.S. Army ARTA
Aviation Applied Technology Directorate
Ft. Eustis, VA 23604-5577
(804) 878-5732

PRINCIPAL INVESTIGATOR: A. Berens
University of Dayton
Dayton, OH 45409

OBJECTIVE: Develop an improved methodology for predicting the structural life of metallic and composite helicopter components. This methodology will provide the certification agencies with an equitable basis for evaluation of proposals, reduce the review burden, and minimize incidental differences between contractor's life predictions. The methodology will also provide helicopter manufacturers with a foundation to enhance their fatigue life determination techniques. Current methods of determining the fatigue lives of helicopter components with emphasis on load prediction techniques, spectrum fatigue, and reliability statistics will be evaluated.

TITLE: Structurally Efficient Composite Main Rotor Hub Flexures

RESPONSIBLE INDIVIDUAL: C.F. Swats
U.S. Army ARTA
Aviation Applied Technology Directorate
Ft. Eustis, VA 23604-5577
(804) 878-2975

PRINCIPAL INVESTIGATOR: N. Phillips
Bell Helicopter Corp
Fort Worth, TX 76101

OBJECTIVE: To develop an improved analytical method to provide a better understanding of the complex stress states within a bearingless composite main rotor hub flexure. This includes consideration of interlaminar stresses. An analytical methodology will be developed which is capable of addressing the structural factors which influence stresses

within a composite flexure. The developed methodology will be used to analyze an existing composite flexure and to redesign the flexure such that critical stresses are reduced. The redesigned flexure will be fabricated and static and fatigue tested to assess the predictive capabilities of the method and any strength improvements realized. The method will be modified/simplified if required after analysis of the test results.

TITLE: Damage Tolerance and Durability of Composites on Helicopter Primary Structures

RESPONSIBLE INDIVIDUAL: S. Spiegel
U.S. Army ARTA
Aviation Applied Technology Directorate
Ft. Eustis, VA 23604-5577
(804) 878-5732

PRINCIPAL INVESTIGATOR: C. Rodgers
Bell Helicopter Corp
Ft Worth, TX 76101

OBJECTIVE: The program objective is to establish and verify state-of-the-art design criteria that will assure damage tolerance and durability of fibrous composite primary structures on helicopters designed for the U.S. Army. The program approach is: (1) survey industry and literature for relevant analytic methodologies and NDE technology; (2) select the best methods for damage detection and quantification, and the subsequent fatigue damage accumulation and damage growth rates in fibrous composites; (3) verify the choice through full-scale fatigue testing of an appropriately flawed helicopter component; and (4) summarize concepts in a set of design criteria for composite primary structures on helicopters. Damage tolerance is predicated upon the assumed existence of flaws resulting from manufacture or helicopter operations. Critical flaw sizes, component life and residual strength will be addressed.

U.S. ARMY BALLISTIC RESEARCH LABORATORY

TITLE: Composite Structures

RESPONSIBLE INDIVIDUALS: B.P. Burns, W.H. Drysdale, E.M. Patton
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-IB-M
Aberdeen Proving Ground, MD 21005-5066
(301) 278-6132, 6123, 6805

PERFORMING AGENCIES:

1. The Ballistic Research Laboratory (BRL) -
E.M. Patton, R.P. Kaste
2. The Lawrence Livermore National Laboratory (LLNL) -
R.D. Christensen, W. Feng, F. Magness
P.O. Box 808
Livermore, CA 94550
3. The Air Force Wright Aeronautical Laboratories
Materials Laboratory (AFWAML) - S.W. Tsai
Wright-Patterson AFB
Dayton, OH 45433

OBJECTIVE: The objective of this project is to develop failure criteria, architecture transition technology, and optimum design technology for thick ballistic structures. Rate of loading effects and layup transition studies are being addressed at the BRL: a special, high-rate, propellant-driven test apparatus is under development to generate uniaxial or triaxial stress states at strain rates of up to 200 per second. Three-dimensional failure criteria and other constitutive effects are being studied and hypothesized by the LLNL: they are also sponsoring studies at the University of Utah and the Pennsylvania State University. Experimental activities to develop failure data are being conducted at both the LLNL and the University of Utah. Additional failure criteria work and extensions to optimal notions for relatively simple structures and layup stacking sequences are under investigation at the AFWAML. This work also features biaxial failure tests.

U.S. ARMY BELVOIR RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

CONTRACT

TITLE: High Stability Truss Chord

RESPONSIBLE INDIVIDUAL: C. Kominos
U.S. Army Belvoir Research, Development, and
Engineering Center
ATTN: STRBE-JBC,
Ft. Belvoir, VA 22060-5606
(703) 664-5176

PRINCIPAL INVESTIGATOR: D. Brookstein
Albany International Research Company
Dedham, MA 02026

OBJECTIVE: Develop composite tubular elements with an ultimate capability of 1,200,000 lbs in axial load and a stiffness of 3.0×10^5 lbs-in², utilizing the triaxial braiding method of fabrication. The triaxial structure will consist of 50x10⁶ psi modulus graphite fiber in the longitudinal direction and 30x10⁶ psi modulus fiber in the bias direction.

U.S. ARMY MATERIALS TECHNOLOGY LABORATORY

IN-HOUSE EFFORTS

TITLE: Mechanical Characterization in Support of Lightweight Materials for the Lightweight Howitzer

RESPONSIBLE INDIVIDUAL: P.J. Doyle
Materials Technology Laboratory
ATTN: AMXMR-STM
Watertown, MA 02172-5522
(617) 923-5554

PRINCIPAL INVESTIGATOR: N. Tsangarakis

OBJECTIVE: The objective of this study is to investigate the fatigue behavior of several commercially available metal matrix composites (MMC). These materials are potential candidates for constructing structural members of the lightweight howitzer. Available techniques for fatigue testing MMC will be examined and evaluated. High cycle fatigue data will be generated initially for FP-aluminum. The mechanics leading to fatigue failure will be examined, and research will be extended to MMC other than FP-aluminum.

TITLE: Mechanics of Composites

RESPONSIBLE INDIVIDUAL: R. Lamothe
Materials Technology Laboratory
Watertown, MA 02172-5522
(617) 923-5427

PRINCIPAL INVESTIGATORS: R. Barsoum, D.W. Oplinger, A. Tessler, J. Mescall, M. Roylance, R. Brockleman, D. Neal

OBJECTIVE: To conduct research in the mechanics of composites leading to improved computational approaches for thick composite shells, delamination failure mechanics, ballistic response of adhesive joints, evaluation of blast loadings on thick composite panels, development of joining technology using Moire and laser speckle holography techniques. These efforts are primarily related to the needs of technology demonstrators and as lightweight towed artillery and Bradley hull test beds. Other activities address continuing efforts related to the response of composites to environmental effects, the development of large scale mechanical property data bases, statistical methodology for structural allowables in composites, reliability estimation, and NDE methodology.

U.S. ARMY MISSILE COMMAND

IN-HOUSE EFFORTS

TITLE: Missile Technology/Structures - Composites Design/Construction Methodology

RESPONSIBLE INDIVIDUAL: L.W. Howard
U.S. Army Missile Command
Research, Development, and Engineering Center
ATTN: AMSMI-RD-ST
Redstone Arsenal, Huntsville, AL 35898
(205) 876-1683

PRINCIPAL INVESTIGATOR: R.J. Thompson

OBJECTIVE: To exploit composite materials advantages to increase performance and reduce cost of Army missile systems. The specific areas under investigation in this task are to develop the tools required by the designer to enable him to design missile structures with advanced composite materials. This task addresses three specific problems confronting the designer; lightweight joints in composite motor cases, high efficiency airframe structures, and high temperature capability of composite materials.

U.S. ARMY NATICK RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

IN-HOUSE EFFORTS

TITLE: Hardened Tactical Shelters

RESPONSIBLE INDIVIDUAL: J. Fanucci
Natick Research, Development & Engineering Center
Natick, MA 01760-5000
(617) 651-4697

OBJECTIVE: There is a requirement to develop tactical shelters hardened against nuclear and conventional threats. The primary technical objective is to develop and evaluate design concepts, analytical methods and construction techniques which will be utilized in designing tactical rigid wall shelters against the overpressure. Alternative panel and frame concepts emphasizing optimum lightweight design for a high level overpressure range will be investigated. Alternative thermal protection concepts will be explored. Different composite materials panel/stiffener designs and weight-trade off studies will be conducted using advanced finite element structural techniques.

TITLE: Advanced Composite Applications in Airdrop

RESPONSIBLE INDIVIDUAL: W. Krainski
Natick Research, Development & Engineering Center
Natick, MA 01760-5000
(617) 651-5264

OBJECTIVE: Future warfare will require an even greater need to rapidly transport troops and EQND equipment over the battlefield. This requirement for increased mobility leads to a concomitant need to lighten the equipment needed to accomplish the task. One area in which lightweight, durable equipment is urgently needed is hardware used in the airdrop of personnel and cargo. A number of present day airdrop hardware items currently made of metal will be selected for composite material application. With the aid of computer finite element structural analysis, these components will be redesigned using composite materials. Full advantage of composite fabrication techniques will be taken during the design process.

END

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