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13. ABSTRACT *(Maximum 200 words)*

This work was concerned with research on the fundamental mechanics and mathematics of material failure mechanisms in nonlinear solids and structures. The specific areas investigated were those of void nucleation and growth due to large deformations in non-linear solids and end effects in anisotropic and laminated structures. Research on cavitation phenomena, which serve as a precursor to fracture, is crucial to the understanding of failure mechanisms in rubber-like solids (e.g. polymers, solid rocket propellants, aircraft tires) and of ductile fracture processes in metals. In particular, the work is relevant to the tire degradation problems of concern to Air Force scientists at Wright Patterson AFB. Mathematically, the work involved investigation of singular solutions of the second-order quasilinear system of partial differential equations describing equilibrium states of nonlinearly elastic bodies. For radially symmetric deformations, the basic problem reduces to a bifurcation problem for a single second-order nonlinear ordinary differential equation. Particular emphasis was placed on the effect of material inhomogeneity, compressibility and anisotropy on void nucleation and growth, including non-axisymmetric problems.

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MATERIAL FAILURE MECHANISMS IN NONLINEAR SOLIDS & STRUCTURES

Abstract. This work was concerned with research on the fundamental mechanics and mathematics of *material failure mechanisms* in nonlinear solids and structures. The specific areas investigated were those of *void nucleation and growth* due to large deformations in nonlinear solids and *end effects* in anisotropic and laminated structures. Research on cavitation phenomena, which serve as a precursor to *fracture,* is crucial to the understanding of *failure mechanisms* in rubber-like solids (e.g. polymers, solid rocket propellants, aircraft tires) and of ductile fracture processes in metals. In particular, the work is relevant to the *tire degradation* problems of concern to Air Force scientists at Wright Patterson AFB. Mathematically, the work involved investigation of singular solutions of the second-order quasilinear system of partial differential equations describing equilibrium states of nonlinearly elastic bodies. For radially symmetric deformations, the basic problem reduces to a bifurcation problem for a single second-order nonlinear ordinary differential equation. Particular emphasis was placed on the effect of *material inhomogeneity, compressibility and anisotropy* on void nucleation and growth, including non-axisymmetric problems. Studies on the micromechanics of particles, in particular the correlation of inclusions to void formation, are receiving much attention from the solid mechanics, applied mathematics and materials science communities. This research emphasis continues to be highlighted in National Committee reports on Solid Mechanics and Materials Science, Research Directions. The work also has impact on *failure mechanisms* due to large deformations in *anisotropic* and *composite materials* and due to extended end effects in composite structures. The end effect problem is of current interest to the Boeing Commercial Airplane Group. Compared to the vast amount of information available on small deformations of composite materials, results on large deformations remain virtually unexplored. Considerations of large deformations in anisotropic or composite materials often lead to striking differences from predictions of corresponding linearized theories. In view of the rapid utilization of advanced composite materials in present day Air Force technology, studies on the fundamental mechanics and mathematics of large deformations of such materials promise to have widespread impact on the AFOSR mission.

2. SUMMARY OF RESEARCH RESULTS

This work was concerned with research on the fundamental mechanics and mathematics of *material failure mechanisms* in nonlinear solids and structures. The specific areas investigated were those of *void nucleation and growth* due to large deformations in nonlinear solids and *end effects* in anisotropic and laminated structures. Research on cavitation phenomena, which serve as a precursor to *fracture,* is crucial to the understanding of *failure mechanisms* in rubber-like solids (e.g. polymers, solid rocket propellants, aircraft tires) and of ductile fracture processes in metals. In particular, the work is relevant to the *tire degradation* problems of concern to Air Force scientists at Wright Patterson AFB. Mathematically, the work involved investigation of singular solutions of the second-order quasilinear system of partial differential equations describing equilibrium states of nonlinearly elastic bodies. For radially symmetric deformations, the basic problem reduces to a bifurcation problem for a single second-order nonlinear ordinary differential equation. Particular emphasis was placed on the effect of *material inhomogeneity, compressibility and anisotropy* on void nucleation and growth, including non-axisymmetric problems. Studies on the micromechanics of particles, in particular the correlation of inclusions to void formation, are receiving much attention from the solid mechanics, applied mathematics and materials science communities. This research emphasis continues to be highlighted in National Committee reports on Solid Mechanics and Materials Science, Research Directions. The work also has impact on *failure mechanisms* due to large deformations in *anisotropic* and *composite materials* and due to extended end effects in composite structures. The end effect problem is of current interest to the Boeing Commercial Airplane Group. Compared to the vast amount of information available on small deformations of composite materials, results on large deformations remain virtually unexplored. Considerations of large deformations in anisotropic or composite materials often lead to striking differences from predictions of corresponding linearized theories. In view of the rapid utilization of advanced composite materials in present day Air Force technology, studies on the fundamental mechanics and mathematics of large deformations of such materials promise to have widespread impact on the AFOSR mission.

Cavity nucleation involving the formation and subsequent growth and coalescence of voids from microscopic inclusions leading to ductile fracture in metals and alloys has long been of concern to metallurgists. The phenomenon of sudden void formation ("cavitation") also arises in rubber elasticity and is also of interest in soil mechanics in connection with pile driving. Because of the role such cavitation phenomena play in failure processes for metals and polymers, such problems have attracted much recent attention from the solid mechanics and applied mathematics communities.

The impetus for much of the recent theoretical developments has been supplied by the mathematical work of Ball in 1982 concerned with *singular* solutions in nonlinear elasticity. Ball has studied a class of *bifurcation problems* for the equations of nonlinear elasticity which model the appearance of a cavity in the interior of an apparently solid homogeneous isotropic elastic body once a critical load has been attained. The alternative interpretation for such problems in terms of the growth of a *pre-existing* micro-void is more attractive from a physical point of view. It is important for us to emphasize here that the idealized mathematical treatment using a bifurcation approach does correctly predict the critical load at which a *pre-existing* microvoid will undergo sudden rapid growth. The critical load is automatically given by this approach - imposition of a failure criterion is not necessary. The bifurcation approach to cavitation may thus be viewed as a convenient analytical tool which furnishes values of the critical load. A treatment of the pre-existing traction-free microvoid problem is more complicated analytically. It is also important to note that *infinitesimal* theories of isotropic solid mechanics (including the classical theories of small strain plasticity) do *not* predict this cavitation phenomenon.

In [1], we have written a comprehensive state-of-the-art review article on cavitation, summarizing the major results obtained to-date. This sets the stage for further advances in this area of crucial importance to Air Force technology (see 5 (B,C) below for details on technology transfer). In [1a,b], we have published two major review articles on anti-plane shear deformations [1a] and on the applications of Korn's inequalities in continuum mechanics [1b]. These articles were prepared specially for a general readership and have been widely acclaimed.

A related material instability phenomenon is examined in [2]. Loss of ellipticity in nonlinear equilibrium problems of elasticity has proved to be a very useful way of modeling shear banding and phase transformations in solids. The paper [2] is concerned with providing a simple criterion for predicting such instabilities in a variety of problems for compressible nonlinearly elastic materials. Further results on these issues are contained in [3].

In [4,5], we return to the issue of slow stress diffusion and Saint-Venant end effects in composite structures. Thin-walled structures such as aircraft and automotive parts, rocket casings, helicopter blades and containment vessels are often constructed of layers of anisotropic, filament or fiber-reinforced materials which must be designed to remain elastic. The extent to which *local* stresses, such as those produced by fasteners and at joints, can penetrate girders, beams, plates and shells must be understood by the designer. Thus a distinction must be made between *global* structural elements (where Strength of Materials or other approximate theories may be used) and *local* elements which require more detailed (and more costly) analyses based on exact elasticity. The neglect of end effects is usually justified by appeals to some form of Saint-

Venant's principle and years of experience with *homogeneous isotropic elastic structures* has served to establish this standard procedure. Saint-Venant's principle also is the fundamental basis for static mechanical tests of material properties. Thus property measurements are made in a suitable *gage section* where *uniform* stress and strain states are induced and local effects due to clamping of the specimen are neglected on invoking Saint-Venant's principle. Such traditional applications of Saint-Venant's principle require major modifications when strongly anisotropic and composite materials are of concern. For such materials, local stress effects persist over distances *far greater* than is typical for isotropic metals.

Explicit analytic results of the type described above are crucial to the complete analysis of *local* or *end effects* in anisotropic or composite materials and structures. Previous work has shown that such end effects decay *much more slowly* than in isotropic materials. For transversely-isotropic (or specially orthotropic) materials, our earlier work has led to *specific design formulas* for the distance beyond which Saint-Venant edge effects can be neglected. The results, which have important implications for the experimental techniques used to measure material properties, have led to modifications of the ASTM standard test and are now quoted routinely in text- and hand-books on mechanics of composite materials. Our current research deals with more complicated degrees of anisotropy, including the general orthotropic symmetry relevant to the off-axis tension test, and with effects of nonlinearity. Analytic results of the type obtained are *crucial complements to large-scale computational analyses.* They have been used in a technology application by the Boeing Commercial Airplane Company (see 7(C) below).

In [4] the purpose is to further investigate the effects of material inhomogeneity and the combined effects of material inhomogeneity and anisotropy on the decay of Saint-Venant end effects. Saint-Venant decay rates for self-equilibrated edge loads in symmetric sandwich structures are examined in the context of anti-plane shear for linear anisotropic elasticity. The problem is governed by a second-order, linear, elliptic partial differential equation with discontinuous coefficients. The most general anisotropy consistent with a state of anti-plane shear is considered, as well as a variety of boundary conditions. Anti-plane or longitudinal shear deformations are one of the simplest classes of deformations in solid mechanics. The resulting deformations are completely characterized by a single out-of-plane displacement which depends only on the in-plane coordinates. They can be thought of as complementary deformations to those of plane elasticity. While these deformations have received little attention compared with the plane problems of linear elasticity, they have recently been investigated for *anisotropic* and *inhomogeneous* linear elasticity. In the context of linear elasticity, Saint-Venant's principle is used to show that self-equilibrated loads generate local stress effects which quickly decay away from the loaded end of a structure. For homogeneous *isotropic* linear elastic materials this is welldocumented. Self-equilibrated loads are a class of load distributions that are statically equivalent to zero, i.e., have zero resultant force and moment. When Saint-Venant's principle is valid, pointwise boundary conditions can be replaced by more tractable resultant conditions. It is shown in the [4] that material inhomogeneity significantly affects the practical application of Saint-Venant's principle to sandwich structures. A new way of presenting results for the plane problem in a form accessible to designers is given in [5].

It has been known for some time that certain radial anisotropies in some linear elasticity problems can give rise to stress singularities which are absent in the corresponding isotropic problems. Recently related issues were examined by other authors in the context of plane strain axisymmetric deformations of a hollow circular cylindrically anisotropic linearly elastic cylinder under uniform external pressure, an anisotropic analog of the classic isotropic Lamé problem. In the isotropic case, as the external radius increases, the stresses rapidly approach those for a traction-free cavity in an infinite medium under remotely applied uniform compression. However, it has been shown that this does *not* occur when the cylinder is even slightly anisotropic. In [6], we provide further elaboration on these issues. For the externally pressurized hollow cylinder (or disk), it is shown that for radially orthotropic materials, the maximum hoop stress occurs always on the inner boundary (as in the isotropic case) but that the stress concentration factor is infinite. For circumferentially orthotropic materials, if the tube is sufficiently thin, the maximum hoop stress always occurs on the inner boundary whereas for sufficiently thick tubes, the maximum hoop stress occurs at the outer boundary. For the case of an *internally* pressurized tube, the anisotropic problem does *not* give rise to such radical differences in stress behavior from the isotropic problem. Such differences do, however, arise in the problem of an anisotropic disk, in plane stress, rotating at a constant angular velocity about its center, as well as in the three-dimensional problem governing radially symmetric deformations of anisotropic externally pressurized hollow spheres. The anisotropies of concern here do arise in technological applications such as the processing of fiber composites as well as the casting of metals.

In [7], a comprehensive updated review on results concerned with Saint Venant's principle in solids and structures is presented. This updates material discussed in two previous review articles. In [8], results on the decay for end effects for anisotropic nonlinear elasticity are obtained. This is the first such result known in the literature. A shape optimization problem is examined in [9]. Such results have AFOSR relevance, e.g., to aircraft wing design.

In [10], an analysis of Saint-Venant's principle is carried out for incompressible linearly elastic materials. It is well known that the constraint of incompressibility causes severe difficulties , for example, in a finite element analysis. In [10], we avoid such difficulties by using a device due to Babuska and Aziz . The work [11] is concerned with the effect of imperfect bonding on decay of stresses in multilayered structures. It is shown that imperfect bonding decreases the decay of end effects in such structures. In view of the widespread use of sandwich and other layered structural elements in aircraft, these results are of significant AFOSR relevance.

3. PERSONNEL SUPPORTED:

P.I.: C. O. Horgan, Wills Johnson Professor

Graduate Students: Sarah C. Baxter (Ph.D., May 1995). Now Assistant Professor, Dept. of Mechanical Engineering, University of South Carolina, Columbia, SC; Monica R. Scalpato (Partially supported by AASERT Grant with this parent grant); M.S., May 1997. Ms. Scalpato is now a Senior Information Technology Consultant, Ernst and Young LLP, Boston, MA.

4. PUBLICATIONS:

(List of recent papers, theses and dissertations that have been supported, or partially supported, by AFOSR.)

1. Cavitation in nonlinearly elastic solids: a review (C. O. Horgan and Debra A. Polignone), Applied Mechanics Reviews **48,** 1995, 471-485.

1a. Anti-plane shear deformations in linear and nonlinear solid mechanics, SIAM Review **37,** 1995, 53-81.

1b Korn's inequalities and their applications in continuum mechanics, SIAM Review **37,** 1995, 491-511

2 Remarks on ellipticity for the generalized Blatz-Ko constitutive model for a compressible nonlinearly elastic solid, J. of Elasticity, **42,** 1996, 165-176.

3. Material instabilities for large deformations of the generalized Blatz-Ko material, Applied Mechanics Reviews **50,** 1997, S93-S96.

4. Anti-plane shear deformations of anisotropic sandwich structures: end effects (Sarah C. Baxter and C. O. Horgan), Int. J. of Solids and Structures **34,** 1997, 79-98.

5. Further analysis of end effects for plane deformations of sandwich strips (A. C. Wijeyewickrema, C. O. Horgan, and J. Dundurs), Int. J. of Solids and Structures **33,** 1996, 4327-4336.

6. Effects of curvilinear anisotropy on radially symmetric stresses in anisotropic linearly elastic solids (C. O. Horgan and S. C. Baxter), J. of Elasticity, **42,** 1996, 31-48.

7. Recent developments concerning Saint-Venant's principle: a second update Applied Mechanics Reviews **49,** 1996, S101-S111.

8. Spatial decay estimates for a class of second-order quasilinear elliptic partial differential equations arising in anisotropic nonlinear elasticity (C. O. Horgan and L. E. Payne), Mathematics and Mechanics of Solids, **1,** 1996, 411-423.

9. A semi-inverse shape optimization problem in linear anti-plane shear (C. O. Horgan and P. Villaggio), J. of Elasticity , **45** , 1996, 53-60.

10. Saint-Venant's principle in linear isotropic elasticity for incompressible or nearly incompressible materials (C. O. Horgan and L. E. Payne), J. of Elasticity, **46,** 1997, 43-52.

11. End effects in multilayered orthotropic strips with imperfect bonding (N. Tullini, M. Savoia and C. O. Horgan), Mechanics of Materials, **26,** 1997, 23-34.

5. INTERACTIONS/TRANSITIONS:

A. Participation/Presentations at Meetings, Seminars, Etc.:

1. "End effects in sandwich structures." Invited lecture at Boeing Commercial Airplane Group, Seattle, Washington, May 1995.

2. "Cavitational failure mechanisms in rubber." Invited lecture at AFOSR Workshop on "Structural Analysis of Shells with Application to Aircraft Tire Performance and Service Life," Flight Dynamics Directorate, Wright Patterson AFB, Ohio, July 27, 1995.

3. "Anti-plane shear: an intriguing mathematical problem in solid mechanics." Colloquium lecture at Inst. for Appl. Math, UVA, Charlottesville, Sept. 1995.

4. "Asymptotic behavior of solutions of partial differential equations." Colloquium, Dept. of Mathematics, University of Tennessee, Knoxville, November 1995.

5. "Anti-plane shear in nonlinear elasticity." Colloquium, Dept. of Mathematics, University of Tennessee, Knoxville, Nov. 1995.

6. "Cavitational instabilities in solids." Colloquium, U. S. Naval Academy, Annapolis, MD, Jan. 1996.

7. "Cavitational failure mechanics in solids." Colloquium, U. S. Army B.R.L., Aberdeen Proving Ground, MD, Jan. 1996.

8. Session Chairman, Symposium in honor of J. L. Ericksen, ASME AMD/Materials Summer Meeting, Johns Hopkins University, Baltimore, MD, June 1996.

9. Fourteen invited colloquium lectures delivered at universities in Italy, Switzerland, and Ireland, Spring 1996 and 1997.

10. "Saint-Venant edge effects in sandwich structures" (with Sarah C. Baxter). Presented at 14th U.S. Army Symposium on Solid Mechanics, Myrtle Beach, S.C., Oct. 1996.

11. "Remarks on ellipticity for the generalized Blatz-Ko constitutive model for a compressible nonlinearly elastic solid." Invited lecture at Special Session on "Elasticity," 33rd Annual Meeting, Society of Engineering Science, Arizona State University, Tempe, AZ, Oct. 1996.

12. "Material instabilities for large deformations of the generalized Blatz-Ko material." Invited lecture at 5th Pan American Congress on Applied Mechanics, San Juan, Puerto Rico, Jan. 1997.

13. "Saint-Venant's principle for sandwich structures" (with Sarah C. Baxter). Invited lecture at EUROMECH 360, "Mechanics of Sandwich Structures," Saint-Etienne, France, May 1997.

14. Midwest Mechanics Seminar Lectures 1996/1997 : Eight lectures presented at the major research universities in the Midwest.

B. Consultative and Advisory Functions:

Considerable interaction has been developed with Air Force Flight Dynamics Directorate, Vehicle Subsystems Division, WPAFB, Ohio. Main contact: Dr. Arnold H. Mayer, WL/FIV. P.I. visited WPAFB and gave an invited presentation, detailed in 2 above. There was extensive consultation with other Air Force Research Personnel at WPAFB.

Telephone and written contact with Aeronautics and Astronautics Laboratories, Solid Rockets Division, Edwards AFB, have also been maintained. Main contact: Dr. C. T. Liu.

Extensive contact with Boeing Commercial Airplane Company (see under C below).

Extensive contact with Prof. B. A. Szabo at Washington University, St. Louis on relevance of Horgan's work to finite element analyses performed by Szabo's group under AFOSR support.

C. Transitions:

Cavitational failure mechanisms are very relevant to the tire degradation problem being addressed by Dr. Mayer and associates at WPAFB. The work on end effects in anisotropic and composite structures is being used by the Boeing Commercial Airplane Group, Seattle, Washington, in the Boeing (NASA) Advanced Technology Composite Aircraft Structures Program (ATCAS). Main contact: Dr. W. B. Avery. P.I. visited Boeing on July 1, 1994 and May 26, 1995 to further this technology transfer. See attached letter from Dr. Avery (July 1996).

6. INVENTIONS/PATENTS: None

7. HONORS/AWARDS:

1) C. O. Horgan began term of office as a member of the Board of Directors, Society of Engineering Science, Inc., January 1994/re-elected to second term, October 1996.

2) C. O. Horgan was named the Wills Johnson Professor of Applied Mathematics & Mechanics, University of Virginia, July 1, 1994.

3) Dr. Horgan is a Fellow of the American Society of Mechanical Engineers (ASME) and the American Academy of Mechanics. He is the author or co-author of over 120 publications on Applied Mathematics and Mechanics.

4) Dr. Horgan was appointed to the Editorial Board of the following journals: *International Journal of Nonlinear Mechanics, J. of Elasticity, SIAM Journal on Applied Mathematics.* He is a founding editor of the new journal *Mathematics and Mechanics of Solids.* He also serves as Associate Editor for *Applied Mechanics Reviews.*

5) Dr. Horgan spent a period during the Spring of 1996 and 1997 as Visiting Professor, Universita di Pisa, Italy. He lectured extensively during that period in Italy, Switzerland, and Ireland.

6) Dr. Horgan was a Mid-West Mechanics Seminar Lecturer for 1996/1997, lecturing at 8 of the major research universities in the Mid-West.

7) Dr. Horgan presented the J. L. Nowinski Lecture at the Dept. of Mechanical Engineering, University of Delaware, March 7, 1997. The lecture was entitled: "Saint-Venant end effects in composite structures."

A Technology Transfer Example

A Boeing/NASA Advanced Technology Composite Aircraft Structures (ATCAS) Program has been active since 1989. The primary objective of this program is to:

> "Develop an integrated technology (manufacturing & structures) and demonstrate a confidence level that permits cost-and weight-effective use of advanced composite materials in primary structures of aircraft with the emphasis on pressurized fuselages."

In this program, a section of a widebody aircraft (244" dia) just aft of the wing/body intersection is being analyzed by the Boeing Commercial Airplane Group in Seattle, Washington. Sandwich structures are being used for the side and keel of this section. The particular structures consist of Hercules' AS4/8552 for the skin and Hexcel's HRP honeycomb core (see next page for details on layup etc.). Compression testing of laminate coupons indicate the need to incorporate Saint-Venant end effects in interpretation of the test data. The work of the PI's is being utilized in this effort. One of the P.I's (C. O. H.) visited the Boeing Group in Seattle on July 1, 1994 and on June 1/2, 1995 to consolidate this interaction. Collaborative research with the Boeing scientists (Dr. W. A. Avery, coordinator) is being initiated.. One objective is to develop a systematic testing program to be carried out by Integrated Technologies, Inc. (Intec), Bothell, WA, under subcontract to Boeing. Preliminary tests by Intec have indicated problems due to end effects in the sandwich panels under investigation. It is anticipated that the results obtained in our research program will have direct application to these problems. In fact, the interaction with the Boeing/Intec mechanics and materials group is providing additional motivation and stimulus to our efforts in understanding the extent of Saint-Venant end effects in advanced composite materials and structures.

Table 1 Material Types

Panel ID	Skin Material	Form	No of Plies	Nominal Ply Thickness *(in)*	Layup ID	Core Type	Core Thick-ness *(in)*
AK7	8-256	Tow	12	0.0080	Keel 1	HRP-3/16-8.0	0.75
AK8	8-256	Tow	12	0.0080	Keel 1	HRP-3/16-8.0 & TPC-3/16/5.5	0.75
AK10a	AS4/8552	Tape	12	0.0073	Keel 1	HRP-3/16-8.0	0.75
AK10b	AS4/8552	Tape	12	0.0073	Keel 3	HRP-3/16-8.0	0.75
AK10c	AS4/8552	Tow	12	0.0073	Keel 1	HRP-3/16-8.0	0.75
AK10d	AS4/8552	Tow	12	0.0073	Keel 1/ Keel 3	HRP-3/16-8.0	0.75

Table 2 Layups

Layup ID	Number of Plies	Ply Orientation
Keel 1	12	[45/0/-45/90/0/-45/45/0/90/-45/0/45]
Keel 3	12	[30/-30/0/90/0/-45/45/0/90/0/-30/30]

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July 5, 1996
BYH20-BFB-L96-043

BOEING

Dr. Arje Nachman
Program Director, Applied Analysis
AFOSR, 110 Duncan Ave., Suite B115
Bolling AFB
Washington, DC 20332-0001

Dear Dr. Nachman,

I few days ago Cornelius Horgan from the University of Virginia asked me to write you and explain the relevance of his work to Boeing. I am happy to do so. This letter is the response to that request.

In 1989 Boeing started work on the Advanced Composite Technology Aircraft Structure (ATCAS) program, which is funded by NASA's Advanced Composite Technology (ACT) initiative. In this program Boeing has been developing the materials, structures, and manufacturing technology for a composite fuselage for a widebody aircraft. The goal is to design the structure such that there is significant savings in both cost and weight.

Early in the program we identified sandwich structure as having a high potential to save cost because the tooling and manufacturing processes for skin-stringer structures are expensive. Consequently we baselined sandwich construction for the fuselage keel and side panels.

When we started collecting our structural database we compression tested several solid laminate and sandwich coupons, many of them with holes. The failure loads were higher than expected, and we realized that we may have not been getting the full stress concentrations at the edges of the holes. This was confirmed through some photoelastic analyses of additional coupons. Part of the problem was test method related. But a review of some of Dr. Horgan's work helped us understand how St. Venant's effects are different for anisotropic and sandwich structures. His work became useful in guiding us in sizing test coupons based on degree of anisotropy and the particular configuration of the sandwich structure. Essentially, we found that we needed a longer specimen in order to get uniform load into the test coupon. Dr. Horgan's analyses helped us quantify that increase in length.

I appreciate Dr. Horgan's effort to keep in touch with Boeing and solicit ideas for research. I find him very "customer oriented". His work has been helpful to us. If you have any questions please feel free to contact me.

Regards,

William Avery, Ph.D.
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Edge Effects in Composite Structures

C. O. Horgan and J. G. Simmonds
School of Engineering & Applied Science
University of Virginia

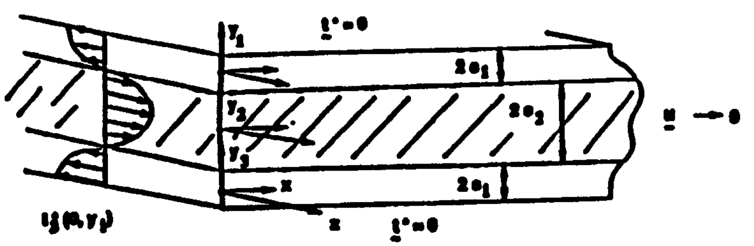
Assumptions

I. Sandwich Structures

- Anti-plane shear
- Linear elasticity

$\delta = \dfrac{\mu_1}{\mu_2}$, f = volume fraction, $\bar{d}$ = decay length

Results



Decay length for semi-infinite sandwich strips subjected to self-equilibrated end loads.

The characteristic decay length (i.e., the distance over which end effects decay to 1% of their end values) versus a nondimensional material parameter (the ratio of face to core shear modulus) is plotted in Fig. 2. In Fig. 3, the plot is for varying volume fraction and fixed δ. The decay length is seen to be *smallest* for a homogeneous isotropic material, δ = 1, as shown in Fig. 2. This decay length is approximately equal to the width of the strip. From Fig. 3, the decay length for fixed δ, is seen to be *largest* at a volume fraction f=.5. These figures (and the associated asymptotic formulas) can be used directly in the design process for sandwich structures.

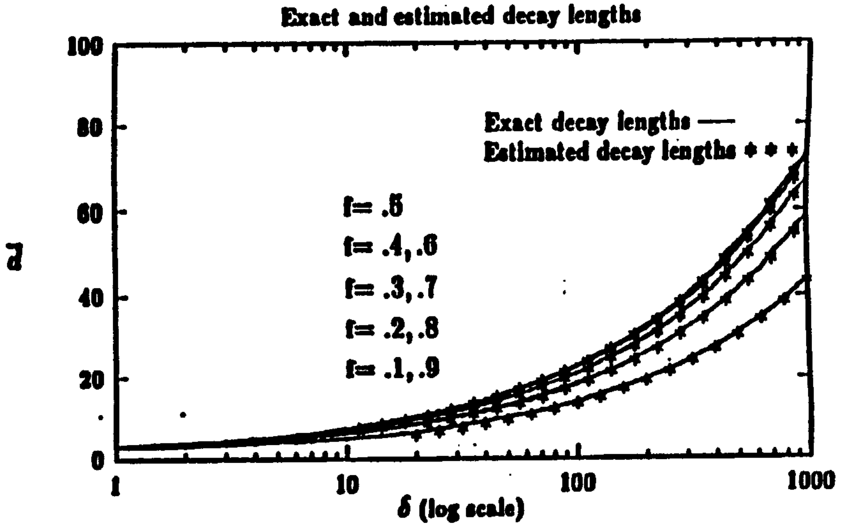


Fig. 2. Scaled decay length vs. δ, for various f

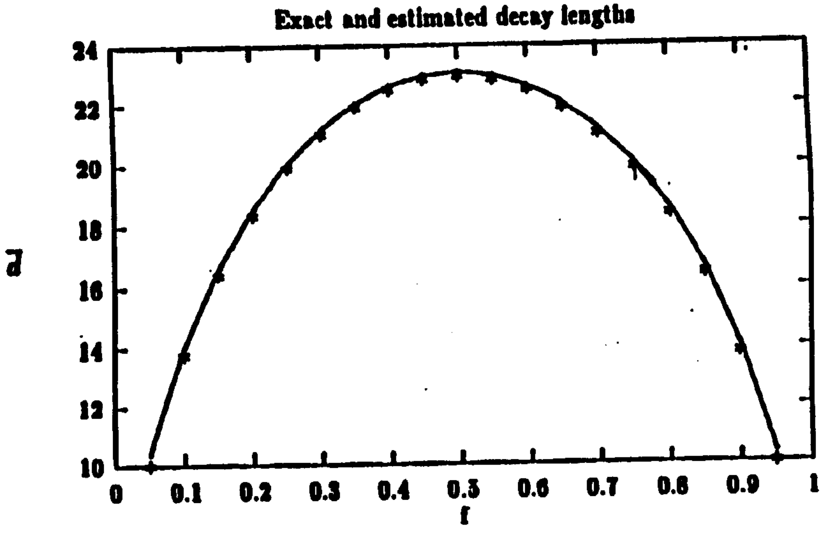


Fig. 3. Scaled decay length vs. volume fraction (δ = 100)

Edge Effects in Composite Structures

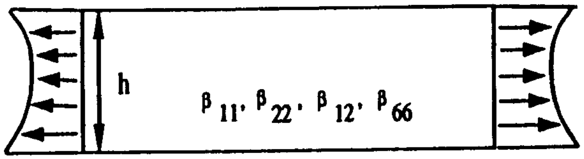
C. O. Horgan and J. G. Simmonds
School of Engineering & Applied Science
University of Virginia

Assumptions

I. Orthotropic material

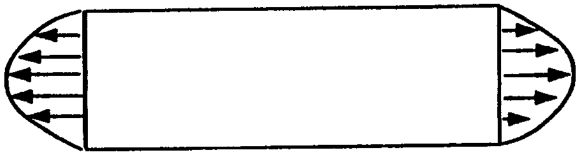
- 2-D plane stress/strain
- Linear elasticity

(extension problem)



II. Statically equivalent loading

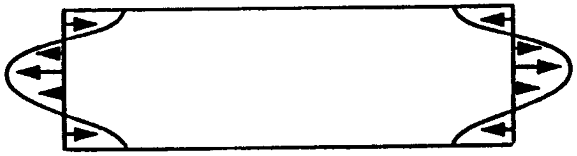
(same resultant force and moment)



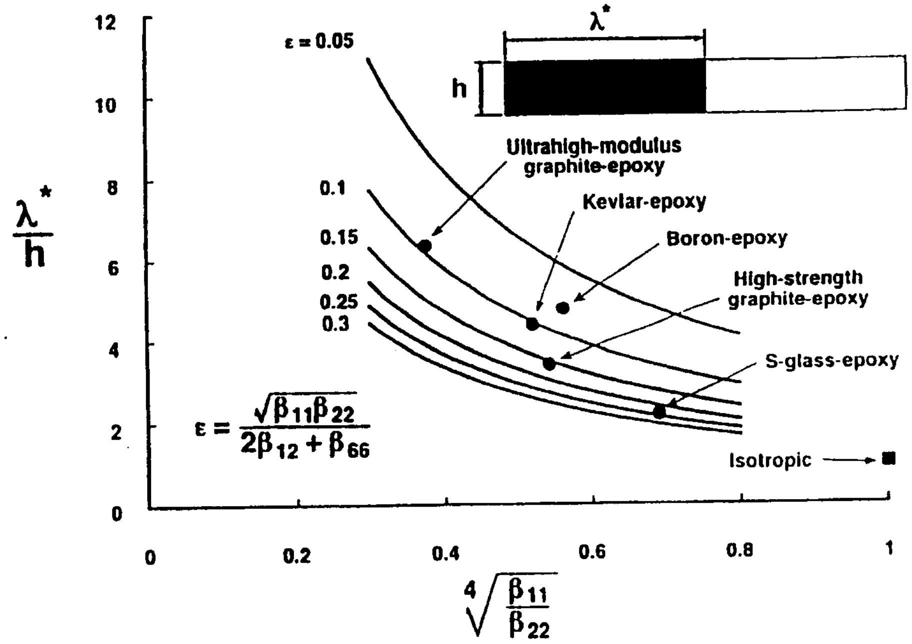
III. Self-equilibrated end loads

- The stress fields decay from the ends
- Rate of decay can be found
- Characteristic decay lengths

(Superposition of I and II)



Results



Decay length λ^* for semi-infinite orthotropic strips subjected to self-equilibrated end loads.

A comparison between several commonly used composite materials is illustrated for specially orthotropic materials. The characteristic decay length (i.e., the distance over which end effects decay to 1% of their end values) versus a nondimensional material parameter is plotted and the results for various materials are indicated by the dots shown on the curves. The decay length for an isotropic material is shown by the dark square. It is seen that the latter has the *smallest* decay length and that this is approximately equal to the width of the strip. This figure can be used directly in the design process to account for anisotropic end effects.

Edge Effects in Composite Structures

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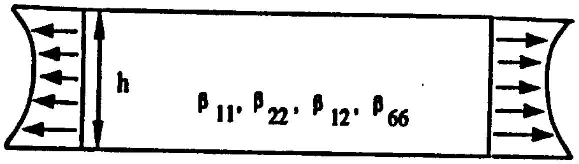
Assumptions

I. Anisotropic material

- 2-D plane stress/strain
- Linear elasticity

(extension problem)



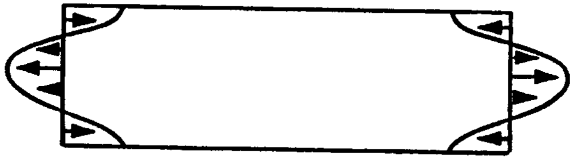
II. Statically equivalent loading

(same resultant force and moment)

III. Self-equilibrated end loads

- The stress fields decay from the ends
- Rate of decay can be found
- Characteristic decay lengths

(Superposition of I and II)



Results

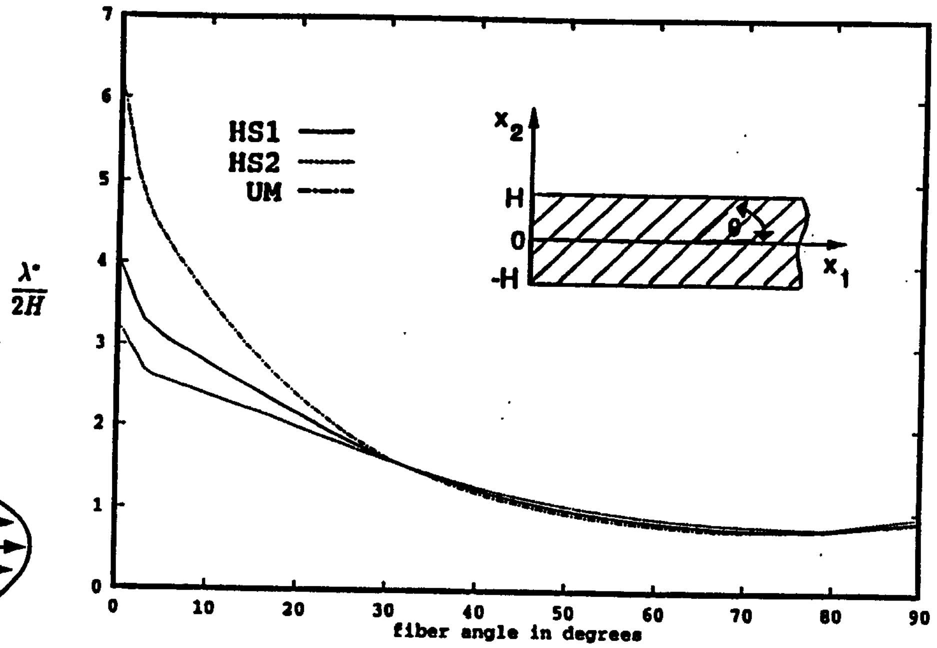


Figure 1. Decay lengths versus fibre angle

Decay length λ^* for semi-infinite anisotropic strips subjected to self-equilibrated end loads.

A comparison between several commonly used composite materials is illustrated. The characteristic decay length (i.e., the distance over which end effects decay to 1% of their end values) versus fiber angle is plotted. The decay length for an isotropic material is approximately equal to the width of the strip. Thus anisotropy has a significant effect on stress decay. This figure can be used directly in the design process to account for anisotropic end effects.

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