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PROCEEDINGS OF THE ANNUAL MECHANICS OF COMPOSITES REVIEW (16^{TH})

Sponsored by:

Air Force Wright Aeronautical Laboratories
Materials Laboratory

APRIL 1997

FINAL REPORT FOR PERIOD 12-13 NOVEMBER 1991

MATERIALS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AFB OH 45433-7734

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13. ABSTRACT *(Maximum 200 words)*

This report contains the basic unedited vu-graphs of the presentations at the "Mechanics" of Composites Review" sponsored jointly by the Non-metallic Materials Division of the Air Force Materials Laboratory, the Structures Division of the Air Force Flight Dynamics Laboratory and the Directorate of Aerospace Sciences of the Air Force Office of Scientific Research. The presentations cover current in-house and contract programs under the sponsorship of these three organizations.

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epoxy-matrix composites; composite materials; resin matrix composites; composite bonded joints; fatigue of graphite/epoxy composites; fracture and fatigue of bi-materials	312
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MECHANICS OF COMPOSITES REVIEW
12-13 NOVEMBER 1991

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FOREWORD

This report contains the abstracts and viewgraphs of the presentations at the Sixteenth 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, and Army. 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.

DEBORAH PERDUE, Meeting Manager
Mechanics & Surface Interactions Branch
Nonmetallic Materials Division
Materials Directorate

ACKNOWLEDGEMENT

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 Barbara Woolsey for managing registration.

AIR FORCE RESEARCH NEEDS IN THE MECHANICS OF COMPOSITES

WALTER F. JONES
Program Manager, Directorate of Aerospace Sciences
Air Force Office of Scientific Research
AFOSR/NA
Bolling Air Force Base, DC 20332-6448

ABSTRACT

The Air Force has long recognized the potential of advanced composite structural materials for aerospace applications. Many important achievements in the development of these materials have been accomplished in programs sponsored by the Air Force Office of Scientific Research (AFOSR). The responsibility of AFOSR is to manage the Air Force Basic Research (6.1) programs in science and engineering. This mission is accomplished through the awarding of grants and contracts to researchers in industry and at universities, and through the support of basic research programs at Air Force laboratories.

Limitations in the understanding of the thermal/mechanical behavior of composite materials have currently limited their role in modern aerospace vehicle designs. There is, however, a virtually limitless potential for the use of composite material systems in current and future aerospace vehicles. Advanced composite materials are considered to be an enabling technology for many future aerospace applications, including most hypersonic vehicles. Many of these applications, however, require operation in extreme environments. The emphasis of Air Force research has thus shifted from traditional composites to emerging material systems such as ceramics, ceramic-matrix composites, carbon/carbon, metal-matrix composites, and a host of hybrid composites. Without exception, all of these material systems are expected to be highly anisotropic and inhomogeneous.

The Air Force is interested in sponsoring research aimed at developing analytical, experimental, and computational tools which will enable the identification, classification, and mathematical description of the deformation and damage processes in such emerging materials. Specifically, the Air Force is interested in constitutive modeling of multi-phase materials, including the interactions associated with the material microstructure, and the onset and evolution of damage as a time-dependent process. The extremely high levels of reliability demanded of these future material 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 areas of interest include transient dynamic thermomechanical modeling, damage development and failure, life prediction and associated diagnostic techniques.

Beginning with Fiscal Year 1989, attention has been focused on these issues through a new research initiative called "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 the belief that real progress in this endeavor can only come about by fostering a closer collaboration between a number of disciplines, including engineering mechanics, applied mathematics, materials science, physics, and chemistry. This initiative is continuing, and has now become a part of AFOSR's core funding.

Three other initiatives were begun in Fiscal Year 1992, including programs in Structural Ceramics, Carbon/Carbon, and Biomimetics. These initiatives are related to the Mesomechanics

Initiative in that they will require multidisciplinary approaches in order to solve difficult problems. The "High Temperature Behavior of Structural Ceramics" Initiative seeks to determine the chemical, processing, and microstructural features of both monolithic and composite ceramic materials that accelerate or inhibit the damage mechanisms. The mechanics goal of the "Fundamentals of Carbon/Carbon" Initiative is to develop the required analytical capability for guiding the development of oxidation protection systems for structurally useful C/C composites. Finally, the "Biomimetics" Initiative seeks to produce aerospace structural materials with superior properties by mimicking the processing and design principles mastered by nature. The AFOSR Directorate of Chemistry and Materials Science is participating in all three of these new initiatives. The goals of these new initiatives will be discussed, along with other current research interests of the Air Force.

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BRIEFER:

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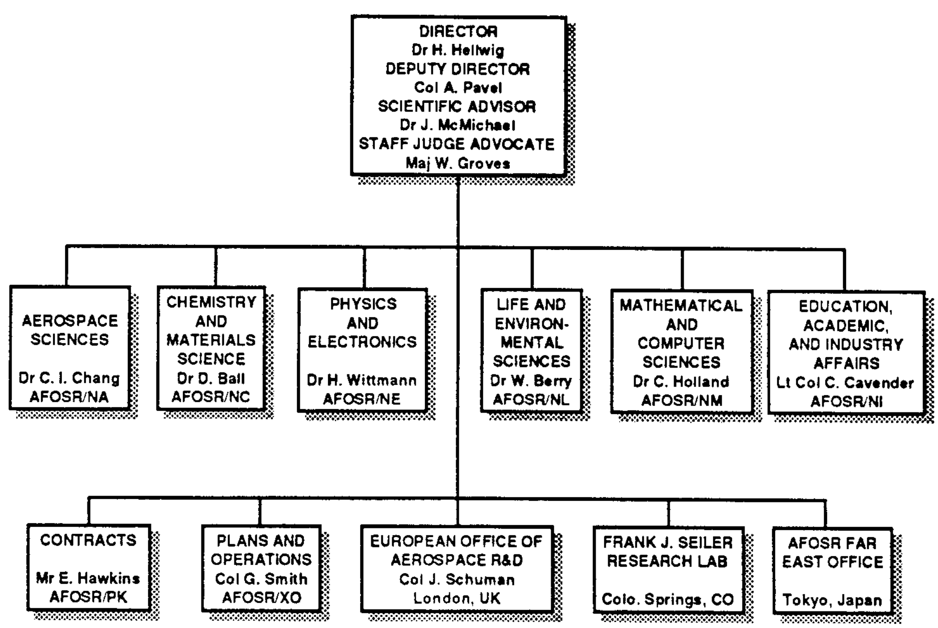
AIR FORCE RESEARCH NEEDS IN THE MECHANICS OF COMPOSITES

16th ANNUAL MECHANICS OF COMPOSITES REVIEW
DAYTON, OHIO
12 November 1991

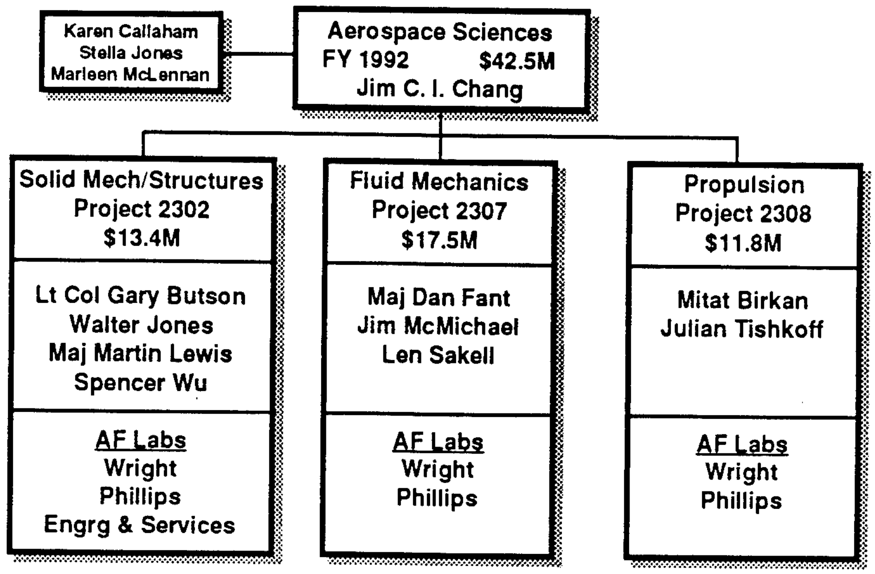
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH



September 1991

Air Force Office of Scientific Research

Directorate of Aerospace Sciences



Air Force Basic Research

Directorate of Aerospace Sciences (202-767-xxxx)

Dr. Jim C. I. Chang, Director (Ext 4987)

Project	Subarea	Program Managers
Solid Mechanics and Structures	Structural Dynamics	Lt Col Gary Butson (Ext 0463)
	Mechanics of Materials	Dr Walter Jones (Ext 0470)
	Particulate Mechanics	Maj Martin Lewis (Ext 6963)
	Structural Mechanics	Dr Spencer Wu (Ext 6962)
Fluid Mechanics	External Aerodynamics and Hypersonics	Dr Len Sakell (Ext 4935)
	Turbulence Structure and Control	Dr Jim McMichael (Ext 4936)
	Unsteady and Separated Flow	Maj Dan Fant (Ext 0471)
	Internal Fluid Dynamics	Maj Dan Fant (Ext 0471)
Propulsion	Rocket Propulsion	Dr Mitat Birkan (Ext 4938)
	Air-Breathing Propulsion	Dr Julian Tishkoff (Ext 0465)
	Diagnostics in Reaction Media	Dr Julian Tishkoff (Ext 0465)

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MESOMECHANICS INITIATIVE

MESOMECHANICS INITIATIVE OBJECTIVES

1. 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 stage.

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

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MESOMECHANICS INITIATIVE

DISCIPLINES/APPROACHES

10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}

SOLID STATE PHYSICS MATERIALS SCIENCE

CHEMISTRY ENGINEERING MECHANICS

ATOMISTIC APPROACHES STRUCTURAL MECHANICS

MICROMECHANICS

FRACTURE MECHANICS

NANOSTRUCTURES MICROSTRUCTURES STRUCTURES

ULTRASTRUCTURES MACROSTRUCTURES

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MESOMECHANICS INITIATIVE

REALISTIC CONSTITUTIVE DESCRIPTION

CURRENT APPROACH: CONTINUUM MECHANICS ← REAL MATERIAL → RESEARCH GOAL: HETEROGENEOUS APPROACH

- Failure Criteria Damage-Independent
- Discrepancies as to Failure Initiation
- Unable to Predict Multiple Failure Modes
- Cannot Predict Interactions Among Damage Modes

- Damage Evolution Included in Constitutive Description
- Failure Criteria Based on Damage State
- Delineate Modes of Damage and Micromechanism Interaction Effects

$$f(\text{stress}_i, \text{strain}_i, \text{strain rate}_i, \text{temperature}, \text{damage}, \text{time}) = 0$$

i = constituent (matrix, fiber, interface, etc.)

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FY 1992 INITIATIVE - STRUCTURAL CERAMICS

THE QUESTION TO BE ANSWERED IS:

WHAT ARE THE CHEMICAL, PROCESSING, AND MICROSTRUCTURAL FEATURES OF BOTH MONOLITHIC AND COMPOSITE CERAMIC MATERIALS THAT ACCELERATE OR INHIBIT THE DAMAGE MECHANISMS?

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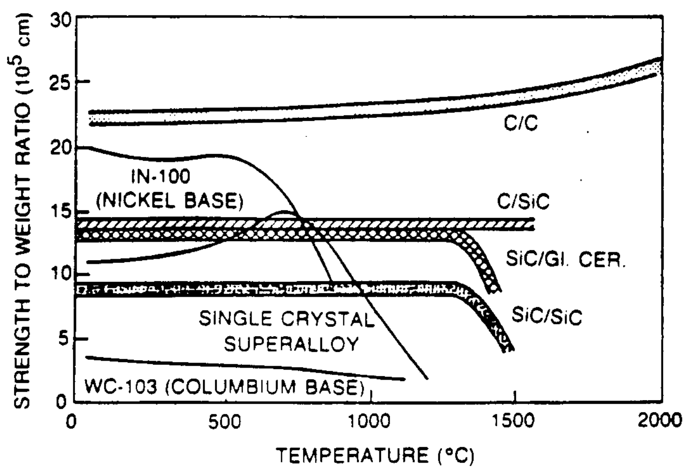
FY 1992 INITIATIVE - STRUCTURAL CERAMICS

HIGH TEMPERATURE MATERIAL SELECTION



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FY 1992 INITIATIVE - STRUCTURAL CERAMICS

SCIENTIFIC ISSUES AND RESEARCH NEEDS: <u>MONOLITHICS AT HIGH TEMPERATURE</u>

TOUGHNESS AND R-CURVE BEHAVIOR
- R-Curve Behavior is Controlled by the Microstructure
- Identify and Model the Effect of Temperature on
    - Grain Boundary Toughness
    - Pullout Strain
    - Internal Stresses
    - Pullout Friction

CREEP
- Understand the Effect of Temperature on the Microstructure

CREEP RUPTURE
- Understand the Nucleation and Growth of Cavities

FATIGUE
- Identify and Model Damage Accumulation
- Understand the Effect of Temperature on Flaw Populations

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FY 1992 INITIATIVE - STRUCTURAL CERAMICS

SCIENTIFIC ISSUES AND RESEARCH NEEDS: <u>HIGH TEMPERATURE INTERFACES IN CMCs</u>

IDENTIFY AND MODEL THE ROLE OF TEMPERATURE ON MECHANISMS INFLUENCING INTERFACIAL BONDING
- Diffusion
- Oxidation
- CTE Mismatch
- Chemical Reactions
- Coefficient of Friction

NEED TO IDENTIFY INTERPHASES THAT ARE
- Stable at High Temperatures
- Bond Poorly to Either Reinforcement or Matrix

IDENTIFY DESIRABLE THERMOMECHANICAL AND CHEMICAL PROPERTIES FOR CANDIDATE COATINGS

DETERMINE APPROPRIATE "FLAVOR" OF MECHANICS FOR TREATING MATERIAL BEHAVIOR (Continuum, LEFM, Damage Mechanics, etc)

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FY 1992 INITIATIVE - CARBON/CARBON

SCIENTIFIC ISSUES AND RESEARCH NEEDS: <u>THE MECHANICS OF CARBON/CARBON COMPOSITES</u>

DEVELOP UNDERSTANDING AND MODEL THE PHYSICAL CONNECTIONS BETWEEN MICROSTRUCTURE AND PROPERTIES OF C/C COMPOSITES, BEGINNING AT THE LEVEL OF THE BASIC CONSTITUENTS

DEVELOP ANALYTICAL PROCEDURES CAPABLE OF
- Simulating the Effects of Proposed Oxidation Protection Systems
- Predicting the Behavior of the Resulting Composites

VERIFY EFFECTIVENESS OF MATHEMATICAL MODELS BY FABRICATING AND TESTED CONTROLLED SPECIMENS

Air Force Basic Research

Directorate of Aerospace Sciences

FY 1992 INITIATIVE - BIOMIMETICS

UNIQUE AIR FORCE BIOMIMETICS GOALS

→ TECHNOLOGY GOAL:

PRODUCE AEROSPACE STRUCTURAL MATERIALS WITH SUPERIOR PROPERTIES BY MIMICKING THE PROCESSING AND DESIGN PRINCIPLES FOUND IN NATURE

→ BASIC RESEARCH GOAL:

UNDERSTAND AND DESCRIBE THE STRUCTURE AND FUNCTION OF NATURALLY-EVOLVED MATERIALS

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FY 1992 INITIATIVE - BIOMIMETICS

A PHYSICAL MODEL OF NACRE

CONSTITUENTS: 95% $CaCO_3$ (Chalk) and 5% ORGANIC GLUE

STRUCTURE: "BRICK AND MORTAR"
$CaCO_3$ BRICKS (0.5 μm thick)
ORGANIC MORTAR (20-30 nm thick)

PROPERTIES: Fracture Strength, $\sigma_F = 185 \pm 20$ MPa

Fracture Toughness, $K_{IC} = 8 \pm 3$ MPa$\sqrt{m}$

COMPARES FAVORABLY WITH MOST "HIGH-TECH" CERAMICS !!

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FY 1992 INITIATIVE - BIOMIMETICS

SUMMARY OF CURRENT AIR FORCE PROGRAMS AND DISCOVERIES

INSECT EXOSKELETONS

- Novel Fiber Sizes and Shapes
- Double Helical Laminar Lay Up
- Graduated Cross-Linking

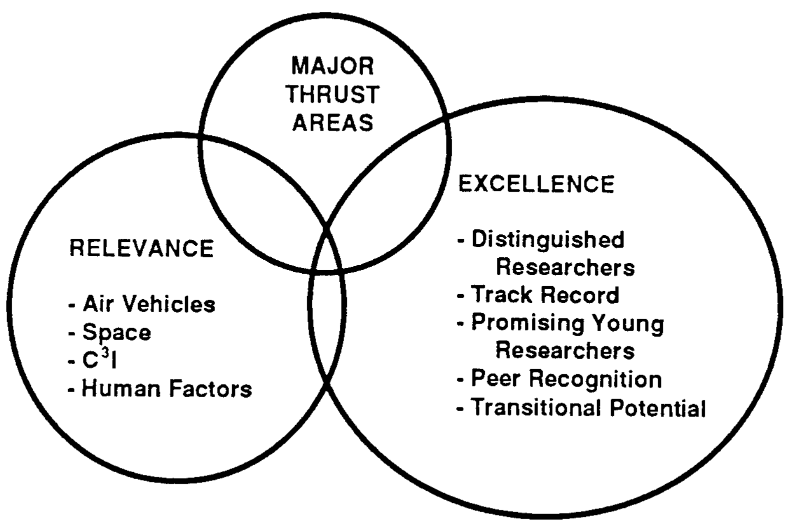
ABALONE SHELLS

- Novel Platelet Design; Highly Ordered Micro-Architecture
- High Modulus Thick Phase and Low Modulus Thin Phase
- Strong Interfaces

Air Force Basic Research

Directorate of Aerospace Sciences

Basic Research Funding Strategy



A COMPREHENSIVE STUDY OF MATRIX FRACTURE MECHANISMS IN FIBER REINFORCED CERAMIC MATRIX COMPOSITES

A. S. D. Wang, M. W. Barsoum and T. M. Tan
Drexel University
Philadelphia PA 19104

The objective of this research is to study the mechanisms and the related material and geometrical factors which influence the initiation and propagation of matrix fracture in unidirectionally fiber-reinforced ceramic-matrix composites. The approach taken is to examine the matrix fracture mechanisms at the scale of the fiber-matrix interface, where the major influencing factors are first identified and then formulated into a generic model; the model can simulate matrix fracture processes in the composite subjected variously applied loads.

Four major research tasks are being carried out:

1. Fabrication of the composites with different matrix-fiber compositions. In each composition, the composite's microstructure (at the matrix-fiber scale) is varied either through the control of the fiber-volume content or through the modification of the matrix-fiber interface bonding condition, or both.

2. Characterization tests for those baseline thermomechanical properties which are either unavailable in the open literature or suspected to be different from the openly quoted values.

3. Mechanical tests (3- and 4-point bend) to examine matrix fracture mechanisms at the matrix-fiber scale, both in-situ and in real-time, and to identify the physical factors that influence the mechanisms at that scale.

4. Formulation of a generic simulation model, based on the observed matrix fracture mechanisms and the identified influencing factors, to predict and compare the collected MCIS data. Accordingly, a quasi-micro model is constructed based on the structural layout of the composite at the matrix-fiber scale, including such local quantities as the fiber-to-fiber spacing, flaws in the matrix and the matrix-fiber interface, etc.

In the presentation, works in tasks 1 and 2 will be only briefly discussed, while details about the MCIS results obtained in tasks 3 and 4 will be fully delineated and examined in terms of the influencing factors that were controlled and varied in the tests.

A summary of findings, along with future works, is given at the conclusion of this presentation.

A COMPREHENSIVE STUDY OF

MATRIX FRACTURE MECHANISMS

IN FIBER -REINFORCED

CERAMIC-MATRIX COMPOSITES

An

URI (AFOSR 90-0712) Program

Drexel University

Duration: 15 February 90 - 15 February 93

Principal Investigators: A. S. D. Wang,
M. W. Barsoum
T. M. Tan

OBJECTIVE OF STUDY

To study the mechanisms and related influencing factors of matrix fracture.

APPROACH OF STUDY

Fabricate test samples with controlled fiber-matrix processing and interface parameters;

Examine matrix fracture at the fiber-matrix interface scale;

Compile data-base over a wide range of processing and interface parameters;

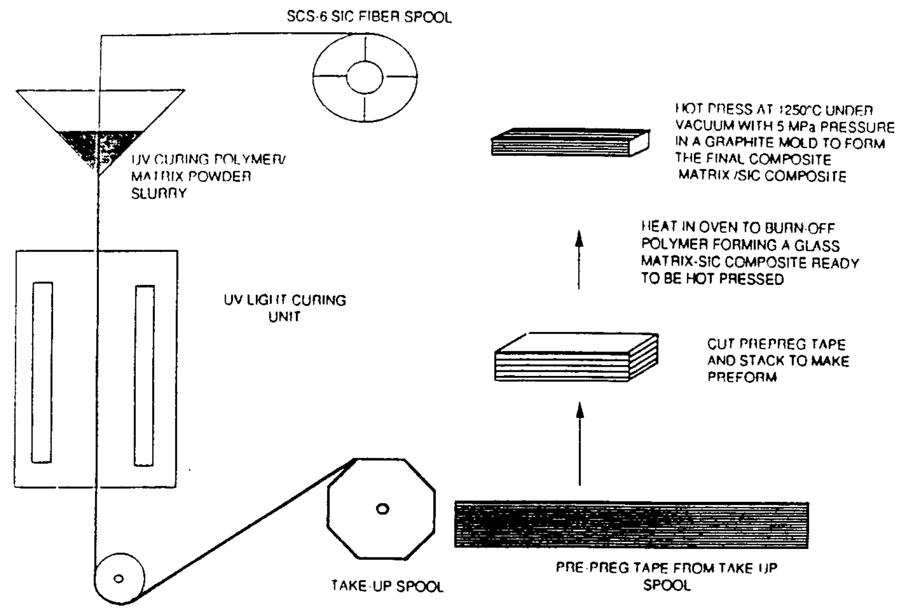
Construct a generic simulation model that includes all of the major parameters.

FOR THE 1991 MECHANICS OF COMPOSITES REVIEW, DAYTON, OHIO.

COMPOSITE FABRICATION PLAN

Composite Systems	Fiber Diameter	Matrix K_{1c} MPa√m	E_f/E_m	$\Delta\alpha_m$-$\Delta\alpha_f$ 10^{-6}C	Interface shear τ	Matrix Strain Point	Test Status
SCS6/7740 untreated fiber	140 μm	0.8	6.5	-3.3	6-8 MPa	520 C	Complete
SCS6/7740 treated fiber	"	"	"	"	> 100 MPa	"	"
SCS6/1723	"	0.8	4.7	-1.9	10 MPa	500 C	"
SCS6/Zircon	"	2.5	2.1	-2.3	39 MPa	1400 C	"
SCS6/SiC	"	2.0	0.85	0	10 MPa	>1400 C	Processing
Nicalon/7740	16 μm	0.8	3.2	0	10 MPa	520 C	Complete
Nicalon/1723	"	"	6.5	1.4	10 MPa	500 C	Complete
SCS9/7740 untreated	70 μm	"	"	-3.3	8 MPa	520 C	Processing
SCS9/7740 treated	"	"	"	"	"	"	"

Composite Fabrication Procedures



BASELINE TESTS

- properties & microstructures -

---

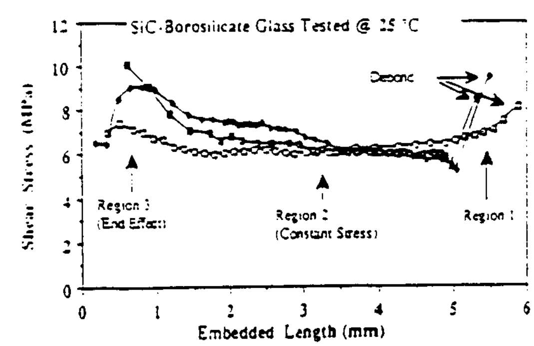
* Matrix: E_m, σ_u, K_{1c}, α_m (type I specimen)
* Fiber: E_f, α_f (long.) (single fiber tests)
* Composite: E_c, α_c (type III specimen)
* Interface: τ (single fiber pull-out tests)
* Random fiber spacing (type II specimen)
* Fiber volume fraction V_f (photomicrograph)

Other properties:

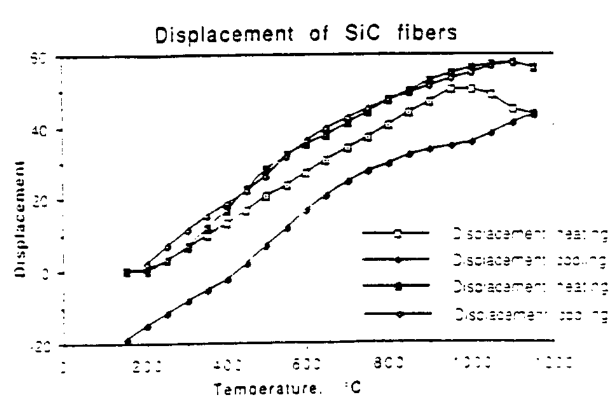
Poisson ratio, fiber diameter, stress-free temperature, matrix strain point, softening point, etc.

SOME TYPICAL RESULTS:

Interface shear strength - SCS-6/7740



Axial thermal expansion of SCS-6

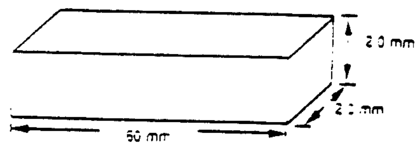


MATRIX CRACKING TESTS

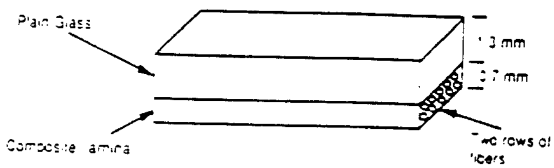
- Initiation & propagation -

* Static 3-point bending (also 4-point bend)
* Matrix cracks on center tensile surface;
* Room temperature to matrix strain point.

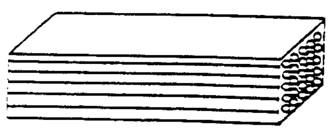
V_f of test samples vary from 0 to 50 v%:



Type I - Plain glass sample



Type II - Laminate composite sample

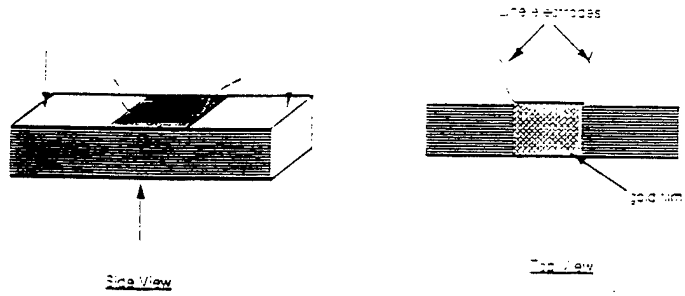


Type III - Uniformly distributed SiC fiber reinforced composite

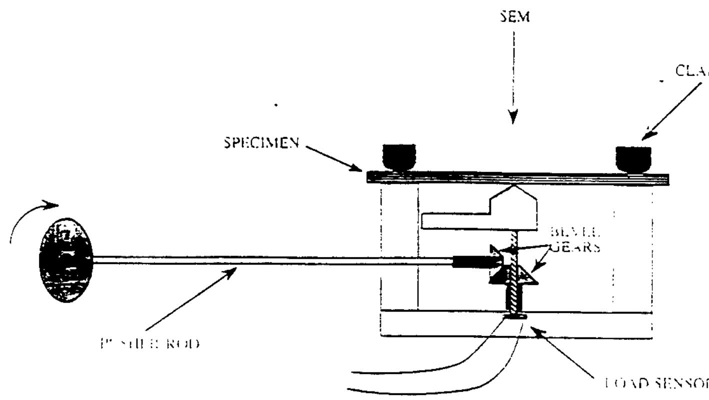
METHODS OF CRACK DETECTION

- the critical crack initiation stress -

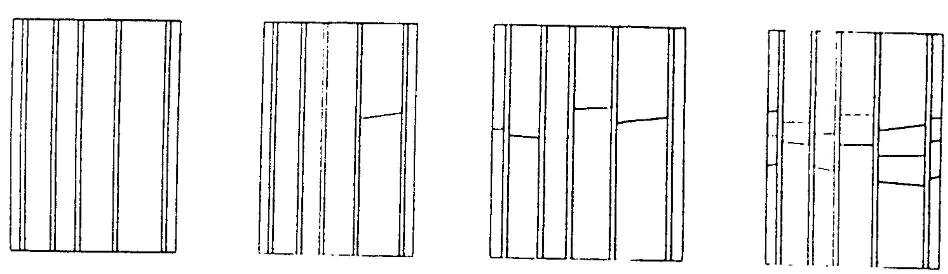
1. Gold-film on the tensile surface.
   - elcetric resistance vs. loading:



2. SEM in-situ observation up to 1000X.
   - under displacement-control loading:



MATRIX CRACKING SEQUENCE



NON-UNIFORM FIBRE DISTRIBUTION

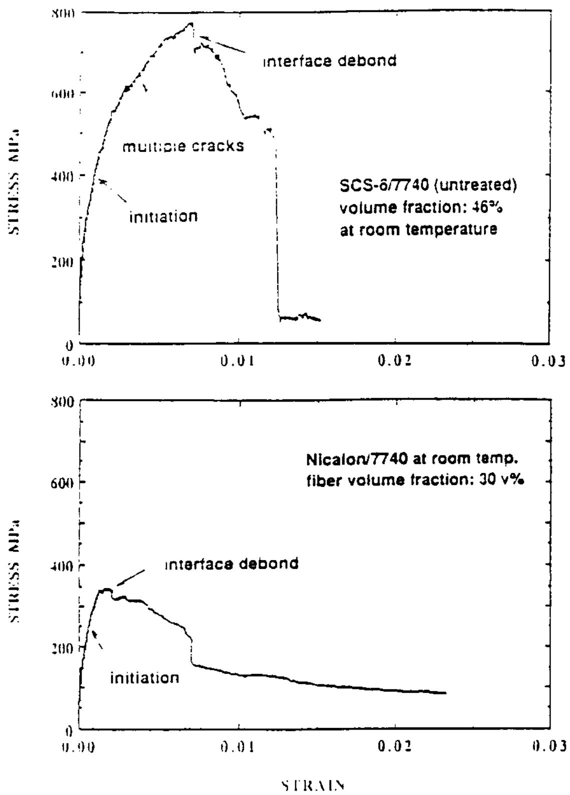
ON LOADING CRACK FORMS IN THE WIDEST SPACING

FURTHER LOADING CAUSES CRACKS ON THE SAME PLANE TO FORM

MORE CRACKS WITH FURTHER LOADING LEADING TO MULTIPLE CRACKS

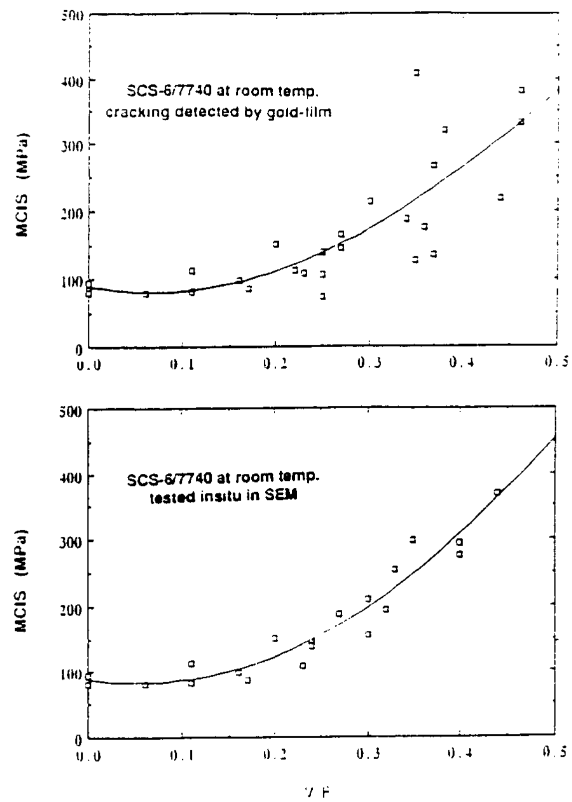
DAMAGE PROGRESSION

- matrix cracking & composite toughness -



MATRIX CRACKING INITIATION

- as a function of fiber volume content -



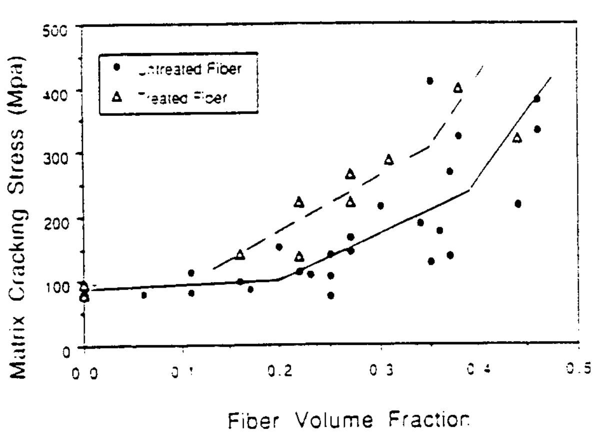
MICROSTRUCTURE FACTORS

- on matrix cracking initiation -

* Interface bonding. SCS-6 fiber heated to 700 ^{o}C in air for 10 minutes:

τ = 6-8 MPa for untreated fiber;

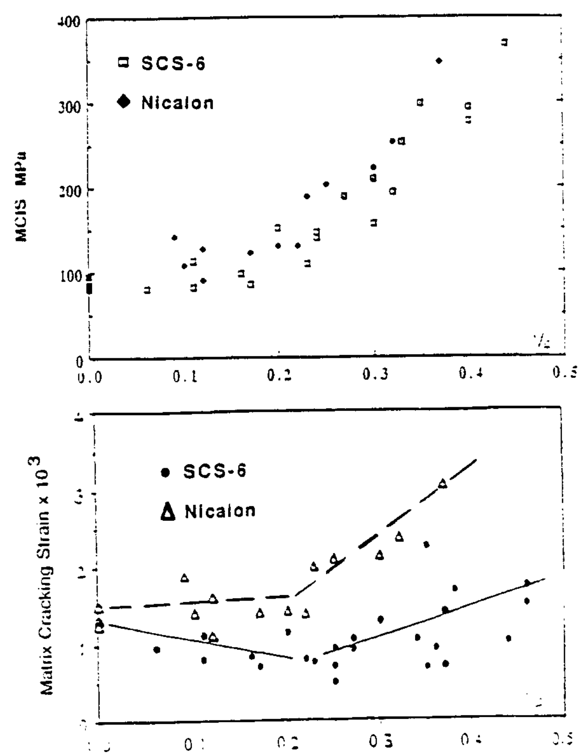
τ > 100 MPa for treated fiber.



EFFECT OF FIBER DIAMETER

for SCS-6: d = 140 μm; E = 400 GPa

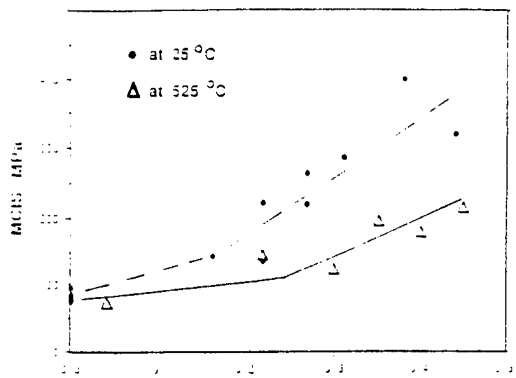
for Nicalon: d = 16 μm; E = 200 GPa

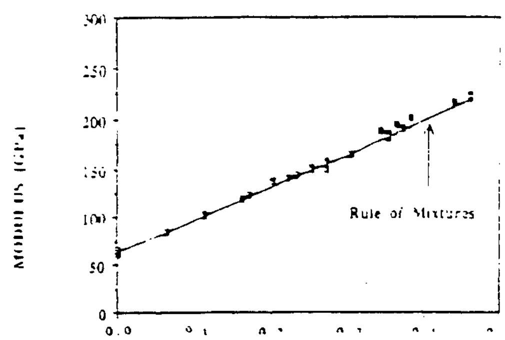


EFFECT OF RESIDUAL STRESSES

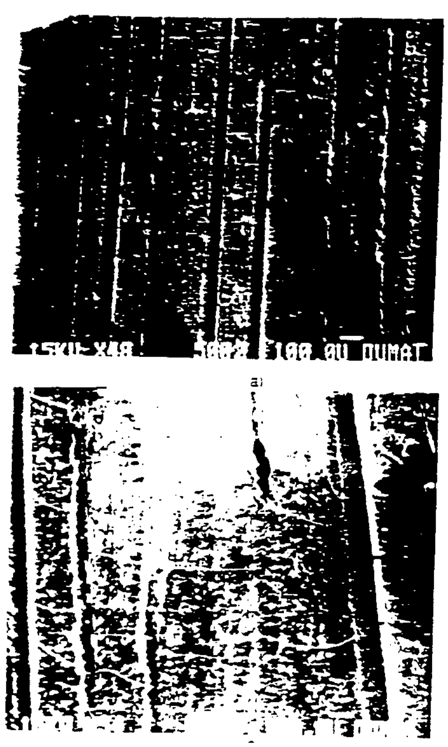
SCS-6(treated)/7740 tested at RT & 525 °C

$\Delta\alpha$ = -3.1x10^{-6} °C, ΔT = -500 °C



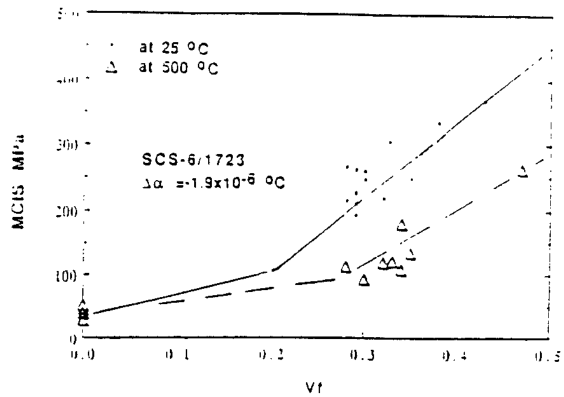


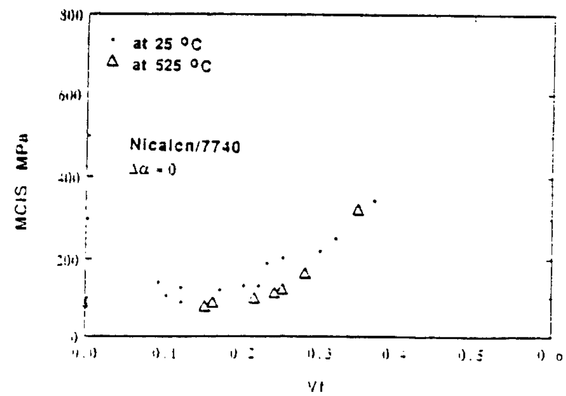
* fiber spacings are locally variant:



above: relative uniform spacing (average 100 µm)
below: non-uniform spacing (average 110 µm)

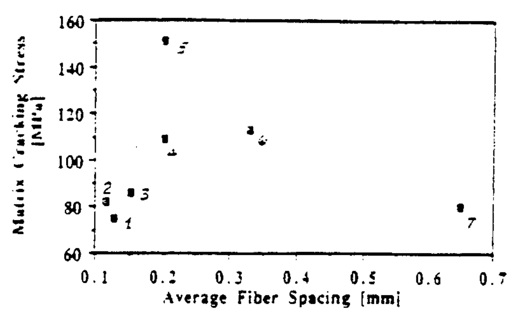
EFFECT OF THERMAL MISMATCH

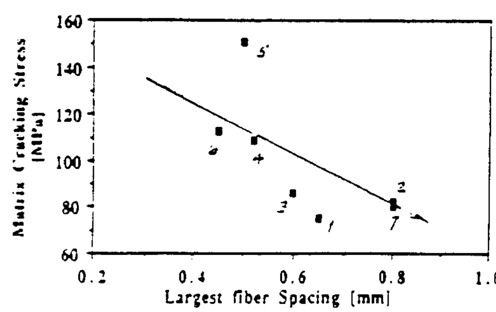




EFFECT OF FIBER SPACING

- from 7 Type-II samples (SCS-6/7740) -

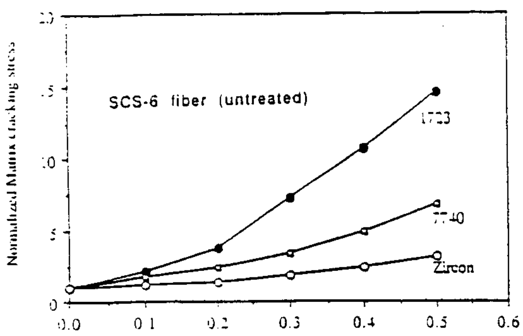


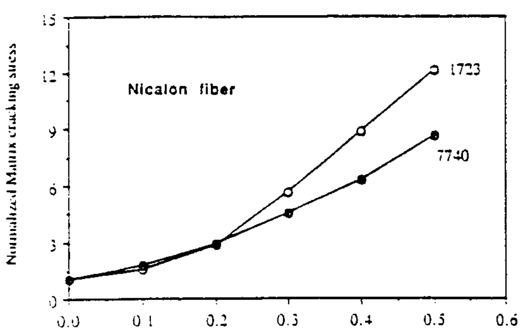


EFFECT OF MATRIX TOUGHNESS

1723 Glass: G = 7 J/m^2 7740 Glass: G = 9 J/m^2

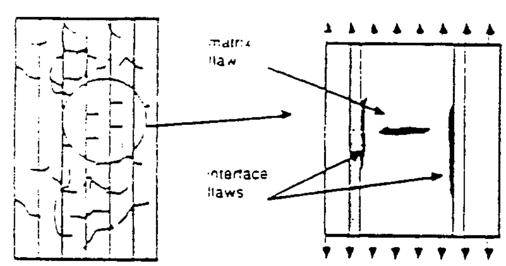
Zircon: G = 31 J/m^2





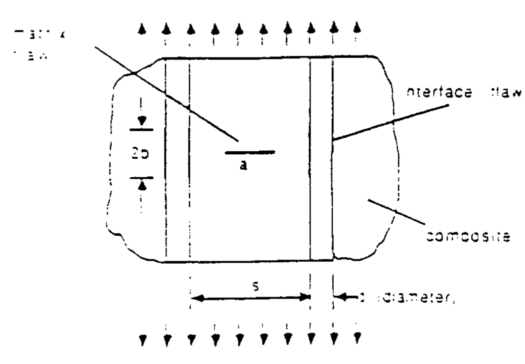
MODELING MATRIX CRACKING

* Abstraction of the microstructure:



unidirectional composite with manufacturing flaws idealized local flaws and interaction configuration

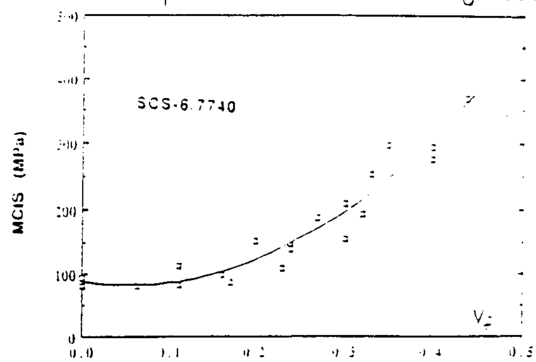
* Isolated Unit-cell:

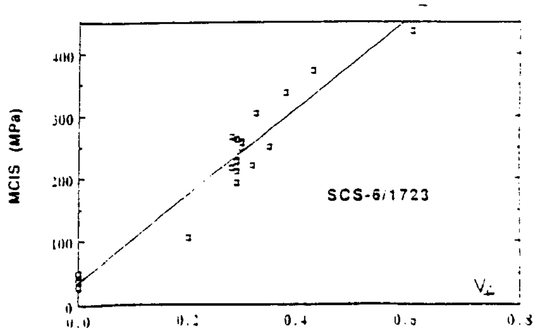


EFFECT OF MATRIX FLAW SIZE

7740 Glass: σ_t = 75-90 MPa, G = 9 J/m^2, a_o = 62 µm

1723 Glass: σ_t = 30-40 MPa, G = 7 J/m^2; a_o = 330 µm





* small a_o/d reduces effect of reinforcement

ELASTIC FRACTURE MECHANICS

* Elastic analysis -> stress field of the cell;

* Fracture mechanics -> propagation of the flaws:

$$G(\text{matrix flaw}) - G_c\ (\text{matrix})$$

$$G=[G_\sigma(a)\sigma^2+G_T(a)\Delta T^2+G_{\sigma T}(a)(\sigma\Delta T)]$$

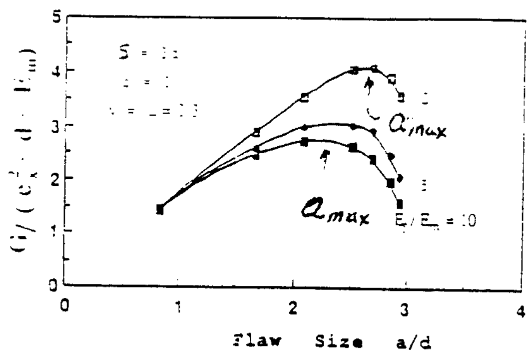
* Factors involved in the model:

1. constitutive - elastic/thermal constants of fiber and matrix;

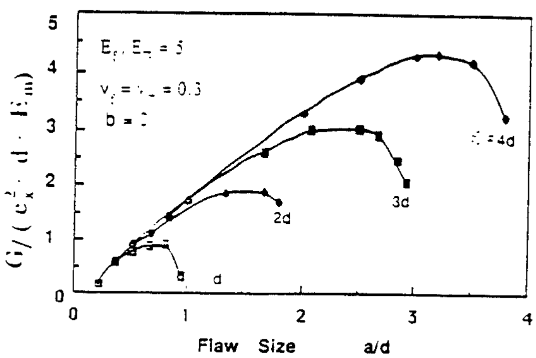
2. processing and interface - flaw sizes, a & 2b (both are random); stress-free temperature, T_o;

3. geometrical - fiber diameter, d; fiber spacing, s (related to V_f).

* The effect of *fiber stiffness*:



* The effect of *fiber spacing*
(and fiber diameter)



PROBABILISTIC BOUNDING OF
EFFECTIVE FLAWS

* Bounds for matrix flaw, a:

$$0 < a < \text{smallest of } (s, a_0, a_{max})$$

where

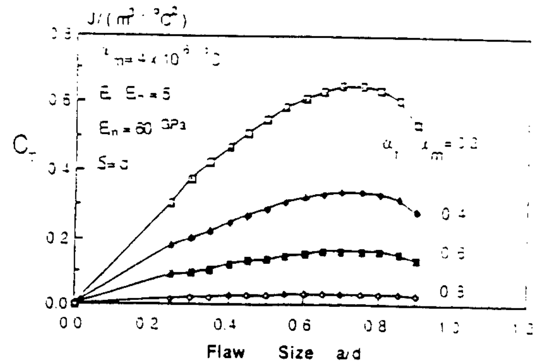
s = fiber spacing#
a_0 = size of flaw in pure matrix
a_{max} = flaw size+ at max. G

* Bounds for interface flaw size, 2b:

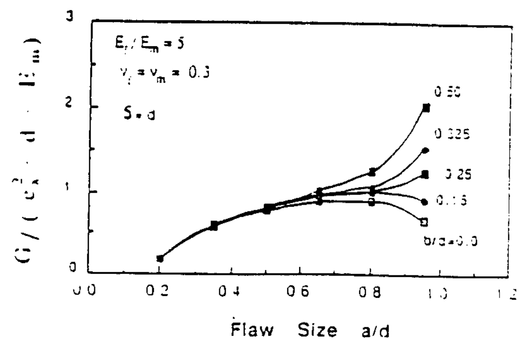
$$0 < b < d$$

when b = 0, interface is perfectly bonded;
when b -> d, interface is locally ineffective.

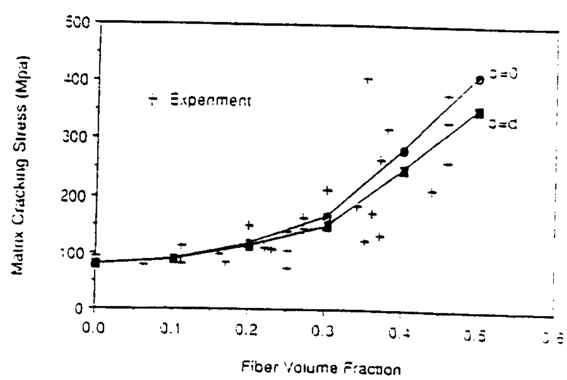
* The effect of fiber/matrix *thermal* mismatch
(residual stress effect)



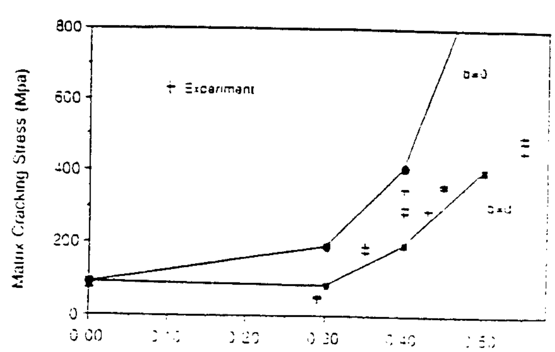
* The effect of *interfacial flaws*



SCS-6/7740 (untreated, RT test):



C/7740 (RT test):



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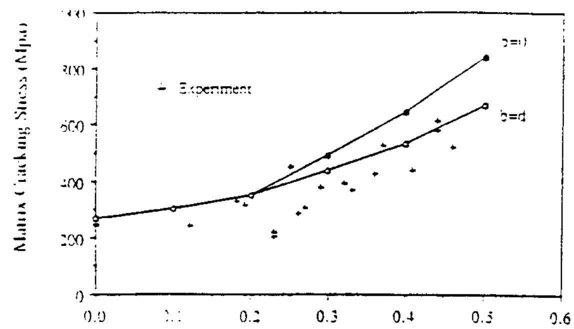
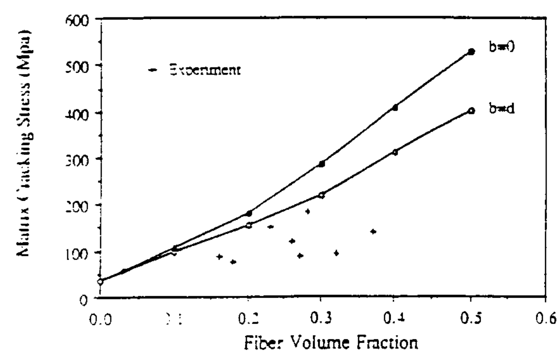
related to d, V_f and fiber packing patterrn.
+ a_{max} is bounded by s

EXPERIMENT AND PREDICTION

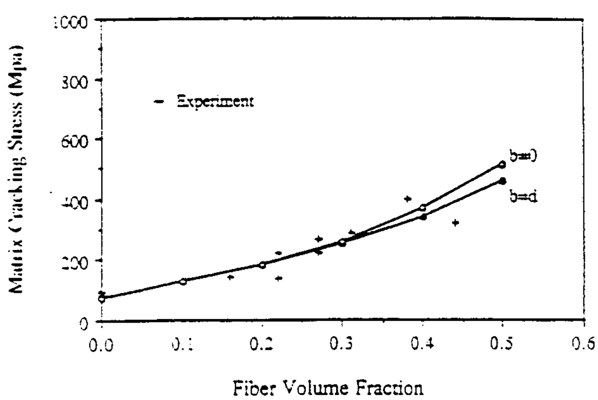
SCS-6/Zircon RT test):



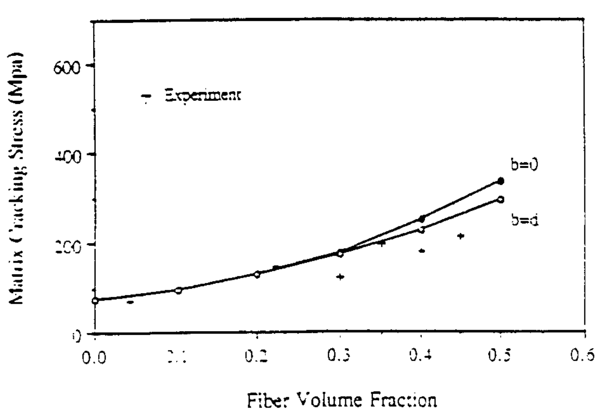
SCS-6/Zircon (800 °C test):



SCS-6/7740 (treated, RT test):

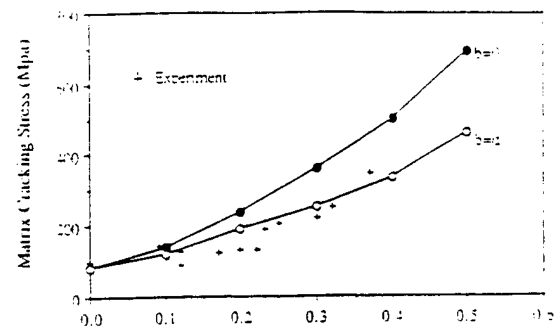


SCS-6/7740 (treated, 525 °C test):

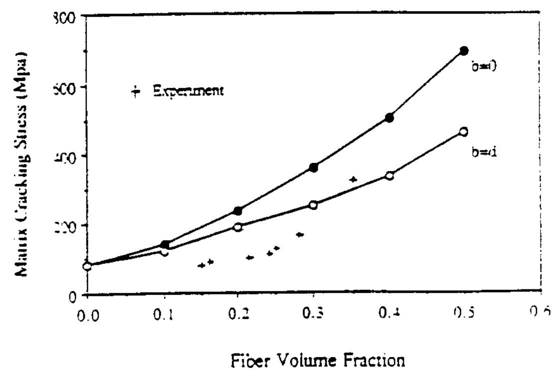


EXPERIMENT AND PREDICTION

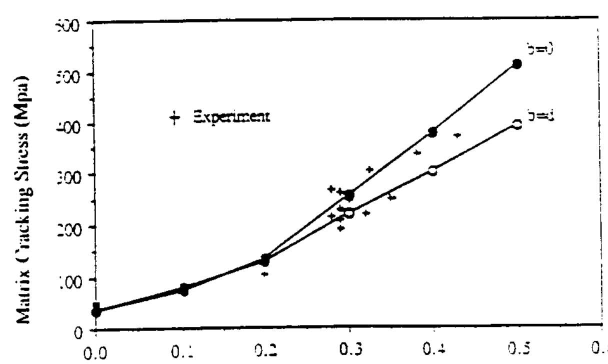
Nicalon/7740 (RT test):



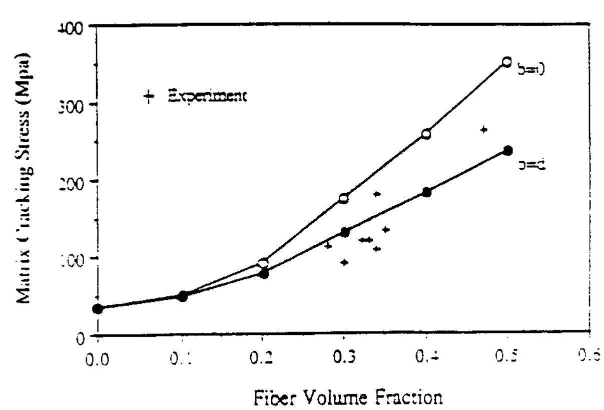
Nicalon/7740 (525 °C test):



SCS-6/1723 (RT test):

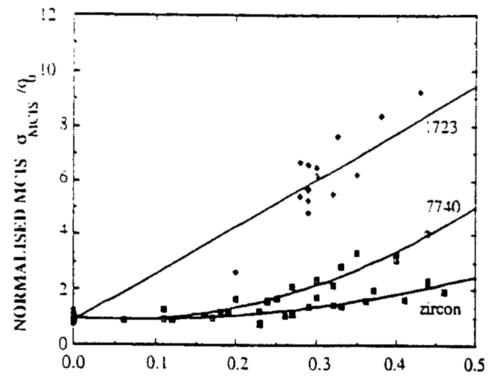


SCS-6/1723 (500 °C test):

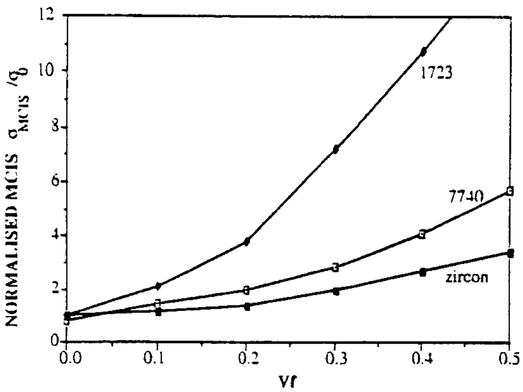


EXPERIMENT AND PREDICTION

SCS-6 with 1723, 7740 and Zircon: experiment



Model prediction:



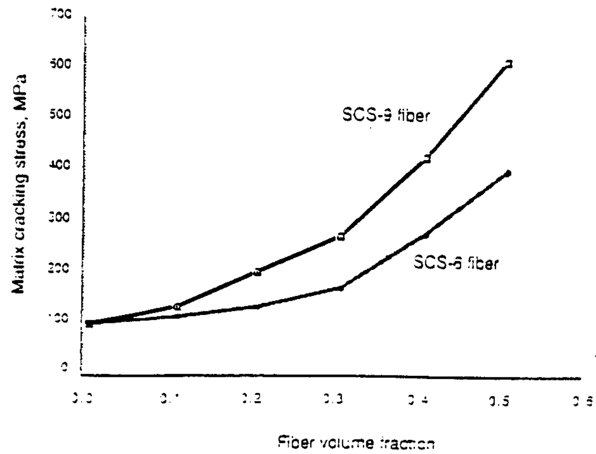
SUMMARY

- Material factors:
  - tougher matrix > 2000 μe
  - stiffer fiber (>12,000 μe); $E_f/E_m > 2$
  - thermal compatibility
- Geometric factors:
  - smaller fiber
  - high fiber volume fraction (> 0.4)
  - smaller fiber spacing
  - uniform fiber distribution
- Interface Factors:
  - adequate chemical bonding desirable
  - frictional bonding unreliable
- Processing Factors:
  - minimize inherent flaws (matrix, fiber and interface)
  - minimize residual stresses.
  - minimize material variability.

VENTURE A PREDICTION

- based on the quasi-micro model-

- SCS-6/7740 system extensively tested (fiber diameter = 140μm)
- SCS-9/7740 system in processing. (fiber diameter = 70μm)



FUTURE WORK

EXPERIMENT:

- matrix crack profile (depth of crack from surface);
- role of interfiber spacing (16 μm and 70 μm fibers);
- role of thermal residual stresses (vary $\Delta\alpha$ and ΔT);
- role of interfacial bonding (preoxidize fiber);
- fabricate systems of high temperature matrices (SiC).

MODELING:

<u>concurrent with experiment</u>:

- parametric simulation of matrix crack initiation.

  fiber size effect, interfiber spacing effect, thermal mismatch effect, interfacial debonding, temperature loading;

- parametric simulation of single fiber pullout.

  fiber size effect, debonding and sliding mechanics, relevance and meaning of τ;

<u>theoretical development</u>

- linking of local matrix cracks;
- time-dependent (high temp) matrix cracking.

PRESSURELESS DENSIFICATION OF CERAMIC MATRIX COMPOSITES-ANALYTICAL MODELING

M.N. Rahaman, L.R.Dharani, R.E. Moore
University of Missouri-Rolla
Rolla, MO 65401-0249

GRADUATE STUDENTS
Wei Hong
Roland E. Dutton, Jr.
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Chen-Lung Fan

SPONSOR: AFOSR (G-90-0267)

ABSTRACT

The presence of hard, inert second phase, referred to rigid inclusions, causes dramatic reduction in densification rates of polycrystalline ceramic materials in sintering process. The reasons for the reduction in densification are still unclear. The commonly suggested explanations include: viscoelastic backstress, sintering damage, differential densification, inclusion network formation, microstructural anisotropy and competition between coarsening and sintering. The current status is that these explanations are assumed and described in general sense, detailed explanation for each of these possible reasons is needed through qualitative and quantitative analysis. The objective of the research is to determine the factors controlling the sintering of polycrystalline matrix composites so that materials with high density inclusions and controlled microstructure can be processed successfully by conventional sintering.

The ceramic matrices are commonly assumed as viscoelastic and the viscoelastic stresses can be solved for by the principle of correspondence and elastic and viscoelastic analogy. However it require that the analytical elastic solution of the same configuration, integral transforms and inverse transforms and homogeneity be available, all of which are

often absent. Also, it is difficult to obtain analytical solutions to problems with nonlinearity which often exists in sintering problem. For example, the free strain rate of the inclusion-constrained matrices depend to some extent on the current densities which are not known a priori.

Finite element analysis has some advantages in dealing with the geometric complexity, nonhomogeneity and nonlinearity. We have developed a computer program based on viscoelastic formulation. The viscoelastic finite element formulation involves large deformation theory and updated Lagrange formulation. The matrices are assumed to obey Maxwell model in which the total strain rate vector is a combination of elastic strain rate, viscous strain rate and sintering free strain rate vectors. Special attention is paid to the fact that the configuration is continuously changing during sintering. The problem is solved in an incremental fashion. The solved density at a point in the matrix is fed back for the use in determining the sintering free strain rate and material properties in the next increment. The average relative density of the matrix is calculated by a weighted integration over the matrix domain.

For polycrystalline materials, the constraints often do not retard coarsening process, such as surface diffusion and grain growth, and all the process influence the sintering kinetics. We defined a few of different patterns of deriving shrinkage coefficients determining the free strain rates in the constrained matrix from experimental data of the unconstrained matrix undergoing an isothermal sintering with considerations of density dependency and other factors. Material properties, such as Young's modulus, shear viscosity and Poisson's ratio are also density dependent. For computational efficiency, we use a composite cylinder geometry in which the core region is treated as a rigid inclusion and the clad as a originally homogeneous, continuum representing the porous polycrystalline matrix. Results from the finite element calculations are plotted as density vs time curves against experimental data. The results from this simple model confirm that viscoelastic stresses induced by the presence of rigid inclusion do not directly reduce densification rates so much as observed in experiments. However, the calculations including the effect of other factors on shrinkage coefficients gave densities close to that observed in experiments. We will consider models concerning sintering damage, differential sintering and pore coarsening in the near future.

PRESSURELESS DENSIFICATION OF CERAMIC MATRIX COMPOSITES- ANALYTICAL MODELING

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16th Ann. Mechanics of Composites Review

November 12-13, 1991

Dayton, OH

ANALYTICAL MODELING

Assumptions:

Matrix material is viscoelastic

Isothermal sintering

Sintering potential depends on density and other factors

Material properties are density dependent

Inclusions are rigid

VISCOELASTIC FORMULATIONS

Strain rate:

$$\{\dot{\varepsilon}\} = \{\dot{\varepsilon}^{e}\} + \{\dot{\varepsilon}^{v}\} + \{\dot{\varepsilon}^{s}\}$$

where

$\{\dot{\varepsilon}\}$ total strain rate vector,
$\{\dot{\varepsilon}^{e}\}$ elastic strain rate vector,
$\{\dot{\varepsilon}^{v}\}$ viscous strain rate vector,
$\{\dot{\varepsilon}^{s}\}$ sintering free strain rate vector.

The free sintering free strain rate vector is

$$\{\dot{\varepsilon}^{s}\} = \{\alpha\ \alpha\ \alpha\ 0\ 0\ 0\}^{T}$$

where α is called as shrinkage coefficient.

Stress rate:

$$\{\dot{\sigma}\} = [D](\{\dot{\varepsilon}\} - [\eta]^{-1}\{\sigma\} - \{\dot{\varepsilon}^{s}\})$$

where $[D]$ elastic stiffness matrix,
$[\eta]$ viscosity matrix.

The strain-displacement relation:

$$\dot{\varepsilon}_x = \frac{\partial u_x}{\partial x} + \frac{1}{2}\left(\frac{\partial u_x}{\partial x}\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial x}\frac{\partial u_y}{\partial x} + \frac{\partial u_z}{\partial x}\frac{\partial u_z}{\partial x}\right) \quad \text{etc.}$$

DETERMINATION OF SHRINKAGE COEFFICIENT IN CONSTRAINED MATRIX

Given $\rho = f(t)$ from pure matrix sintering, we define the follows.

Time-dependent shrinkage coefficient

$$\alpha = -\frac{f'(t)}{3f(t)}$$

Density-dependent shrinkage coefficient

$$\alpha = -\frac{f'(f^{-1}(\rho_c))}{3\rho_c}$$

Shrinkage coefficient dependent on density and other factors (grain size, coarsening)

Assuming $\dot{\rho} = H(\rho)\,G(t)$, given $G(t)$,
i.e. $G(t) = G_o(1+kt)^{-a/3}$, $H(\rho)$ can be determined.

$$H(\rho) = f'(t)/G(t)$$

$$\alpha = -\frac{f'(f^{-1}(\rho_c))}{\rho_c}\left(\frac{1+kf^{-1}(\rho_c)}{1+kt}\right)$$

DETERMINATION OF THE DENSITY DEPENDENT SHRINKAGE COEFFICIENT

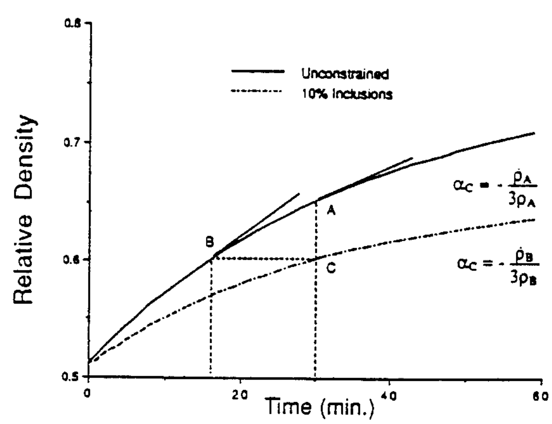

Fig.2. Determination of density-dependent shrinkage coefficient.

BACKGROUND

Experiments show that the presence of dense second phase inclusions (e.g. particles or whiskers) can cause substantially reduced densification rates in polycrystalline matrices.

Glass matrices are easier to densify around an inclusion phase, compared to polycrystalline matrices.

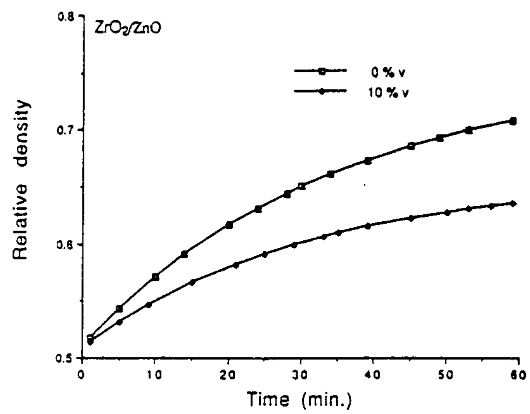

Fig.1. Experimental data of ZnO and ZnO with 10% volume fraction of ZrO_2 inclusion in isothermal sintering at 750 °C

MECHANISMS FOR SUBSTANTIALLY REDUCED SINTERABILITY IN POLYCRYSTALLINE MATRICES

1. Viscoelastic backstresses
2. Differential densification
3. Sintering damages
4. Competition between coarsening and sintering
5. Inclusion network formation
6. Microstructural anisotropy

EXPLANATIONS: CURRENT STATUS

Scherer's model predicts small backstresses.

Differential shrinkage is also rejected.

Sintering damage is not clearly observed in the model experiments.

Coarsening and sintering in model composites currently being addressed.

Network formation unimportant in glass matrices for inclusion content<10-15%.

No studies on microstructural anisotropy.

OBJECTIVE

Determine the factors controlling the sintering of polycrystalline matrix composites so that materials with high density and controlled microstructure can be processed successfully by conventional sintering.

APPROACH

Finite element method has some advantages in dealing with geometric complexity, nonhomogeneity and nonlinearity.

Large deformation theory and updated Lagrange formulation are used.

FEATURES OF FEM PROGRAM

Large deformation

Updated Lagrange formulation

Sintering free strain rate depends on density and other factors

Material properties depend on density

Feedback of solved densities

Dealing with inhomogeneity of density distributions

RESULTS

Results show that the viscoelastic stresses induced by the presence of rigid inclusions do not reduce directly the densification rate so much as observed in experiment, however consideration of other factors gave better agreement with experimental data.

The other factors are among grain growth, pore coarsening, etc. Further investigation of sintering mechanism is being continued.

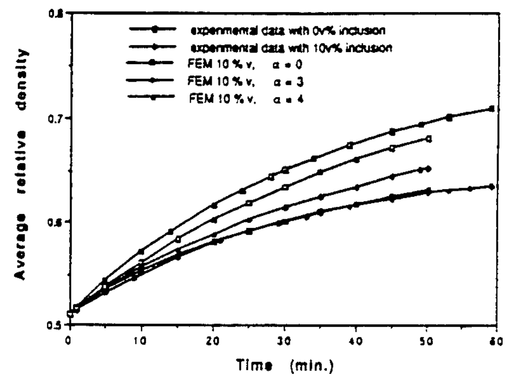

Fig.3. FEM Calculations with different coefficient α against experimental data.

CONFIGURATION AND MATERIAL PROPERTIES

A composite cylinder geometry in which the core is a rigid inclusion and the clad a homogeneous matrix.

The well observed material properties

Young's modulus $E = E_f \exp[-b_1(1-\rho)]$

Shear viscosity $\eta = \eta_f \exp[-b_2(1-\rho)]$

where E_f and η_f are their values at the final relative density.

E_f = 125 GPa $b_1 = 1.6$

η_f = 5.833 GPa min $b_2 = 2.5$

Poisson's ratio $\nu = \frac{1}{2}\sqrt{\frac{\rho}{3-2\rho}}$

FUTURE WORK

Ellipsoidal inclusions

Crack-like damages

Clusters and agglomerates of inclusions

Pore coarsening

3-D ANALYSIS AND VERIFICATION OF FRACTURE GROWTH MECHANISMS IN FIBER-REINFORCED CERAMIC COMPOSITES

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William D. Keat
Michael C. Larson

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SUMMARY

This is a fully 3-D computational and experimental investigation into the mechanics of toughening a brittle ceramic matrix by incorporating long brittle fibers. Particular attention is given to the interfacial decohesion and frictional slipping near the tip of a matrix crack which is impinging upon a fiber (or array of fibers). The Surface Integral and Finite Element Hybrid method, which employs the principle of superposition to combine the best features of two powerful numerical techniques, provides an extremely flexible and efficient computational platform for modelling linear elastic fractures near material inhomogeneities. The computational simulations are being guided by laboratory experiments which record the growth histories of interacting matrix and interface cracks. This program is providing insights into optimal combinations of the key parameters (e.g. residual stresses at interface, friction coefficient, strength of fibers) as a step towards optimizing the design of ceramic composites.

EXTENDED ABSTRACT

The key episode, schematically represented in Figure1, in the fracture of a ceramic matrix/ceramic fiber composite is the interaction that takes place between an advancing crack front and the fiber/matrix interface of individual fibers. A "strong" interface will transmit high crack tip stresses inducing premature fracture of the fibers, while a "weak" interface will blunt the crack-tip and allow the fracture to proceed past intact fibers.

The focus of the project has been on developing fully explicit 3-D computational models of these toughening mechanisms. The problem of a matrix crack growing towards an isolated fiber subject to interfacial slip, which is impractical using conventional methods based on volume discretization, is being modelled using a hybrid numerical method. The use of surface integrals to model the fractures (both matrix and interface) minimizes the number of degrees of freedom and simplifies meshing by requiring only that the fracture surfaces be discretized. Volume effects including residual stresses due to thermal and/or material mismatch are captured using a separate finite element mesh, which remains fixed during the course of growing the fractures.

It is the nature of the problem being investigated that the research has proceeded on several fronts simultaneously. A summary of the overall strategy is represented in Figure 2. Brief descriptions of the areas in which significant progress has been made are reported below:

Stationary 3-D Fractures Near Bonded Bimaterial Interfaces

- Derived the complete set of fundamental solutions corresponding to opening and shear multipoles near a planar bimaterial interface.

- Incorporated the bimaterial influence functions into a surface integral formulation and applied the resulting methodology to solve problems of the following type: (*i*) Mode I fracture near and/or intersecting a single planar bimaterial interface; (*ii*) Mixed-mode fractures of arbitrary orientation with respect to a planar interface.

- Coupled the above surface integral formulation to a finite element code and applied the resulting hybrid method to the following classes of problems: (*i*) Mode I fractures near and/or intersecting multiple planar bimaterial interfaces (see Figures 2 and 3); (*ii*) Fractures near curved interfaces, including for example the capability to model the interaction of a fracture with an arbitrarily-shaped inclusion.

Matrix Prestressing Due to Thermal Effects

- Modified the 3-D hybrid method to account for thermal strains arising either from the presence of temperature gradients or a mismatch in thermal properties between fiber and matrix.

3-D Crack Propagation

- Developed an algorithm which will automatically remesh a growing fracture. The continuous crack front was represented using parametric cubic splines while the interior of the fracture was discretized using a combination of experience-based rules and modern triangulation techniques.

- Ran preliminary numerical tests to begin the precess of evaluating potential fracture criteria.

Interaction of Multiple 3-D Mixed Mode Fractures

- Expanded on the original surface integral formulation for homogeneous media in order to produce the capability to efficiently model any number of mixed-mode planar fractures. This procedure can be used to model the problem of a main crack interacting with an undetermined number of interfacial slip zones.

- The procedure just described was recently adapted to model nonplanar cracks in a piecewise linear fashion.

Evolution of Frictionally Constrained Interfacial Slip

- Developed 2-D and 3-D surface integral models to study the growth of frictional slip zones induced on a planar interface by the incremental pressurization of a stationary main crack (see Figures 5 and 6).

- Modelled the evolving slip zones induced on a curved interface by a local matrix.

Experimental Simulations

- Studied the hydraulically induced growth of a crack in a cementitious matrix towards an isolated glass fiber, under various conditions of interfacial strength. The growth of the main crack was recorded as a sequence of growth rings, produced by intermittently biasing the applied stress field.

- Designed a push-out test for evaluating the interface properties associated with the above experiments.

- Developed a new apparatus that permits direct observation of the frictional slip zones induced by incremental pressurization of a material discontinuity. Generation of results is now in progress.

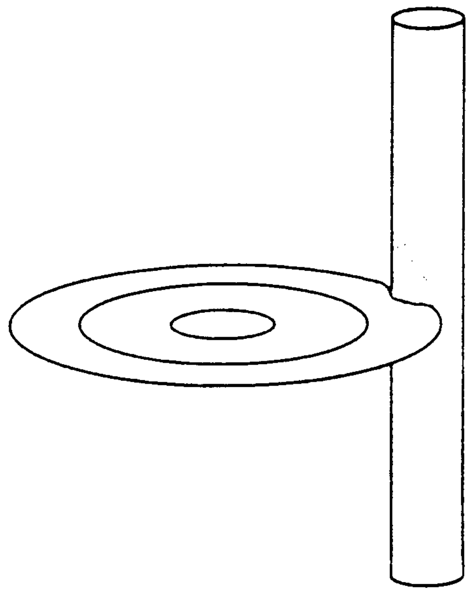

Figure 1. Schematic representation of the near tip interaction between an advancing matrix crack and a fiber. The shaded zone represents the evolving interfacial slip.

RESEARCH PLAN

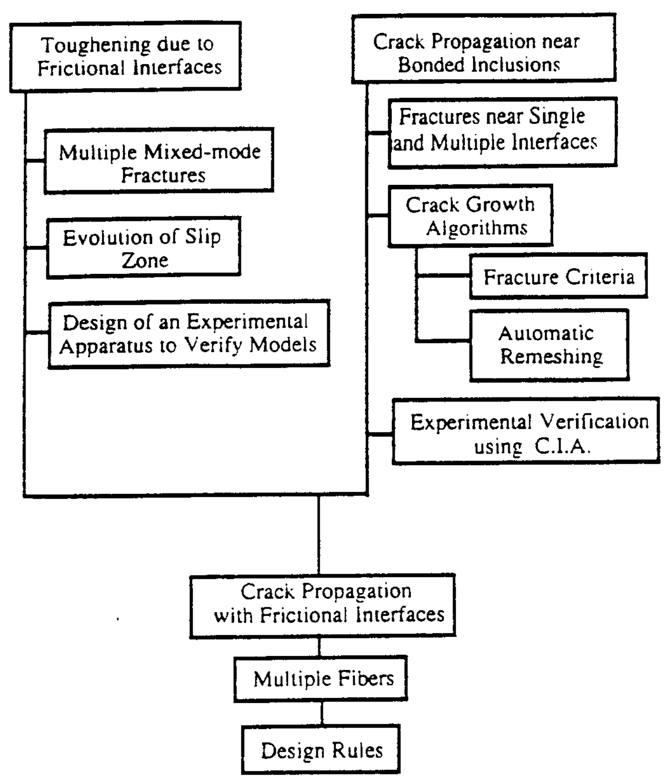

Figure 2. Summary of current and future research.

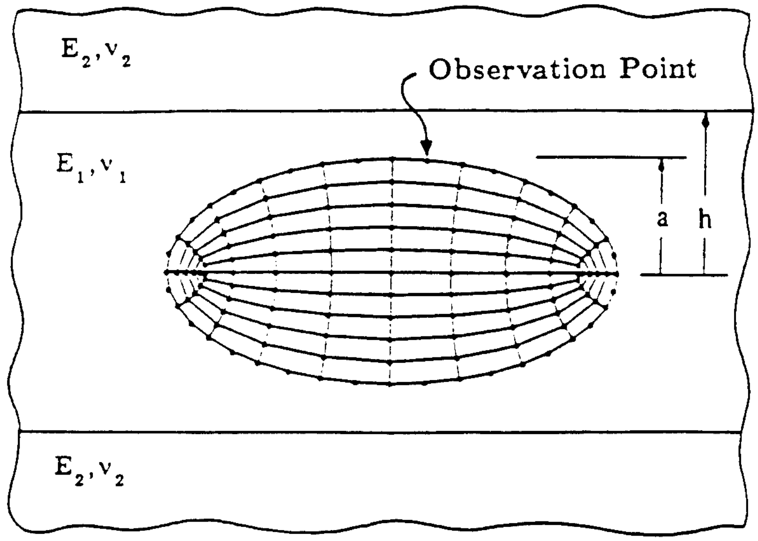

Figure 3. Elliptical fracture approaching two planar bimaterial interfaces. The fracture has been represented by its surface integral discretization.

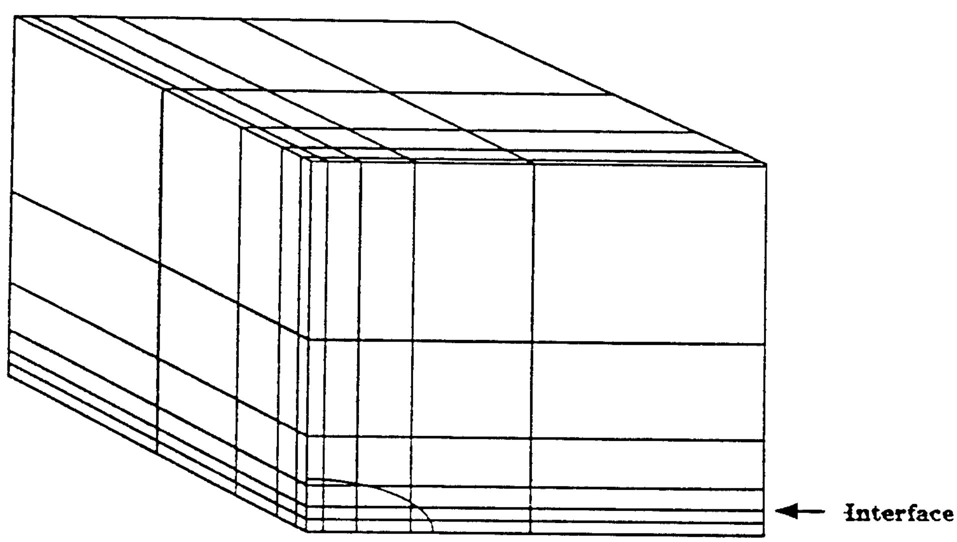

Figure 4. 1/8 symmetric hybrid model of the elliptical fracture in a trilayered domain.

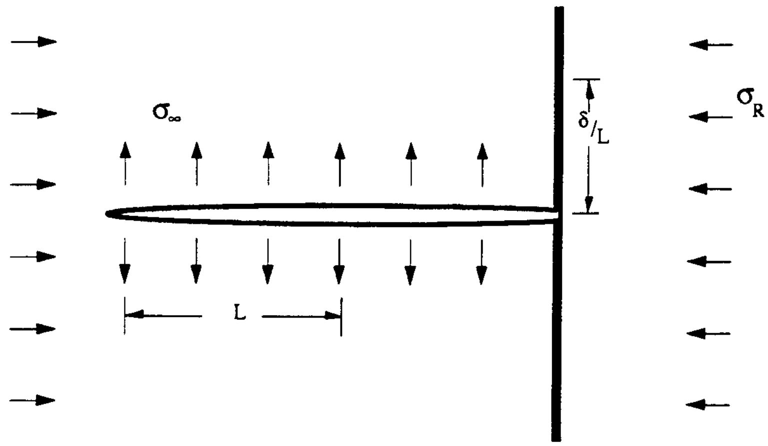

Figure 5. Plane strain geometry of a stationary matrix crack interacting with an evolving slip zone.

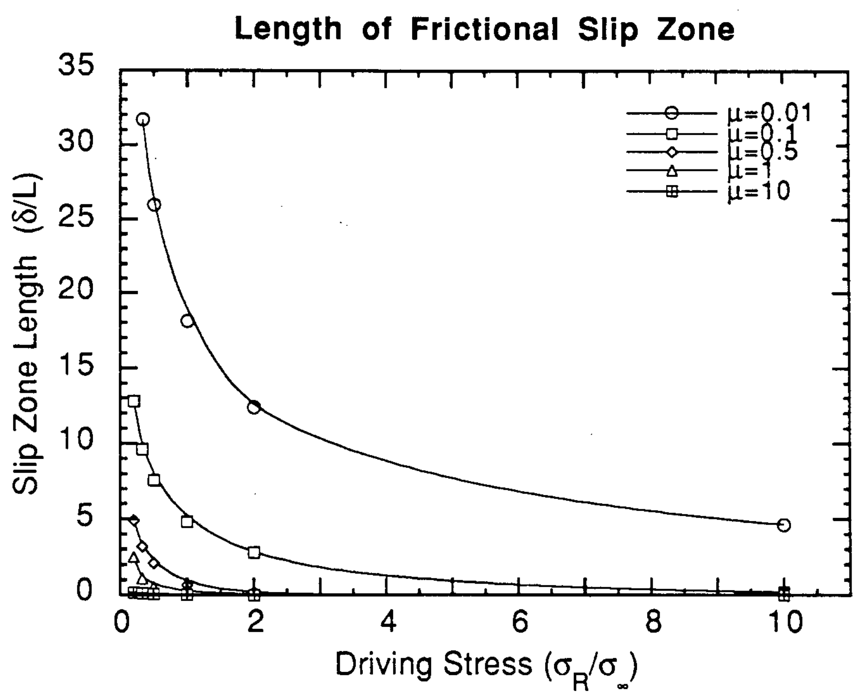

Figure 6. Length of the frictional slip zone as a function of the driving stress and the friction coefficient (plane strain).

DAMAGE OF LAMINATED COMPOSITES RESULTING FROM TRANSVERSE LOADING

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ABSTRACT

An investigation was performed to study the response of laminated composites to transversely concentrated loading. Matrix cracking and delamination were the primary concern of the damage modes. The objective of the study was to fundamentally understand the damage initiation and development in composites due to transverse loading. Both analytical and experimental work were conducted for the study. In order to understand the basic mechanics and mechanism, transversely concentrated line loading was considered initially for simplifying the problem. An analytical model was developed for simulating the response of laminated composite beam subjected to concentrated line loading, from damage initiation to damage propagation. The analysis based on the large deformation theory consists of a stress analysis for calculating deformations, a failure analysis for predicting initiation and propagation of damage, and a contact analysis for modelling the interaction of crack surfaces during loading inside the material.

Extensive experiment have also been performed on both flat and curved composite panels in order to verify the analysis. More than fifty specimens were tested. The results of the calculations based on the model were then compared with the test data. Overall, the predictions agreed with the data very well. In summary, the following remarks can be made based on the study for the damage development in laminated composites resulting from transversely concentrated loading:

1). Intraply matrix cracking is the initial failure mode;

2). There are two basic types of initial matrix cracks: shear crack and bending crack;

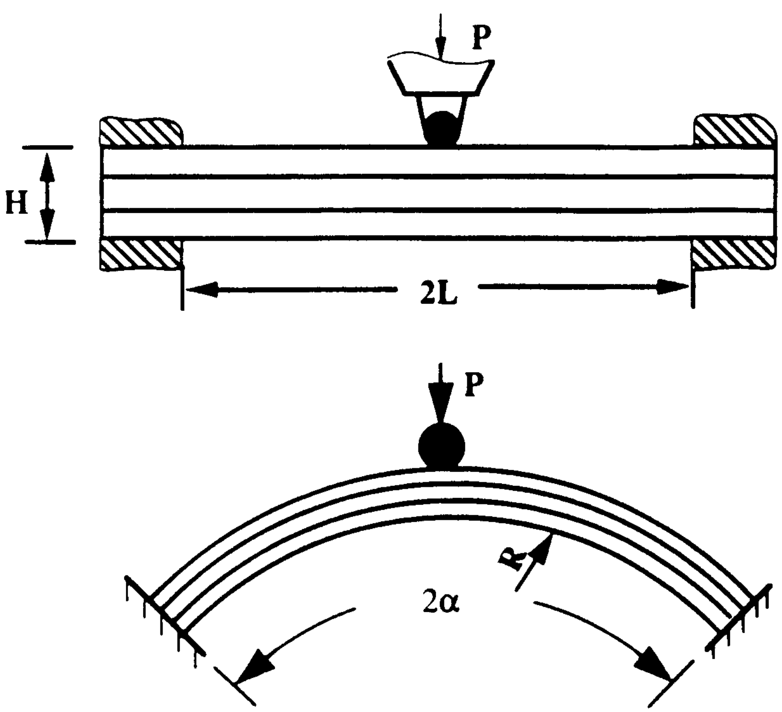
3). Intraply matrix cracking triggers delaminations;

4). Delamination growth induced by a shear crack is very unstable and catastrophic;

5). Delamination growth induced by a bending crack is stable and progressive.

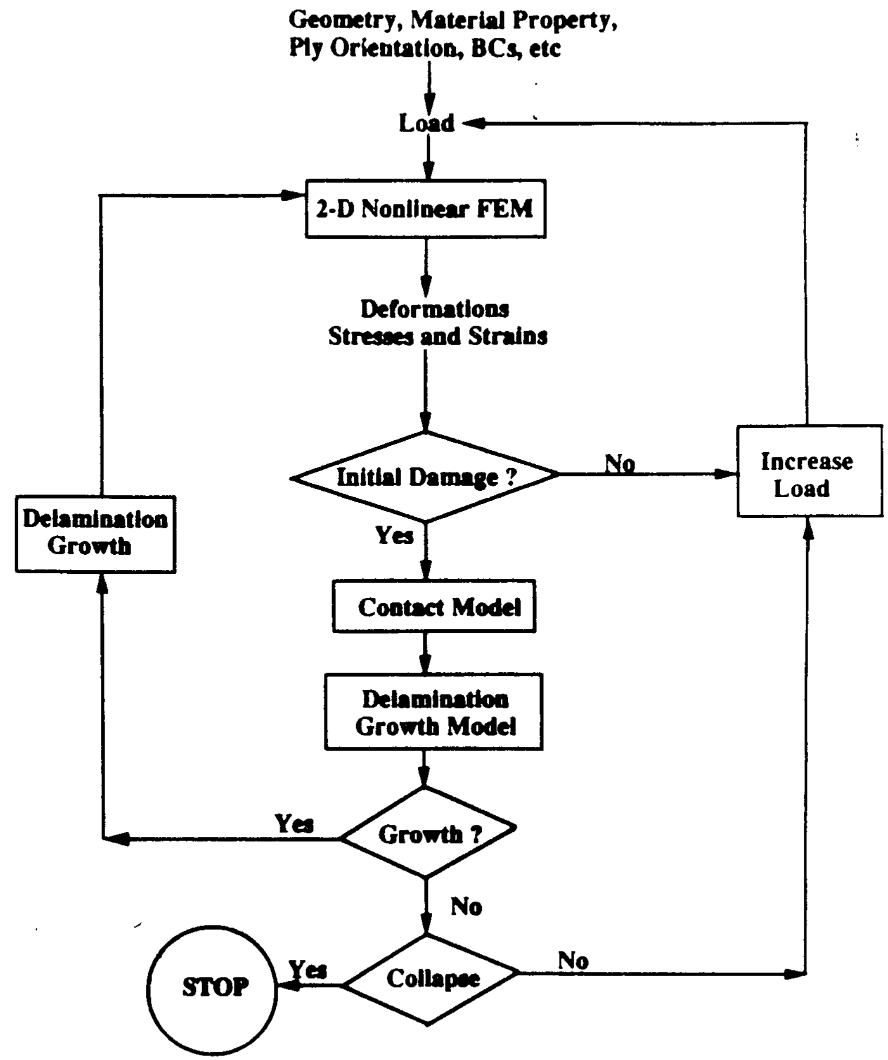
Based on the two-dimensional analysis, a three-dimensional finite element analysis is being developed for simulating the response of laminated composites subjected to transversely concentrated point loading. Special attention has been given to the interfacial contact/slip condition of the delaminations and the two-dimensional delamination growth along the ply interfaces. Experiments will also be performed to generate data for the analysis and to verify the results of the calculations.

PROBLEM STATEMENT

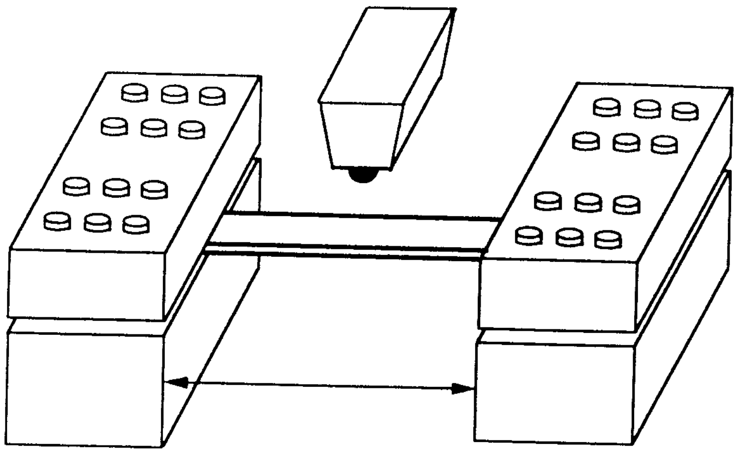


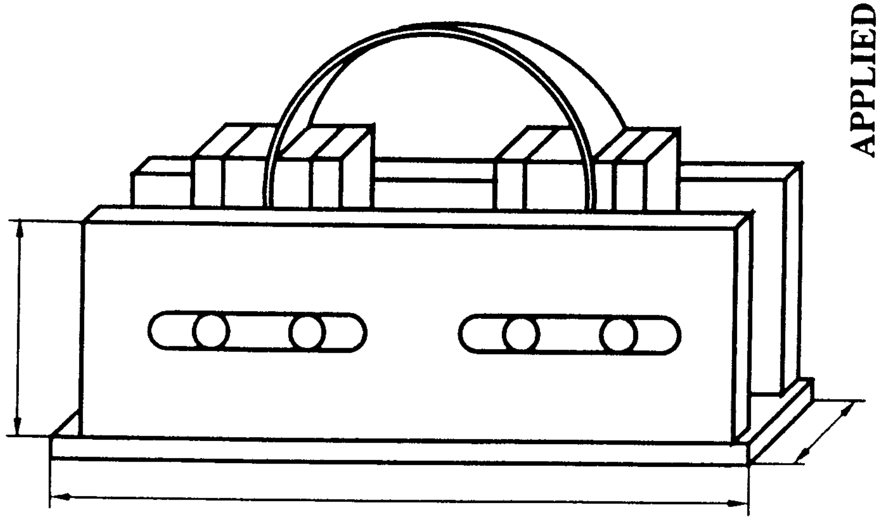
FIND

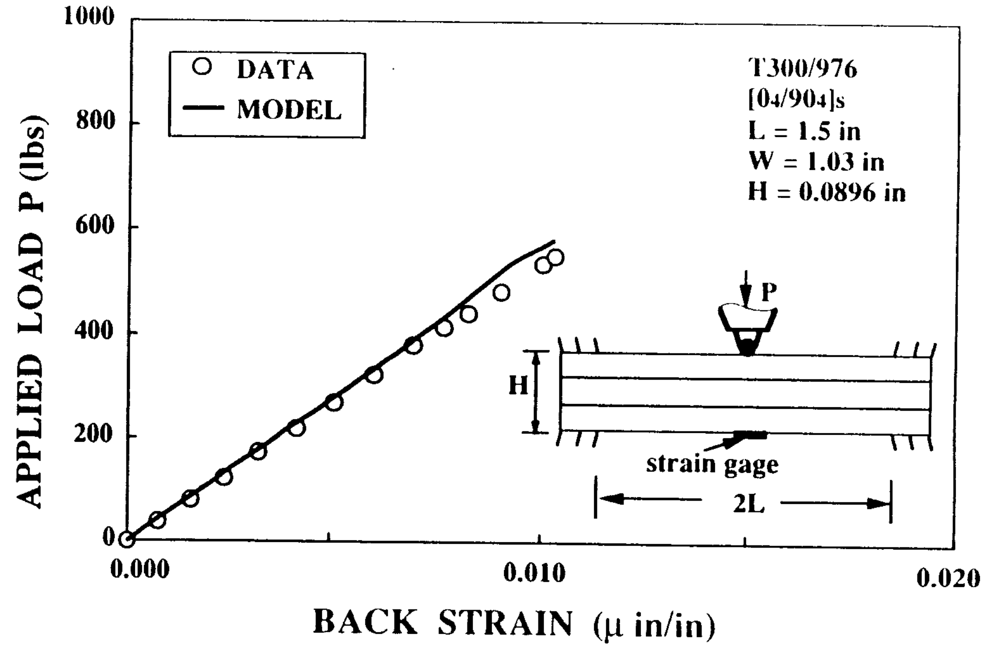
MECHANICAL RESPONSE
INITIAL DAMAGE
DAMAGE PROPAGATION

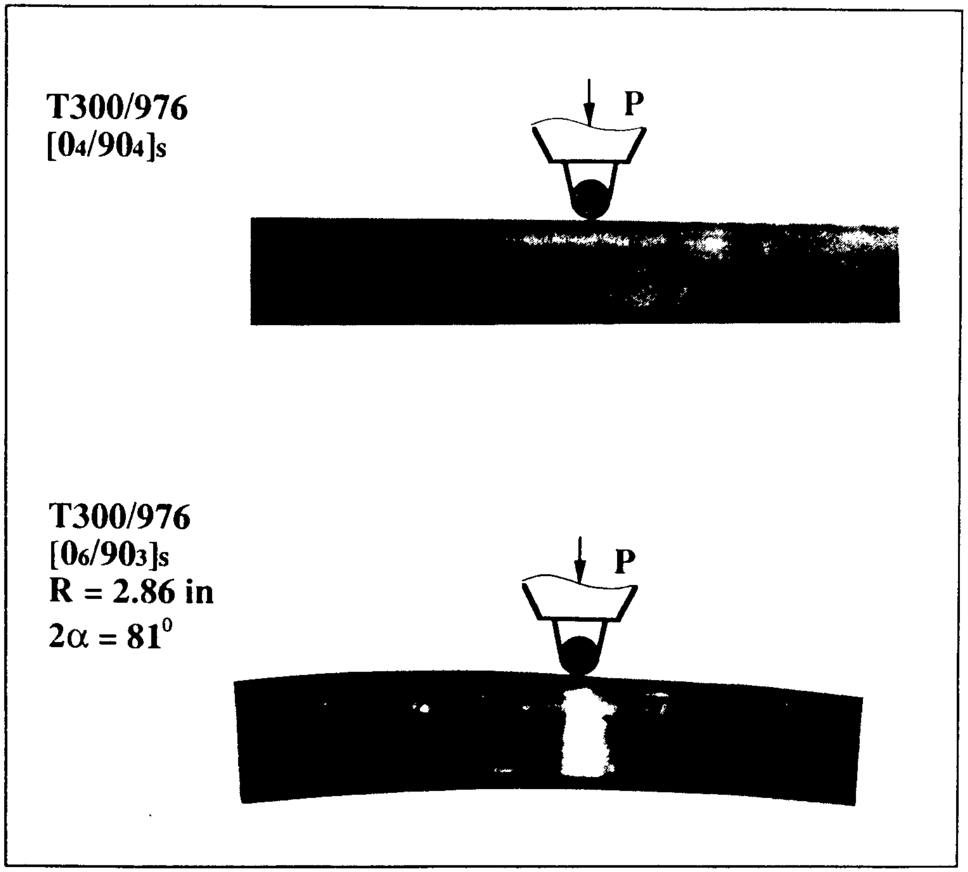


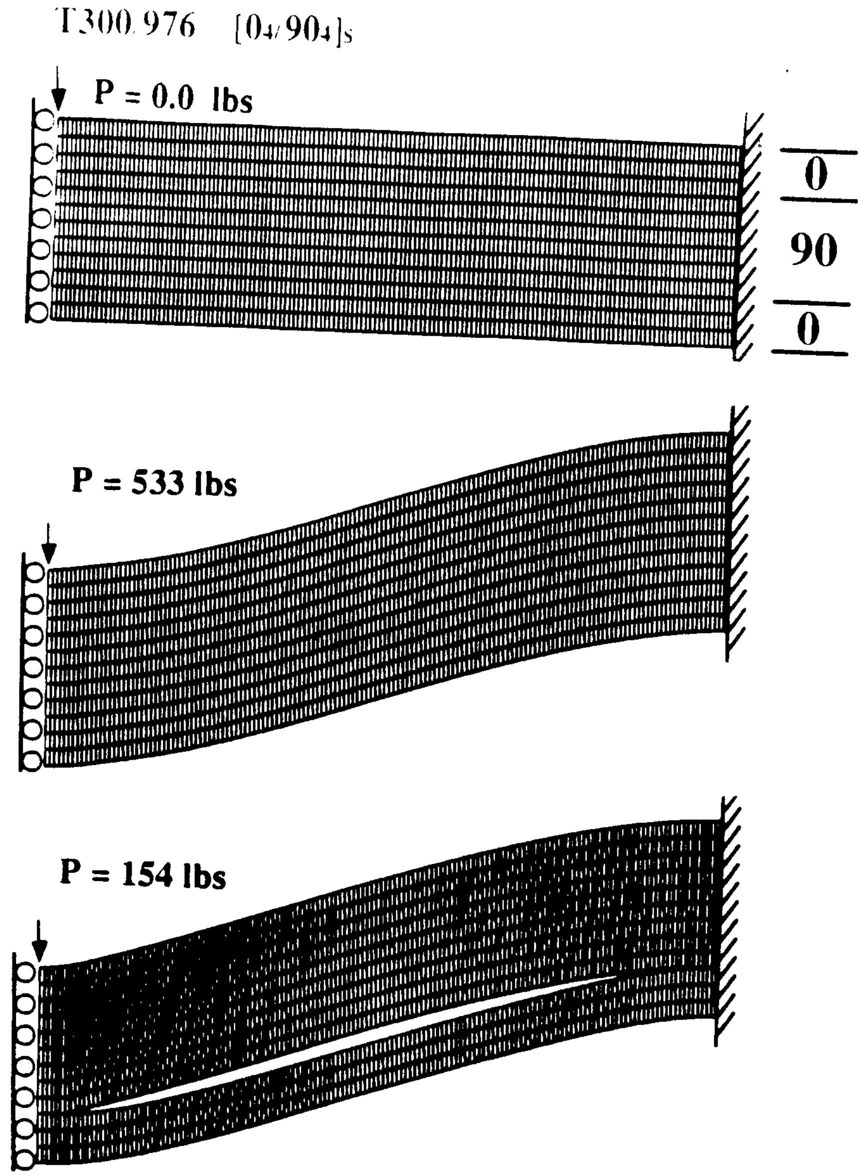
Flowchart of the Progressive Damage Model.

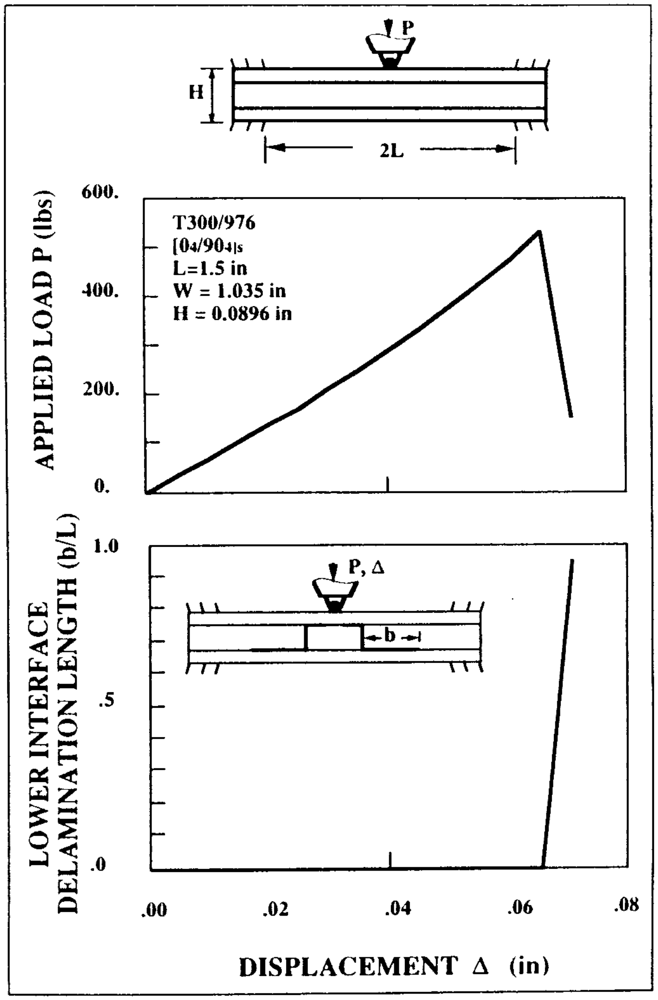




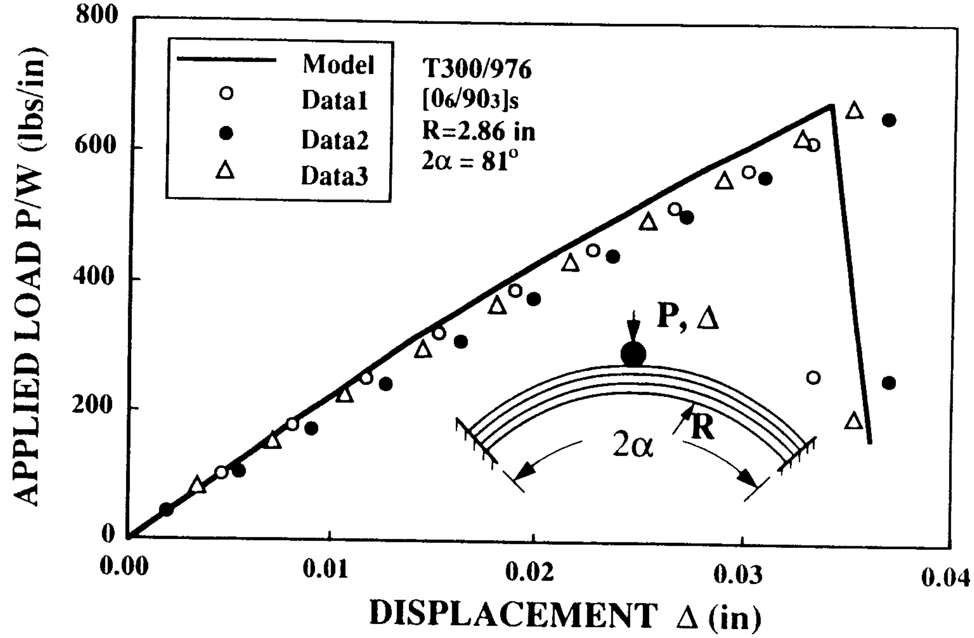

DATA
MODEL
T300/976
[04/904]s
L = 1.5 in
W = 1.03 in
H = 0.0896 in
P
H
strain gage
2L
APPLIED LOAD P (lbs)
0
200
400
600
800
1000
0.000
0.010
0.020
BACK STRAIN (μ in/in)


T300/976
[04/904]s
P
T300/976
[06/903]s
R = 2.86 in
2α = 81⁰
P


T300 976 [04/904]s
P = 0.0 lbs
0
90
0
P = 533 lbs
P = 154 lbs

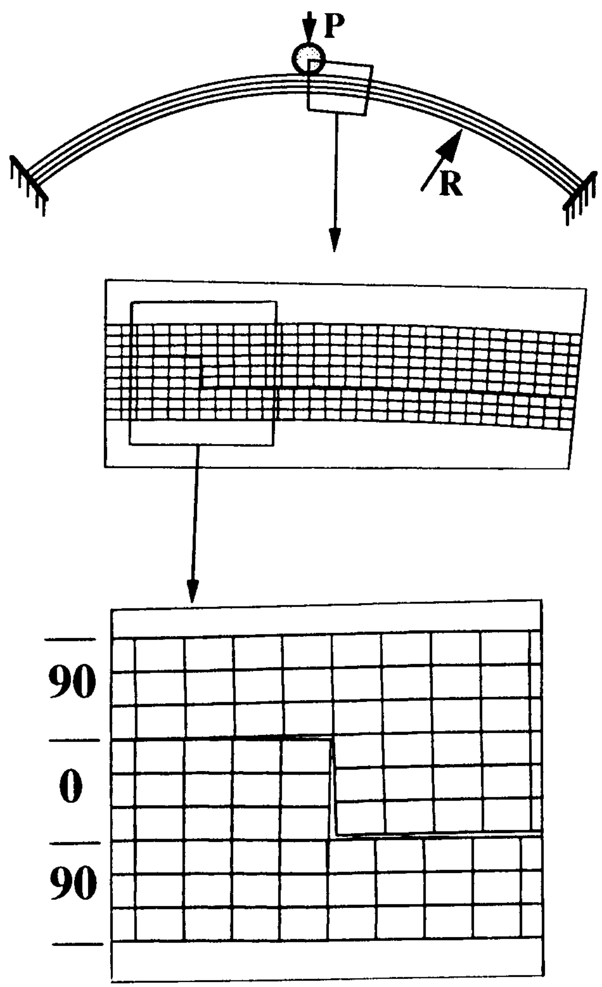


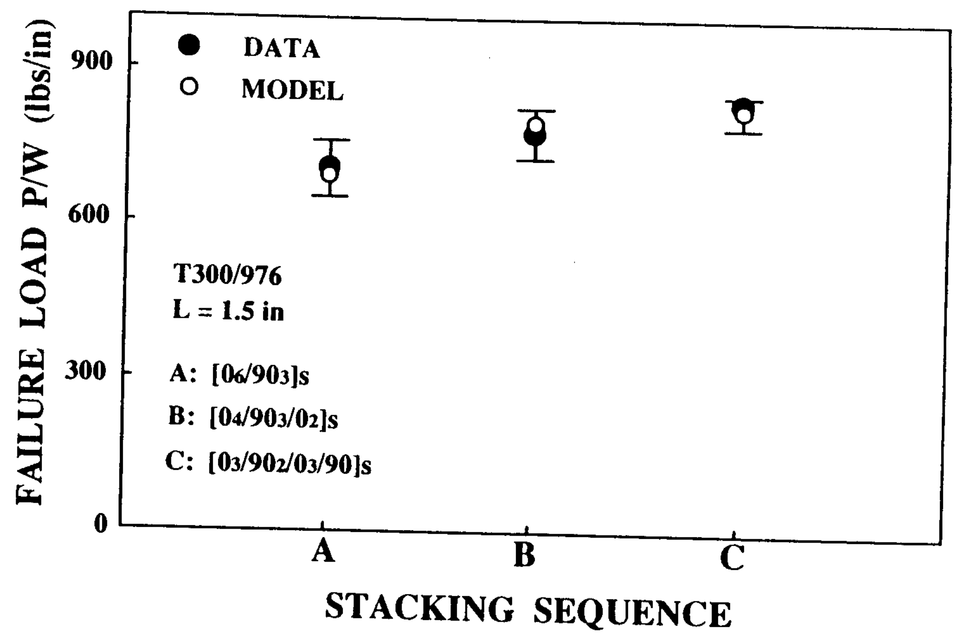
P
H
2L
T300/976
[04/904]s
L=1.5 in
W = 1.035 in
H = 0.0896 in
APPLIED LOAD P (lbs)
600.
400.
200.
0.
P, Δ
b
LOWER INTERFACE
DELAMINATION LENGTH (b/L)
1.0
.5
.0
.00
.02
.04
.06
.08
DISPLACEMENT Δ (in)

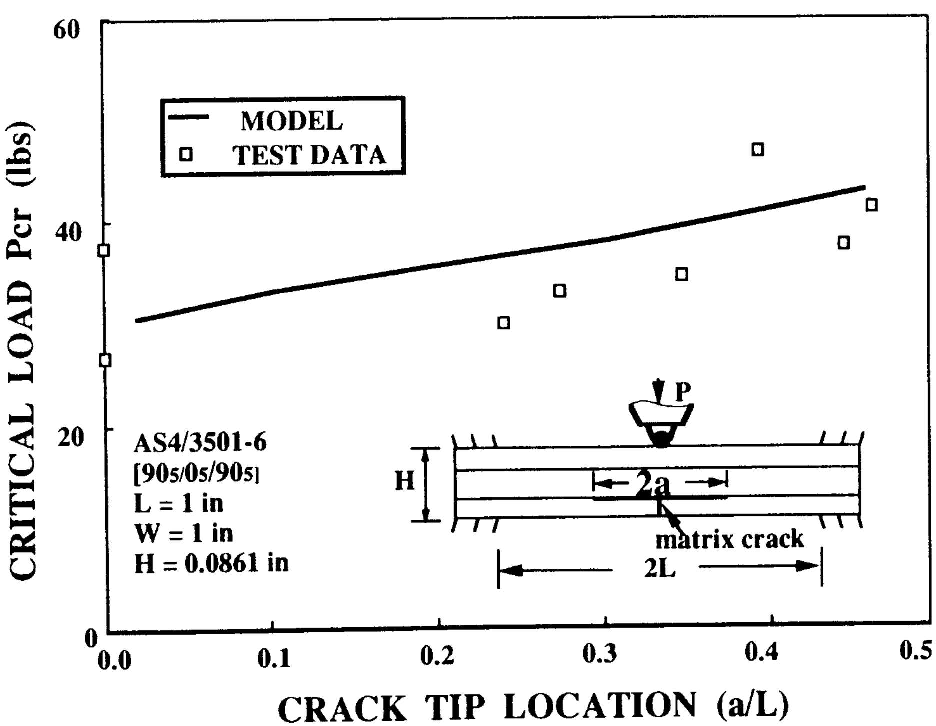


Model
Data1
Data2
Data3
T300/976
[06/903]s
R=2.86 in
2α = 81°
P, Δ
2α
R
APPLIED LOAD P/W (lbs/in)
800
600
400
200
0
0.00
0.01
0.02
0.03
0.04
DISPLACEMENT Δ (in)

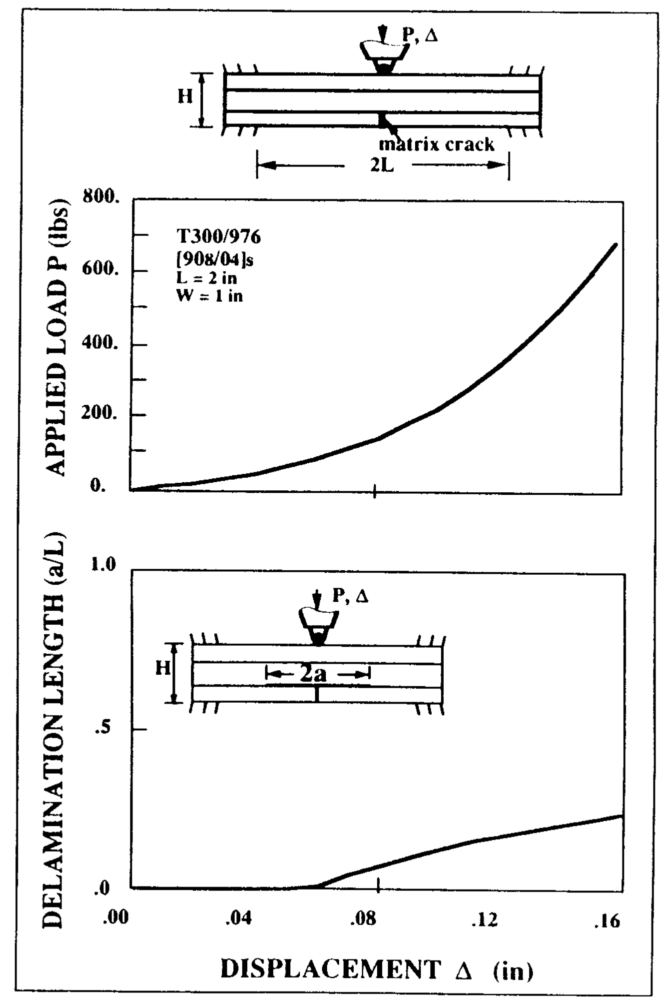
T300/976, $[0_6/90_3]_s$, R = 2.86 in, $2\alpha = 81^{\circ}$





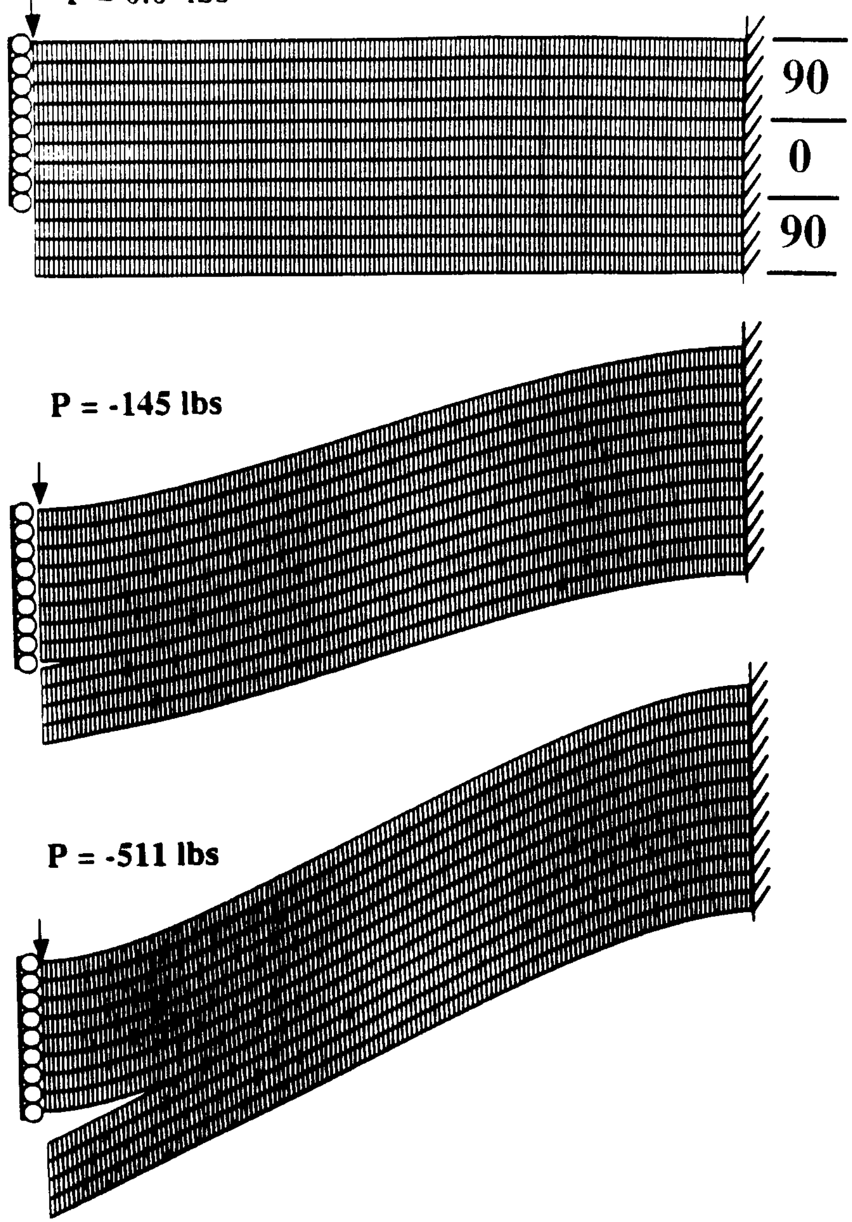


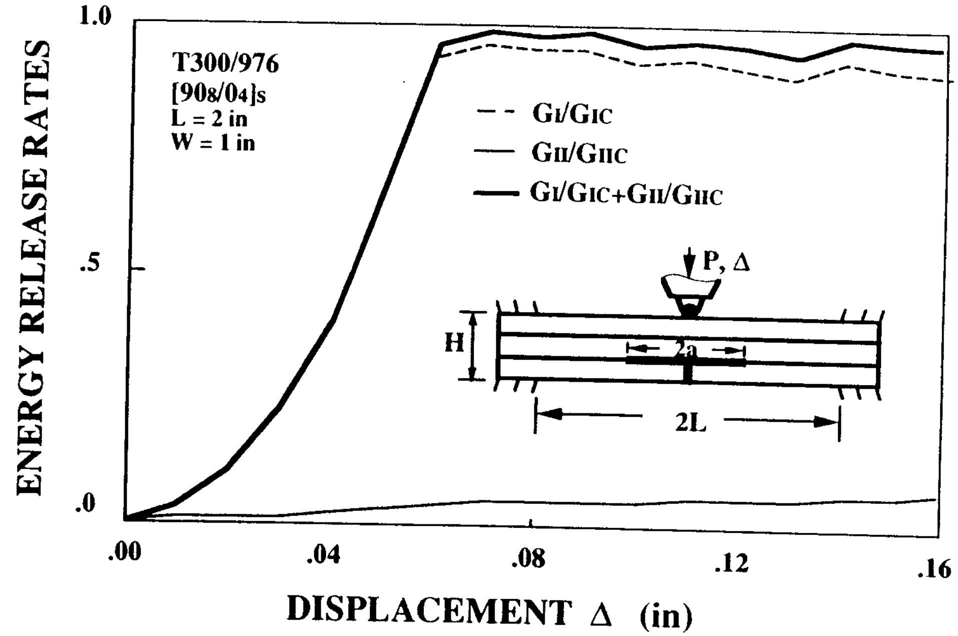
MODEL
TEST DATA
AS4/3501-6
[90s/0s/90s]
L = 1 in
W = 1 in
H = 0.0861 in
P
H
2a
matrix crack
2L
CRITICAL LOAD Pcr (lbs)
CRACK TIP LOCATION (a/L)
60
40
20
0
0.0
0.1
0.2
0.3
0.4
0.5



P, Δ
H
matrix crack
2L
T300/976
[908/04]s
L = 2 in
W = 1 in
APPLIED LOAD P (lbs)
800.
600.
400.
200.
0.
P, Δ
H
2a
DELAMINATION LENGTH (a/L)
1.0
.5
.0
.00
.04
.08
.12
.16
DISPLACEMENT Δ (in)

T300/976 $[90_8/0_4]_s$





FAILURE CRITERIA IN COMPOSITES BASED ON 3D MICROMECHANIC CONSIDERATIONS

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Department of Mechanical Engineering
Salt Lake City, Utah 84112

ABSTRACT

In this investigation, a systematic micromechanics approach is used in which the fibers of a composite layer are modeled as cylindrical inclusions which are embedded into an epoxy matrix plate. Moreover, a 3D stress analysis is used in order to capture any edge effects that may be present. A set of fundamental key problems has been identified and their respective solutions are then used to answer the following fundamental questions which provide direct applications to unidirectional composite plates:

transverse strength
edge delamination
modeling of fiber matrix interface
longitudinal strength (fiber pull out)
residual stresses due to thermal expansion mismatch,

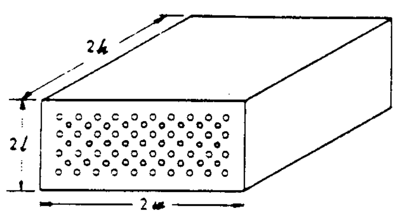
as well as important information to other indirect applications.

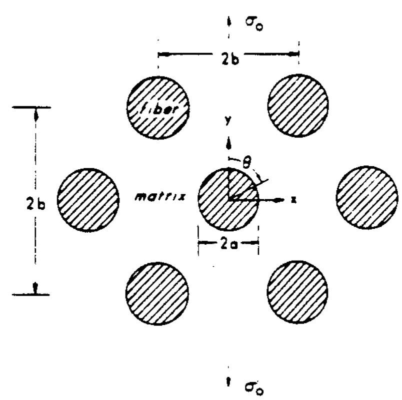
The approach consists of investigating first the 3D stress field due to the presence of one fiber. The results are subsequently extended to also include a doubly periodic array of fibers. It may be emphasized that in this analysis exact boundary conditions are used for the periodic cell configuration used, instead of the usual cylinder models or shear lag models. The latter models simplify the problem considerably and represent only an approximation. The results are then used to derive fracture criteria for crack initiation at the local level. The criteria identify the dependance of the transverse strength, for example, on the material properties as well as on the local and global geometry.

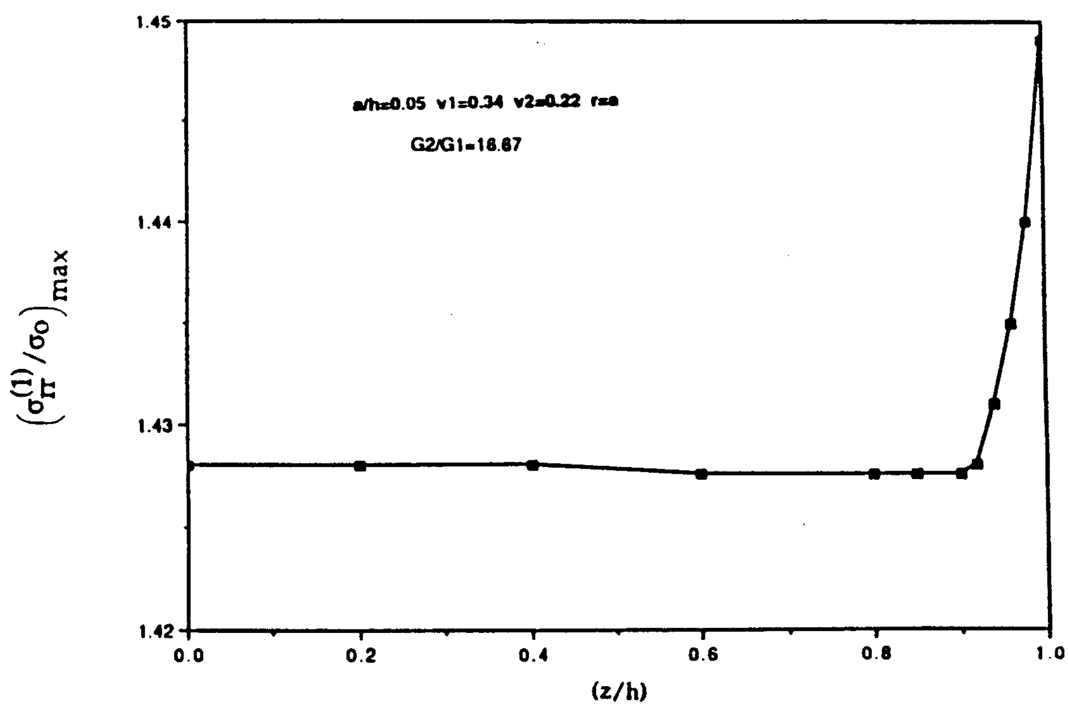
The investigation also provides important information regarding the regions of applicability of results based on macromechanical theories. The reader may recall that such theories predict the stress values at edges to be finite, except in the vicinity of an interface where the singularity strength is shown to be very weak. Thus, macromechanical theories

tend to underestimate the actual stress levels at such edges, e.g. surface of a hole, surface of a crack etc. However, if one is to study damage evolution at such neighborhoods, knowledge of the local stress field is essential. Thus, a coupling between macromechanical and micromechanical results may indeed be desirable for the prediction of local damage due to fracture.

Preliminary investigation has shown that it may now be possible to bridge the gap between the macro and micro theories via certain correlation functions. As a practical matter, once such correlation functions have been established, results based on macromechanical considerations may then be used to also answer questions on damage at the local level. This certainly presents a challenge. An example of a [0/ 90] composite plate weakened due to the presence of a circular hole is discussed.







ANALYSIS BASED ON 3D MICROMECHANICAL CONSIDERATIONS

* debonding along a fiber/matrix interface initiates at a fiber edge

* the failing stress at an edge is reduced by a factor of 10, which explains why delamination usually initiates at edges

* the failure criterion for debonding initiation away from the fiber edge (for small β) is

$$(\sigma_0)_{cr} \approx 1.8186 F(V_f)\sqrt{\frac{\gamma_{12} G_m}{2a_f \beta}}$$

* no interaction effects exist between fibers if they are spaced four diameters center to center

* for a glass fiber/ epoxy matrix composite with the properties

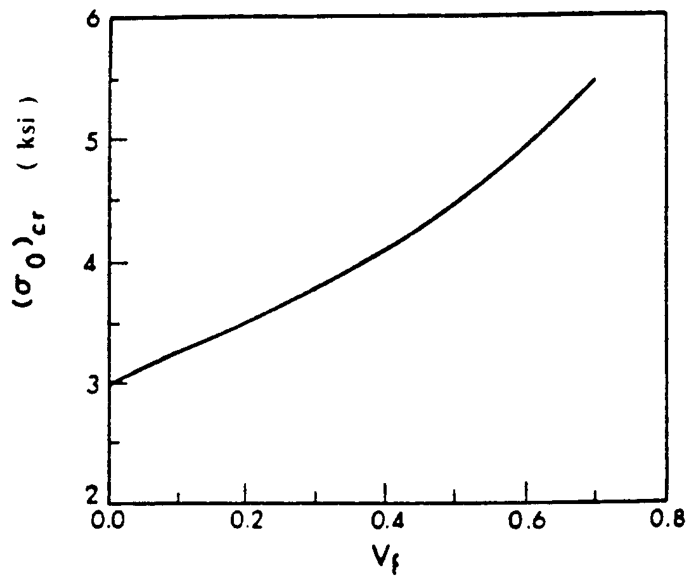
$$G_m = 2.10GPa \quad \nu_m = 0.34 \quad 2a_f = 10^{-3}cm \quad \beta = 60^{\circ}$$
$$G_f = 35.00GPa \quad \nu_f = 0.22 \quad 2\gamma_{12} = 70J/m^2 \quad V_f \leq 0.70$$

the critical stress to failure at the fiber edge becomes

$$(\sigma_0)_{cr} \approx 2.985 F(V_f) \ ksi; \text{at the fiber edge}$$

where $F(V_f)$ is a function of the fiber volume fraction

* as the fiber volume fraction V_f increases, so is the critical failing stress

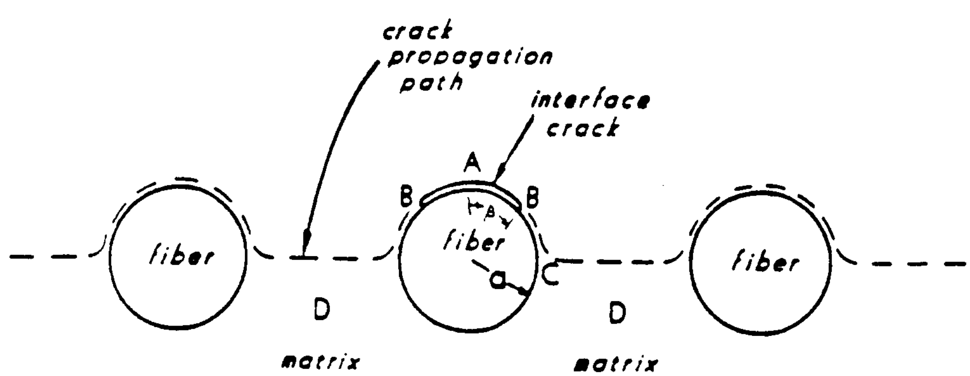


* away from the fiber edge, the max. σ_{rr} occurs at r= 1.2 a , which implies that a crack will initiate in the matrix if the fiber/matrix interface is well bonded

* the concept of a linear elastic modified shell matrix has a minimal reduction effect

* a debond crack initiates at $\theta = 0$ and advances to $\theta = 60$, where it begins to curve into the matrix

* edge delamination may now be modeled as the progressive failure of a row of fibers , thus the critical delamination stress is that given above



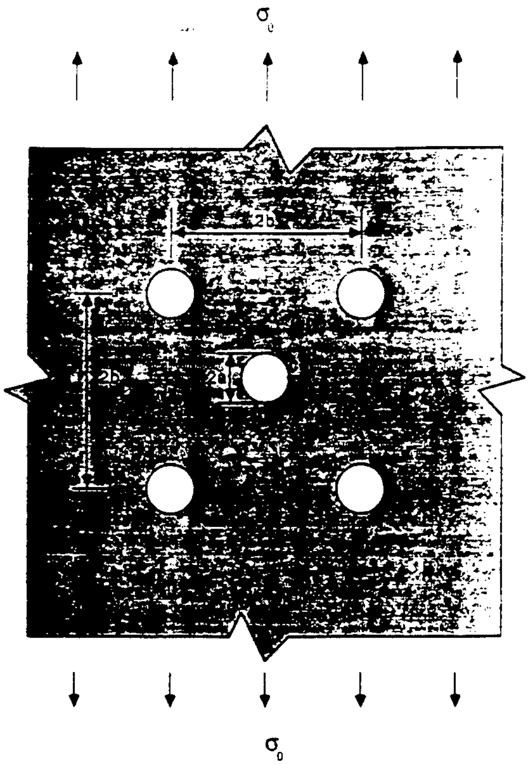
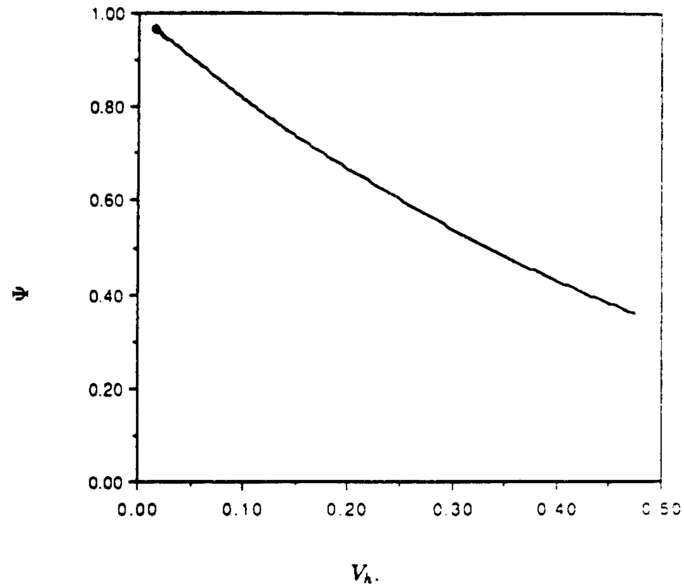


Plate weakened by a periodic array of holes and a small crack



$$\left\{\frac{3.10}{3.00}\frac{\sigma_o}{\Psi(V_h)}\right\}\sqrt{\pi c}F(\frac{c}{a_h}) \approx 2\sqrt{\frac{\gamma_m G_m}{1-\nu_m}},$$

Table 1

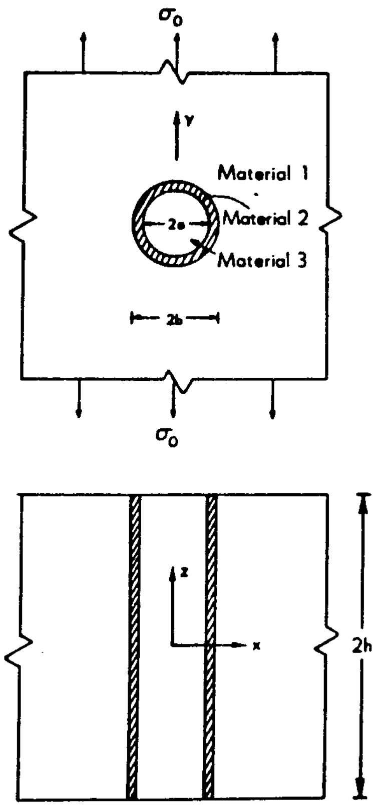
$(\frac{c}{a_h})$	0.00	0.10	0.20	0.30
$F(\frac{c}{a_h})$	3.36	2.73	2.30	2.04

Assuming next a crack length of $0.10a_h$ and an epoxy matrix with the properties:

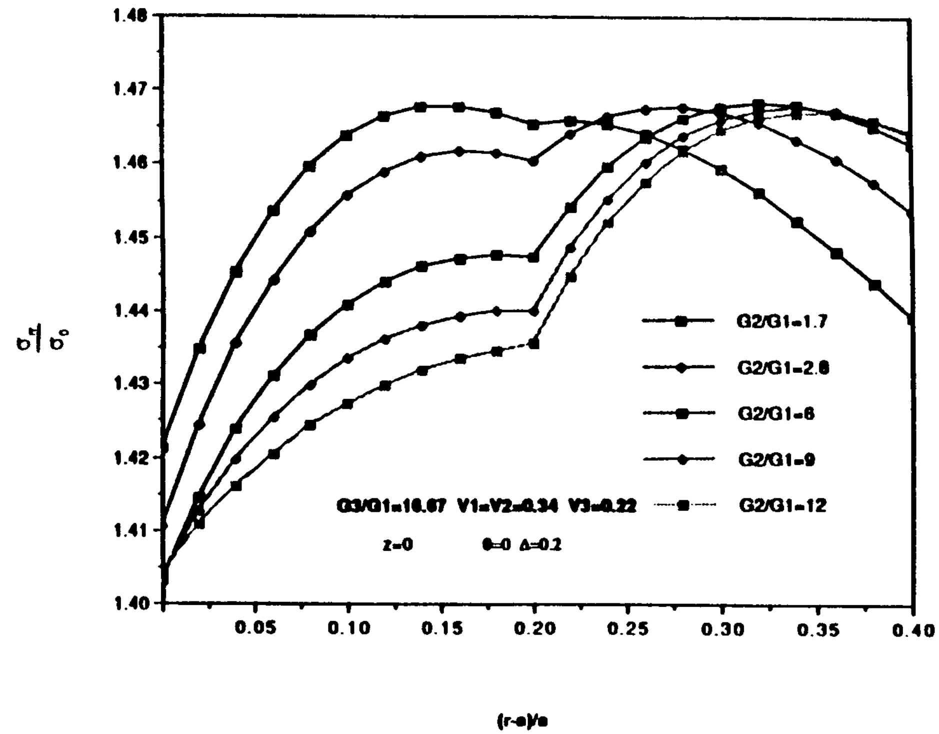
$$G_m = 2.10Gpa \qquad \nu_m = 0.34$$
$$2\gamma_m = 123\frac{J}{m^2} \qquad 2a_h = 10^{-3}m$$
$$(\frac{a}{h}) = 0.05 \qquad V_h = 0.357$$

one finds

$$(\sigma_o)_r \approx 24.39\ Mpa \ \approx 3.54ksi.$$



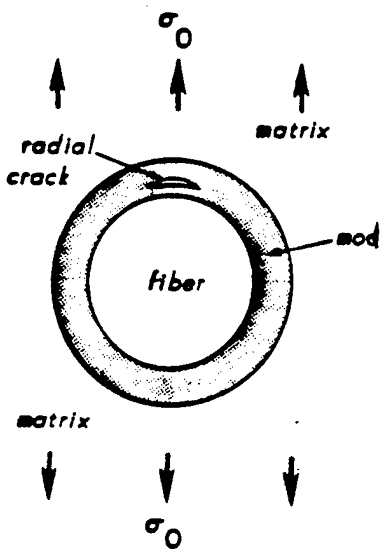
Geometrical configuration

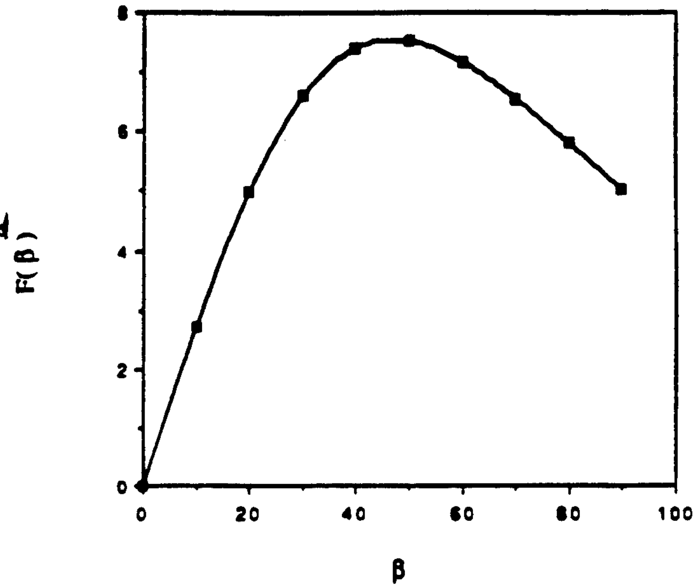


The max. radial stress vs the ratio (r-a)/a for various G2/G1 ratios at z=0.

Brittle fracture

$$(1.47\,\sigma_0)_{cr} = 9.85\sqrt{\frac{2\gamma_m}{\pi 2a_f}\,\frac{G_m}{(1+\frac{l_c}{a_f})}\,\frac{1}{F(\beta)}}$$





If we assume an epoxy matrix with the properties:

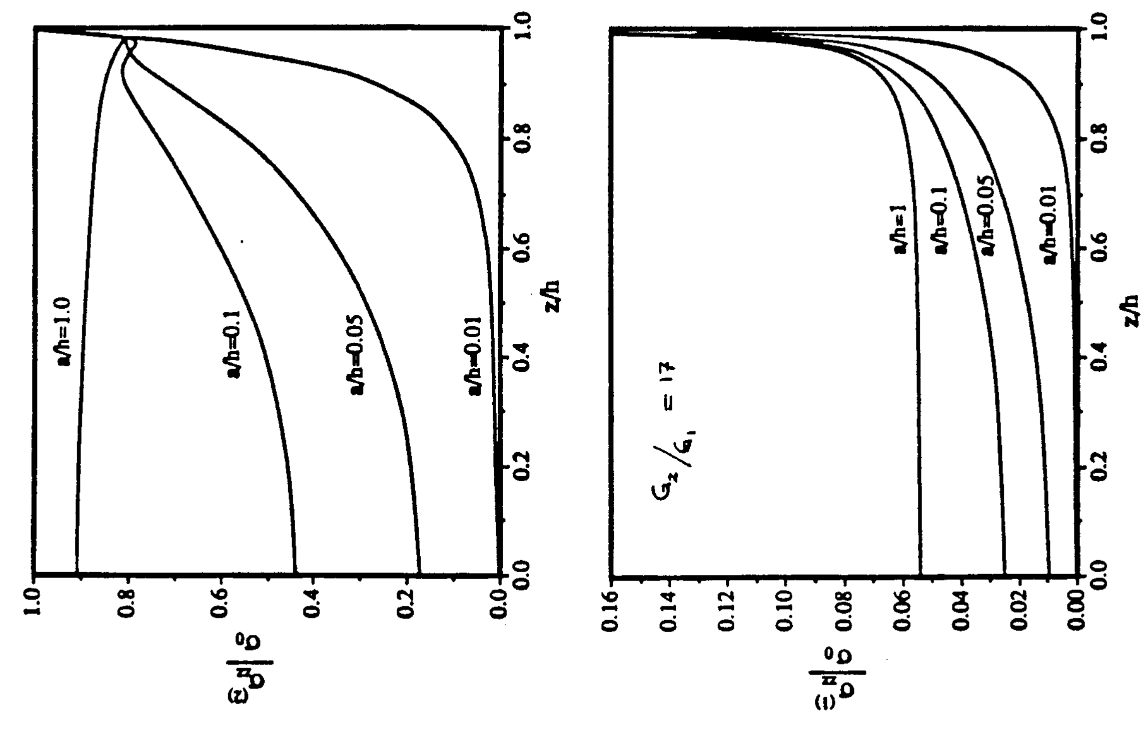
$G_m = 2.1$ GPa $\quad 2a_f = 10^{-3}$m

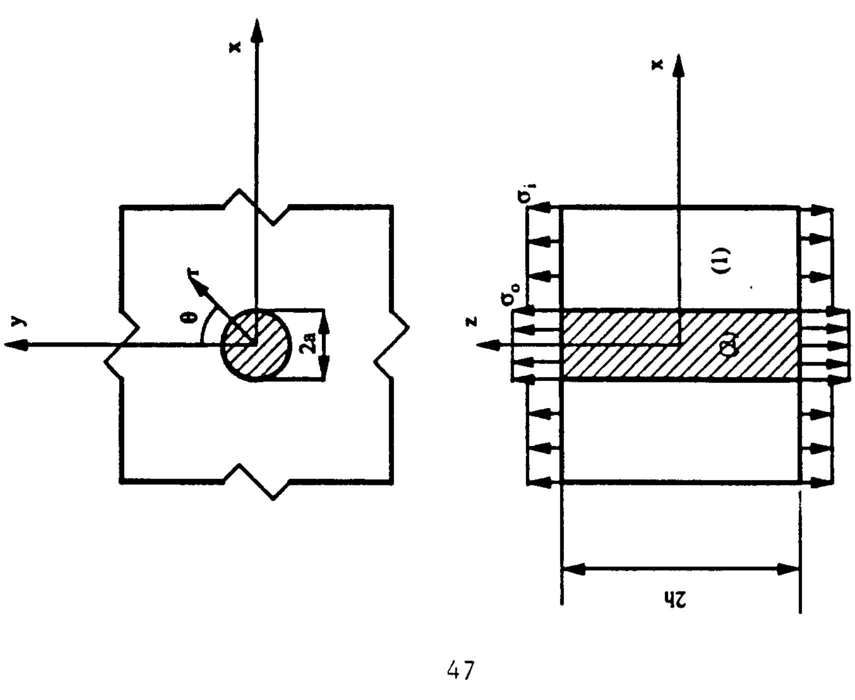
$2\gamma_m = 123\ \frac{J}{m^2} \quad \beta = 20°$

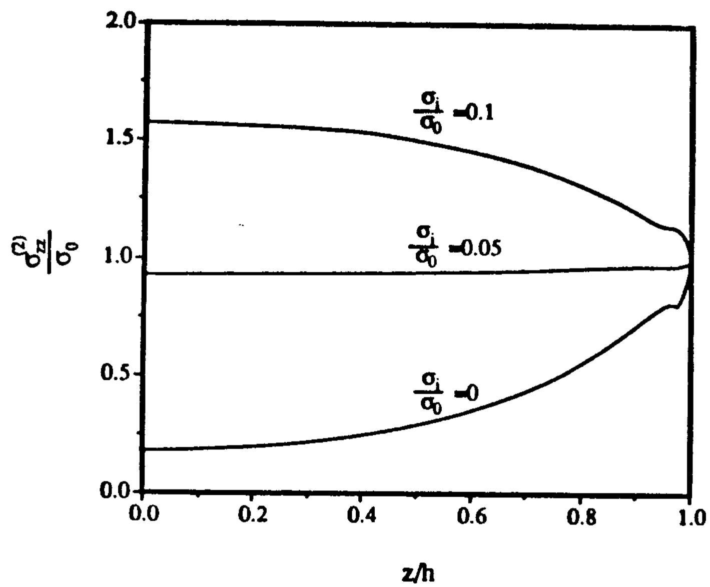
then

$(\sigma_0)_{cr} = 5.40$ ksi.

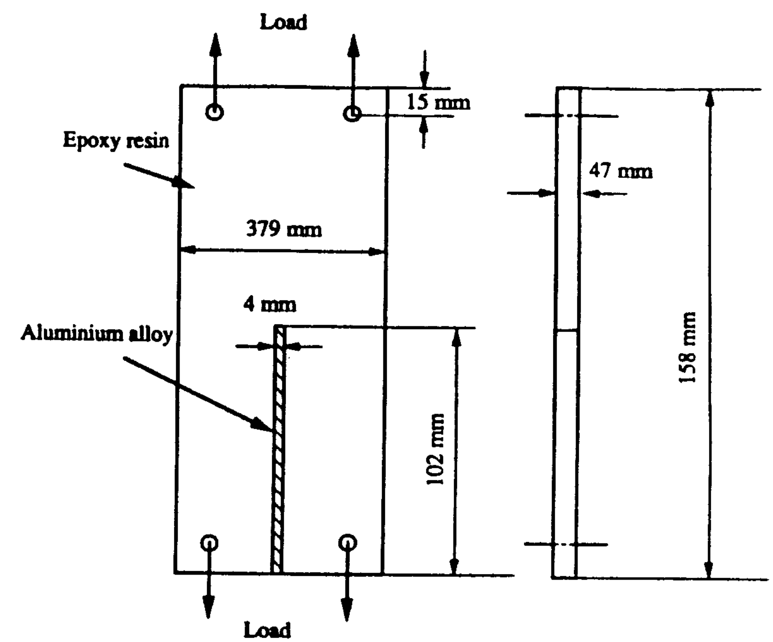
For epoxy resins,the tensile strength ranges between5.08 and14.5 ksi

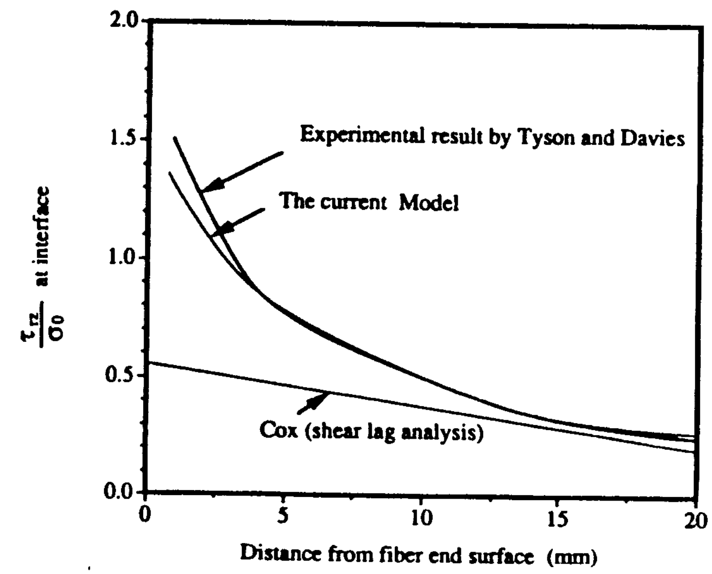

a/h=1.0
a/h=0.1
a/h=0.05
a/h=0.01
z/h
$\frac{\sigma_{zz}^{(2)}}{\sigma_o}$
a/h=1
a/h=0.1
a/h=0.05
a/h=0.01
$G_2/G_1 = 17$
$\frac{\sigma_{zz}^{(1)}}{\sigma_o}$

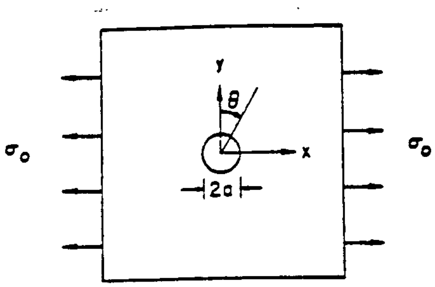

x
y
θ
r
2a
z
σ_o
σ_i
(1)
(2)
2h

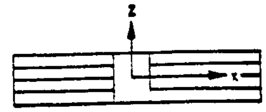


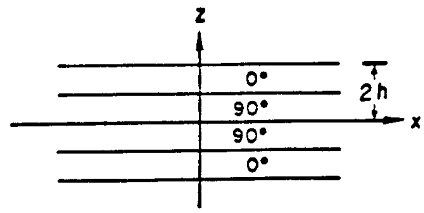
Stress $\sigma_{zz}^{(2)}$ vs z/h for perfect bonding Model 2
where $\nu_1=\nu_2=0.33$; $\mu_2/\mu_1=17$ and $a/h=0.05$

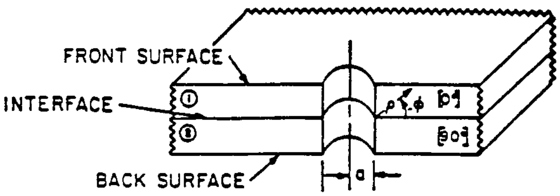




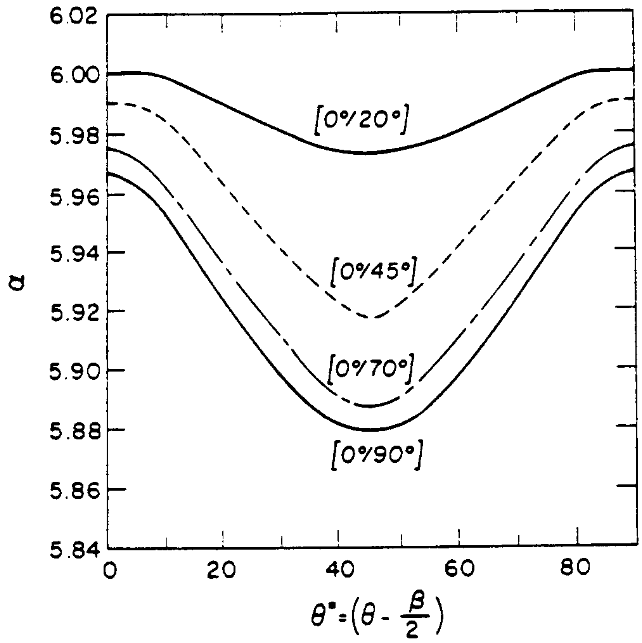


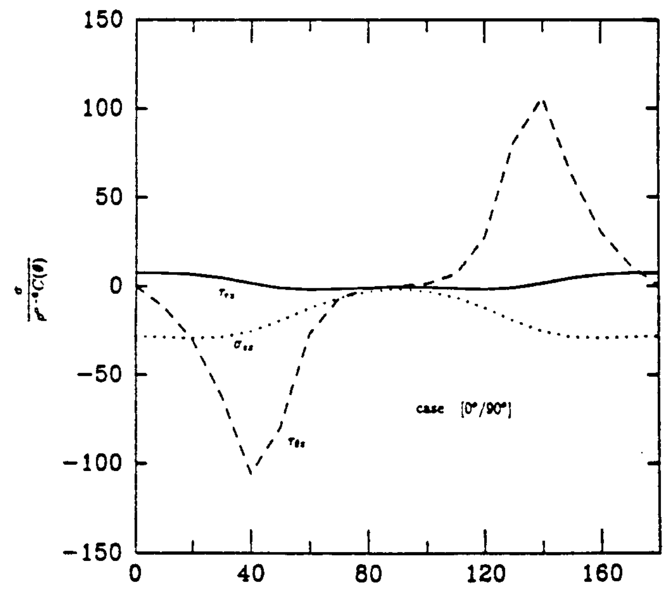






$$\sigma_{3i} \sim \rho^{\alpha-6} f_{3i}\left(\theta, \phi; C_{k\ell}, \tilde{C}_{mn}\right)$$





MECHANISMS OF ELEVATED TEMPERATURE FATIGUE DAMAGE IN FIBER-REINFORCED CERAMICS

(AFOSR Grant No. 91-0106)

Principal Investigator: John W. Holmes

The University of Michigan
Ceramic Composites Research Laboratory
Department of Mechanical Engineering and Applied Mechanics
2250 G. G. Brown
Ann Arbor, MI 48109-2125

ABSTRACT

To-date, the project has investigated the mechanisms responsible for the frictional heating which occurs in fiber reinforced ceramics which are subjected to cyclic loading. This work has led to the development of an approach for determining the interfacial shear stress which exists during the fatigue loading of fiber-reinforced ceramics. The mechanisms responsible for frictional heating in fiber reinforced ceramics has been examined experimentally and analytically [1-2]. In the experimental portion of the project, unidirectional Nicalon™/CAS composites were subjected to fatigue loading at sinusoidal frequencies between 5 and 75 Hz. The results show that the temperature rise is influenced by loading frequency, peak fatigue stress and the average spacing of matrix cracks. The temperature rise at 75 Hz and a peak fatigue stress of 160 MPa ranged from 28 K for a crack spacing of 228 μm to approximately 50 K for a crack spacing of 181 μm.

As part of the research program, several models of varying degrees of sophistication were developed to estimate the dynamic frictional shear stress which exists during the cyclic loading

of fiber-reinforced composites [3,4]. The models developed consider the frictional energy dissipation which occurs when fractured and unfractured fibers slip along debonded interfacial slip-zones. The models were used to predict the change in frictional shear stress which occurs during long-duration ambient temperature cyclic loading of $[0]_{16}$ Nicalon™/CAS composites. The results indicate that cyclic loading causes an initially rapid decrease in interfacial shear stress, followed by a partial recover.

References

1. J. W. Holmes and C. Cho, "Frictional Heating in a Fiber-Reinforced Ceramic Composite," *J. Mater. Sci. Lett.*, in press.

2. J. W. Holmes and C. Cho, "An Experimental Investigation of Frictional Heating in Fiber-Reinforced Ceramics," *J. Am. Ceram. Soc.*, accepted for publication.

3. C. Cho, J. W. Holmes and J. R. Barber, "Estimation of Interfacial Shear in Ceramic Composites from Frictional Heating Measurements," *J. Am. Ceram. Soc.*, in press.

4. C. Cho, J. W. Holmes and J. R. Barber, "Energy Dissipation During the Cyclic Loading of Fiber-reinforced Ceramics: Influence of Fiber Fracture", to be submitted to *J. Am. Ceram. Soc.*

Frictional Heating in Ceramic Matrix Composites

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Ann Arbor, MI

Funding: AFOSR

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Objectives

- mechanisms of frictional heating in fiber-reinforced ceramics
- influence of loading history and microstructural damage
- fundamental and practical implications

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Experimental studies: Nicalon™/CAS-II

- simpler unidirectional Nicalon™/CAS composites
- determine if frictional heating conincides with matrix cracking
- determine influence of loading frequency and crack spacing on heating

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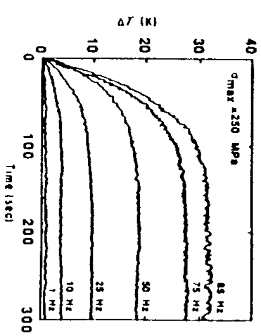
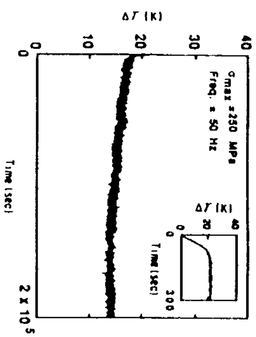
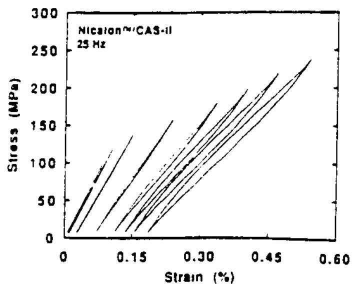


ΔT *vesus* frequency: C-fiber/SiC

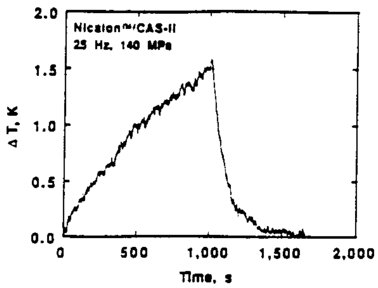


Decay in temperature: long duration fatigue

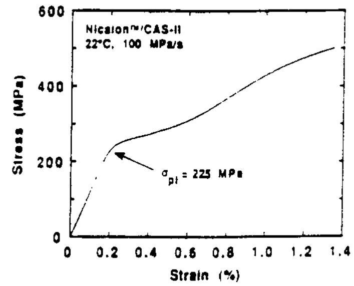
Holmes and Shuler, *J. Mater. Sci. Lett.*, *1990*



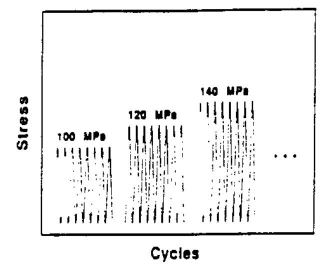
Cyclic stress-strain behavior.



Temperature rise at 140 MPa.

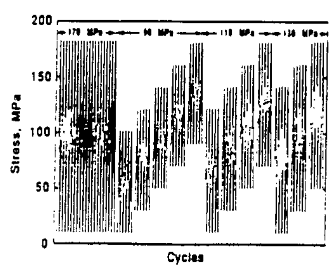


Monotonic tension: Nicalon™/CAS

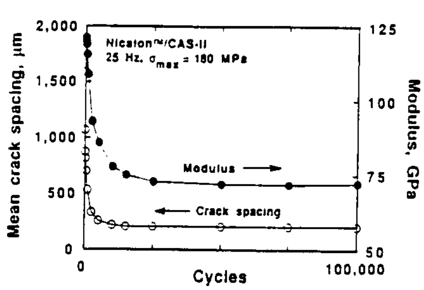


Loading sequence: initiation of internal heating.

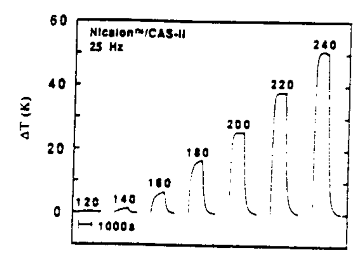
Holmes and Cho, *J. Mater. Sci. Lett.*, 1991.



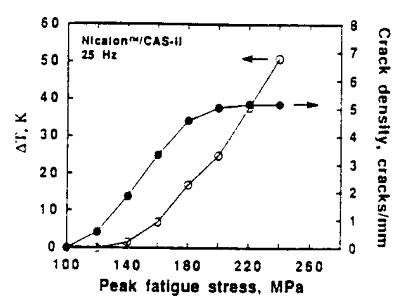
Loading history: constant stress range



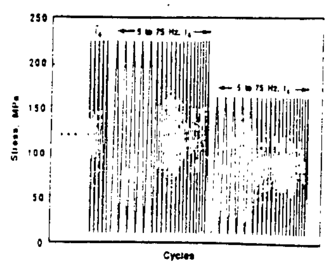
Crack spacing and modulus.



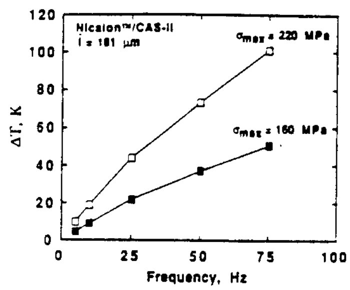
Stress dependence of temperature rise.



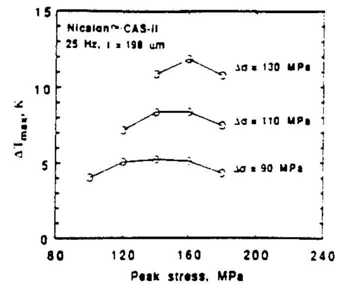
ΔT and crack density *vs.* peak stress.



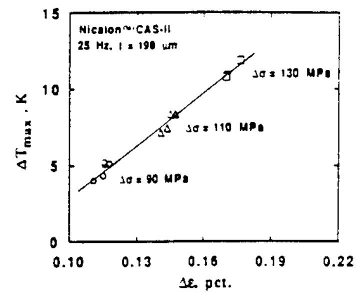
Loading history: ΔT *vs.* crack spacing and freq.



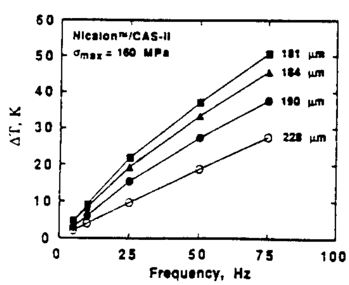
ΔT versus frequency - fixed crack spacing.



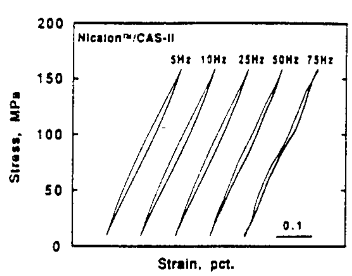
Temperature rise: constant stress range.



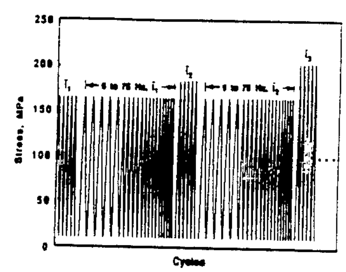
Strain range *versus* temperature rise.



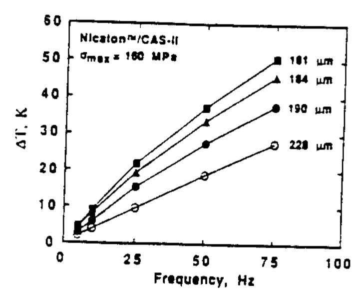
ΔT *versus* crack spacing - fixed stress



Hysteresis loops at 160 MPa.



Loading history: ΔT *vs.* crack spacing and freq.



ΔT versus crack spacing at 160 MPa.

Implications of frictional heating in CMC's

⇒ the temperature rise in the vicinity of the interface will be much higher than the bulk temperature rise

- differential thermal expansion between the fiber and matrix can promote debonding
- frequency dependence of interfacial shear
- increased rate of chemical diffusion at the interface

⇒ CMC's are under development for use in gas turbines and as structural members in aerospace structures

- acoustic fatigue (dimensional changes, damping)

Conclusions

- frictional heating coincides with the onset of matrix cracking
- the mechanism of heating involves the frictional sliding of fibers along interfacial slip-zones
- the extent of heating is influenced by mean crack spacing
- many fundamental and practical implications remain to be explored

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Estimation of Dynamic Interfacial Shear in Ceramic Composites from Frictional Heating Measurements

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Dept. of Mech. Engr. and Applied Mechanics
The University of Michigan
Ann Arbor, MI

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Topics

- frictional heating in fiber-reinforced ceramics (overview)
- relating temperature rise data to interfacial shear

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Overview

- frictional heating in fiber reinforced-ceramics coincides with the onset of matrix cracking
- frictional heating involves the cyclic slip of fibers along debonded interfacial slip-zones
- the extent of heating depends upon loading frequency, stress range and the damage state of the composite

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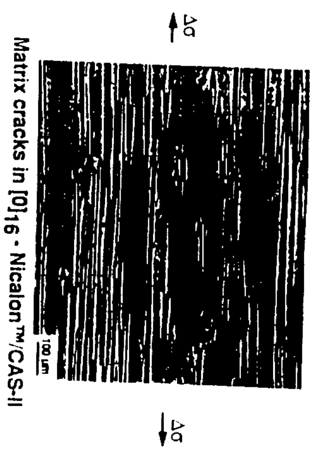
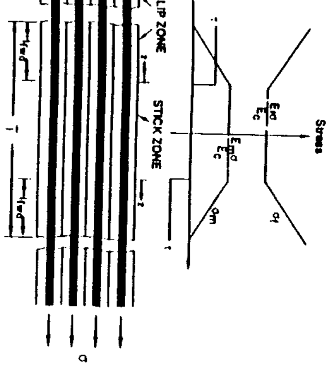
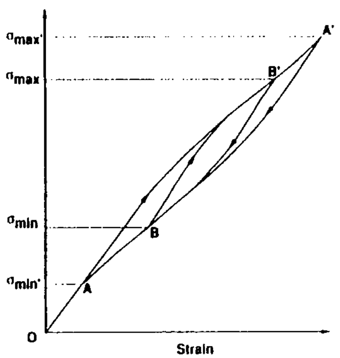


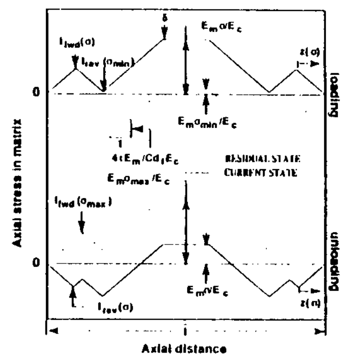
Matrix cracks in $[0]_{16}$ - Nicalon™/CAS-II



Idealized representation of fatigue damage.

Case I: Partial slip





Stress distribution in matrix

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- Using an approach similar to that used by Thouless and Evans (1988), the forward slip-zone length $l_{fwd}(\sigma)$ is

$$l_{fwd}(\sigma) = \frac{Cd_f}{8\tau}(\sigma - \sigma_{min'})$$

- Increments in fiber and matrix displacement:

$$\delta l_f(z) = \int_0^{l_{fwd}} \frac{\delta\sigma_f}{E_f} dz = \frac{(\sigma - \sigma_{min})z}{E_c} + \frac{4\tau z^2}{d_f E_f}$$

$$\delta l_m(z) = \int_0^{l_{fwd}} \frac{\delta\sigma_m}{E_m} dz = \frac{(\sigma - \sigma_{min})}{E_c}\left(z - \frac{z^2}{2l_f}\right)$$

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- The relative incremental displacement between the fiber and matrix, δl_{slide}:

$$\delta l_{slide}(z) = \delta l_f(z) - \delta l_m(z) = \frac{4\tau z^2}{C d_f v_f E_f}$$

- Defining $\Delta\sigma = \sigma_{max} - \sigma_{min}$, the total frictional work performed during loading from σ_{min} to σ_{max} is

$$W_{load} = 2\int_0^{l_{fwd}(\sigma_{max})} \delta l_{slide}(z)\,[\pi d_f \tau]\,dz = \frac{\pi d_f^3 C^2 \Delta\sigma^3}{(3)(64) v_f E_f \tau}$$

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- The total frictional work during unloading is equal to the total frictional work during loading:

$$W_{fric} = 2W_{load}$$

- The frictional energy dissipation per unit volume is:

$$\frac{dw_{fric}}{dt} = \frac{f C^2 d_f \Delta\sigma^3}{24 E_f l \tau}$$

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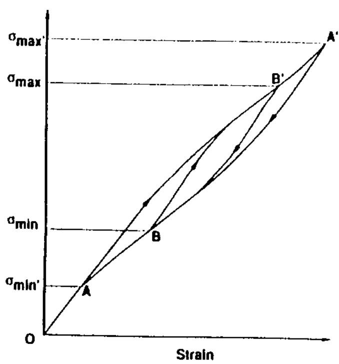
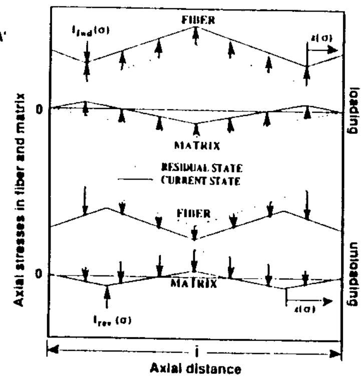
Case II: Full frictional slip





Stress distribution in the fiber and matrix

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(i) Partial slip: $\sigma_{min} < \sigma < \sigma_{min} + 2\sigma_{slip}$ ($\sigma_{slip} = 2\tau l/Cd_f$)

$$W_{load} = \frac{\pi d_f^3 C^2 (2\sigma_{slip})^3}{(3)(64) v_f E_f \tau}$$

(ii) Full slip: $\sigma_{min} + 2\sigma_{slip} < \sigma < \sigma_{max}$

$$W_{load} = \left(\frac{\pi d_f^2 \bar{l}}{4 v_f}\right)\left(\frac{\bar{l}\tau}{d_f}\right)\left(\frac{\Delta\sigma - 2\sigma_{slip}}{E_f}\right)$$

- For this case, the total frictional work is

$$\frac{dw_{fric}}{dt} = \frac{2f\bar{l}\tau\Delta\sigma}{d_f E_f} - \frac{16 f \tau^2 \bar{l}^2}{3E_f C d_f^2}$$

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SUMMARY

Case I: Partial slip

$$\frac{dw_{fric}}{dt} = \frac{f C^2 d_f \Delta\sigma^3}{24 E_f \bar{l} \tau}$$

Case II: Full frictional slip

$$\frac{dw_{fric}}{dt} = \frac{2f\bar{l}\tau}{d_f E_f}\left[\Delta\sigma - \frac{8\tau\bar{l}}{3Cd_f}\right]$$

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Calculation of heat loss during fatigue

- The rate of energy loss per unit volume, dw_h/dt:

$$\frac{dw_h}{dt} = \frac{q}{V} = \left[h\Delta T + \varepsilon\beta(T_s^4 - T_a^4)\right]\frac{A_{conv}}{V} + \frac{2kA_{cond}}{V}\left|\frac{\Delta T}{\Delta z}\right|$$

convection, radiation, conduction

$$\frac{dw_{fric}}{dt} = \frac{dw_h}{dt} \rightarrow \tau$$

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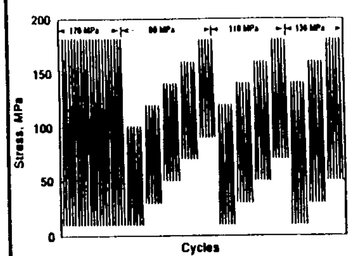
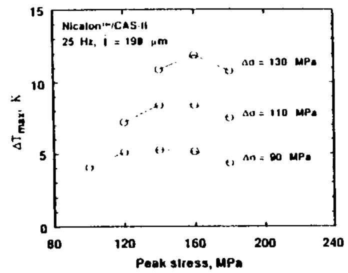
Experimental results



Loading history - influence of stress-range on temperature rise.



Temperature rise versus stress range.

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Data used to estimate τ for a unidirectional 16-ply Nicalon™/CAS-II composite.

Parameter	Comments
E_f = 200 GPa	Shimansky and Hahn (1989)
E_m = 88 GPa	"
f = 25 Hz	loading freq. used in fatigue
h = 5 - 8 W/m^2-K	Holman, Heat Transfer (1986)
k (// to fiber) = 5.16 W/m-K	Corning Glass Works.
$\bar{l}$ = 198 μm	mean crack spacing (measured)
v_f = 0.35	determined through microscopy
ε = 1.0	surface emissivity (assumed)

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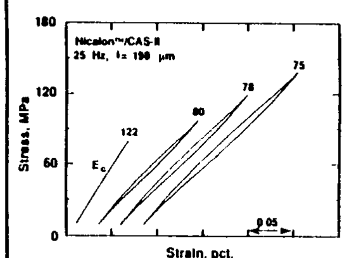
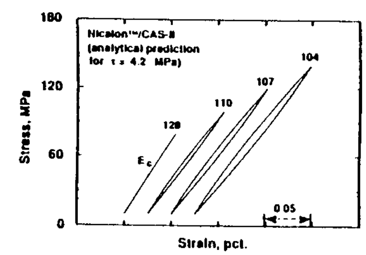
Experiment



Hysteresis loops formed during cyclic loading.

Analysis



Hysteresis loops predicted for the case of partial frictional slip.

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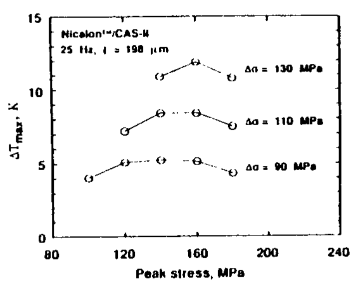
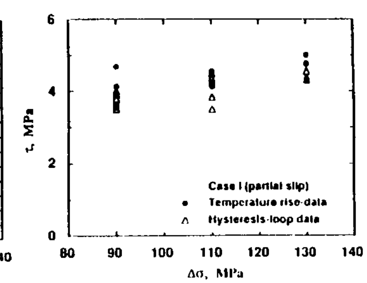
Results



Temperature rise versus stress range.



Frictional shear stress, τ.

- Note: Wang et. al. (1990) measured 10 - 14 MPa for Nicalon™/CAS-II using pushout experiment.

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Conclusions

- the frictional shear which exists in fatigue loaded specimens can be estimated from measurement of the temperature rise associated with the frictional slip of fibers along debonded interfacial slip-zones

- the approach developed allows determining the change in dynamic interfacial shear which occurs during cyclic loading (this allows determining the dynamic interfacial shear as a function of loading frequency)

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Dispersion of Elastic Wave Velocities in a Graphite-Epoxy Composite

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Continuous fiber reinforced polymeric composites are often designed to satisfy the specific loading requirements of a structure. The adopted design is usually based on the elastic properties of the composite as calculated from the elastic properties and geometrical layups of its constituents. These methods have provided useful design data and have pointed out difficulties associated with such an endeavor especially when information about the elastic properties of a thick composite is to be obtained. Two sources, relevant to these difficulties, are non-uniformity of layups used in the fabrication of such a composite and paucity of elastic wave velocity data as a function of wave frequency. Both of these sources contribute to inappropriate prediction of the elastic constants of the composite and thereby its performance under static or dynamic loading conditions. The objectives of the present work are to determine the variability in the measured values of elastic constants of thick graphite epoxy composite specimens obtained from a bar and to determine the variation in its measured values of elastic constants due to frequencies of ultrasonic wave, in other words to measure dispersion of sound waves in the composite.

The graphite-epoxy composite investigated in the present work was fabricated from Hercules IM7-8551-prepreg material. The IM7 fiber bundle diameter was around 5μm (microns). The thickness of the cured prepreg was 0.127±0.013μm. The prepregs were arranged in $[0^o/\pm45^o/0^o]_s$, s being equal to 36. The 0^o orientation of fibers was designated to be along the x-axis and prepregs were laid in the x-y plane. The stacking direction of the prepregs was along the z-axis. Then the y-axis was taken as normal to those two axes. The approximate dimensions of a rectangular bar of the graphite-epoxy composite were 32 cm x 6.3 cm x 2.1 cm. An examination of the layup in this composite suggested that it may be orthotropic. This formed the basis for conducting measurements of sound wave velocities in various specific directions of this composite. The assumption of orthotropic symmetry implied that the elastic property of the composite can be described completely by nine independent elastic constants. In other words, at least nine independent elastic wave velocity measurements are required to determine the values of these constants of the composite. The density of the specimens of the composite varied between 1.491±0.005 and 1.564±0.005 Mg/m^3. Its average density was 1.53 Mg/m^3.

For elastic constant determinations, phase velocities of ultrasonic waves are measured. Phase velocity is defined as the velocity of individual cycles in a continuous wave, and is given as

$$V = f\lambda = \omega/k \qquad (1)$$

where V is the phase velocity, f is the frequency of sound wave, λ is the wavelength, ω is the angular frequency $2\pi f$, and k is the wave number $(2\pi/\lambda)$. If the phase velocity is non-dispersive, i.e., it does not vary with frequency in a material, then its elastic constants remain unchanged under static or dynamic loading conditions for infinitesimally small strains.

For these phase velocity measurements, an image superposition method similar to the pulse - echo overlap method was used. This method employs bursts of ultrasonic vibrations rather than continuous waves . The bursts consist of a continuous wave amplitude-modulated by sinusoidal pulses synchronized with the wave. The repetition rate of the pulses is 1/2048 times the frequency of the continuous wave. Along with the sinusoidal envelope of the pulses, their duration is made long enough to encompass many cycles of the wave in order to make it as monochromatic as possible. Images of the pulses are superposed by control of the timing of pulses relative to the timing of oscilloscope sweeps. The control of timing is done by means of digital circuitry.

The results of wave velocity measurements are presented
(i) to show the extent of variability in the measurement of wave velocities in different specimens of the graphite epoxy composite,
(ii) to show the dispersion of ultrasonic waves with frequency of the wave in the composite,
(iii) to determine the values of the nine independent elastic constants from these wave velocity measurements at various frequencies,and
(iv) to compare the results of higher ultrasonic measurements with those obtained at lower frequencies and static measurements.

The results of the present work indicate that if the graphite-epoxy bar, from which different specimens with various orientations were used to measure elastic wave velocities, is representative of the fabrication technology of such a composite, then one can expect the material to possess non-uniform elastic properties. The variations in the measured elastic wave velocities in different specimens with the same orientation can arise due to (i) misorientation of fibers in prepregs, ii) misorientations in (0 ± 45^o,0) layups of prepregs, (iii) density variation in the bar, (iv) and specimen orientations. The precision of the velocity measurements by the ultrasonic image superposition technique amounts to 2 percent. The observed density variation could account for 2.4 percent. Finally, misorientation of 0.5^o amounts to 0.6 percent error. Then any observed variation in the measured velocities for a given mode exceeding 5 per cent has to be accounted by factors (i) and (ii). However, this hypothesis needs to be confirmed by direct observation of the layups and fibers.

A second conclusion that can be made is that the elastic constants of such a composite do vary with the frequency of ultrasonic waves and where precise determination of the elastic response of such a material is of concern, elastic constants determined at a single frequency may lead to misleading prediction of its performance. This is amply illustrated by the values of C_{11}, C_{22}, C_{12}, C_{13}, and C_{23} at frequencies 0 to 2 MHz for this composite. These variations in the values of elastic constants are quite large except for C_{13}. C_{13} also happens to be the only elastic constant which increases with an increase in the frequency of the ultrasonic wave. At present we do not have a satisfactory model or explanation for the observed dispersion of longitudinal waves in the x- and y- directions and the nondispersion of longitudinal waves in the z-direction and the shear waves in this composite.

Lastly, the limited number of shear wave velocity measurements made in long thin specimens of the composite by means of wire transducer show that it is a reliable technique for this purpose in addition to its conventional use for the measurement of flexural wave velocity, and therefore determination of Young's modulus of a material. However, more experiments need to be performed to establish this technique on a firm basis for the measurement of shear modulus. An advantage of the technique is that it does not require a large size specimen.

Organization of the presentation (talk)

- Motivation
- Material
- Experiments
- Results
- Conclusions

Motivations:

- To provide a complete set of elastic constants of an orthotropic graphite-epoxy composite in an internally consistent manner
- To provide data base for the development of in-situ ultrasonic wave technique to assess the mechanical relaibility of a component made of such a composite in the field
- To determine heterogeneity of such a composite bar from the variabilities in the measured values of wave velocity and density
- To measure wave dispersion
- To enable one to test validity of various proposed models to predict elastic constants of such a composite

Material

Description

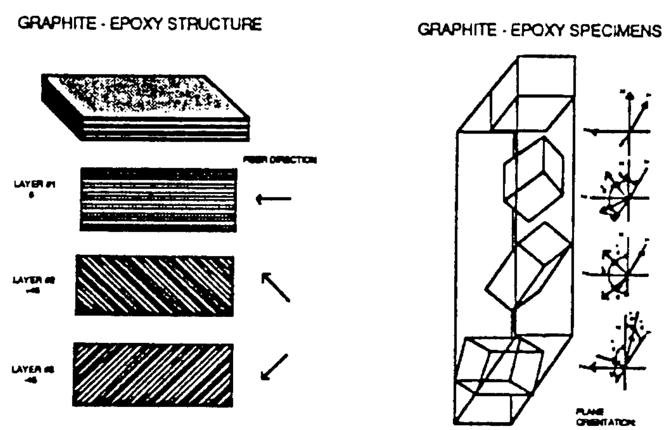
Schematic of Layup

Symmetry & Working Hypothesis

Description of Graphite-Epoxy Composite

- Fabricated from Hercules IM7-8551 prepreg
- IM7-fiber bundle diameter 5 μm
- Cured prepreg thickness 0.127 ± 0.013 mm
- Prepreg layups [0 / ± 45 / 0] s; s = 36
- Composite bar dimensions 32 cm x 6.3 cm x 2.1 cm

Schematic of prepreg layup and its designated coordinates



0° orientation of the fiber bundle designated to be along x-axis
Stacking direction of prepregs (x y plane) along z-axis

Working Hypothesis

- Composite is orthotropic
- Nine independent elastic constants, namely
- C_{11}, C_{12}, C_{13}, C_{22}, C_{23}, C_{33}, C_{44}, C_{55}, and C_{66}

Experiment

- ° Measurement Techniques
- ° Working relations for measurements
- ° Specimen orientation
- ° Block diagram of instrumentation

Measurement technique:

Determination of elastic constants from phase velocity (v) measurements of waves.

- ° Low Frequency ($\lambda \gg$ cross sectional dimensions of the specimen)

  $v = (\rho s)^{-1/2}$

  [wire transducer]

- ° High Frequency ($\lambda \ll$ cross sectional dimensions of the specimen)

  $v = (\rho c)^{1/2}$

  [pulse image superposition]

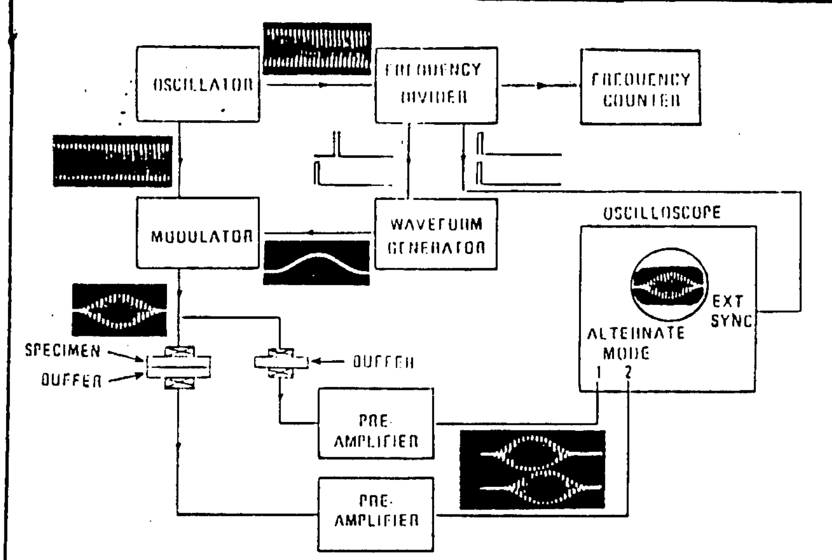
Working Relations for Measurement

- ° Orthotropic symmetry requires at least nine wave velocity measurements
- ° Simplest working relations between wave velocities & elastic constants exist for longitudinal and shear wave velocity measurements in <100>, <010>, <001>, <110>, <101> and <011> directions

Specific relations between wave velocities and elastic constants.

Wave velocity types and their relations to elastic constants of an orthotropic composite as expressed by the products of density (p) and squared value of wave velocity (V).

Wave Velocities: Mode	Direction: Propagation	Particle Motion		$pV^2 =$	Equation
L	<100>	<100>	V_1	C_{11}	6
S	<100>	<010>	V_2	C_{66}	7
S	<100>	<001>	V_3	C_{55}	8
L	<010>	<010>	V_4	C_{22}	9
S	<010>	<100>	V_5	C_{66}	10
S	<010>	<001>	V_6	C_{44}	11
L	<001>	<001>	V_7	C_{33}	12
S	<001>	<100>	V_8	C_{55}	13
S	<001>	<010>	V_9	C_{44}	14
QL	<110>	<110>	V_{10}	$0.5\ C_{66} + 0.25\ (C_{11} + C_{22}) + 0.5\ [(C_{12} + C_{66})2 + 0.25\ (C_{22} - C_{11})2]^{1/2}$	15
QS	<110>	<110>	V_{11}	$0.5\ C_{66} + 0.25\ (C_{11} + C_{22}) - 0.5\ [(C_{12} + C_{66})2 + 0.25\ (C_{22} - C_{11})2]^{1/2}$	16
S	<110>	<001>	V_{12}	$0.5\ (C_{55} + C_{44})$	17
QL	<101>	<101>	V_{13}	$0.5\ C_{55} + 0.25\ (C_{11} + C_{33}) + 0.5\ [(C_{13} + C_{55})2 + 0.25\ (C_{11} - C_{33})2]^{1/2}$	18
QS	<101>	<101>	V_{14}	$0.5\ C_{55} + 0.25\ (C_{11} + C_{33}) - 0.5\ [(C_{13} + C_{55})2 + 0.25\ (C_{11} - C_{33})2]^{1/2}$	19
S	<101>	<010>	V_{15}	$0.5\ (C_{66} + C_{44})$	20
QL	<011>	<011>	V_{16}	$0.5\ C_{44} + 0.25\ (C_{22} + C_{33}) + 0.5\ [(C_{23} + C_{44})2 + 0.25\ (C_{22} - C_{33})2]^{1/2}$	21
QS	<011>	<011>	V_{17}	$0.5\ C_{44} + 0.25\ (C_{22} + C_{33}) - 0.5\ [(C_{23} + C_{44})2 + 0.25\ (C_{22} - C_{33})2]^{1/2}$	22
S	<011>	<100>	V_{18}	$0.5\ (C_{66} + C_{55})$	23



NARROW-BAND BURST PHASE COMPARISON APPARATUS

Results

Wave velocity measurements

- Extent of variability due to inhomogeneity of the composite bar
- Dispersion of ultrasonic waves in the composite
- Test of working hypothesis
- Determination of the nine elastic constants from 18 wave velocity measurements
- Compare the predicted values of elastic constants obtained from the extrapolation of ultrasonic measurements with those measured at 100 KH3 and quasi-statically

Dispersion:

Observed only in longitudinal mode of propagation in <100>, <010>, <110>, <101> and <011>

Dispersion expressed as

$$f = \sum_{i=1}^{3} a_i / \lambda^i$$

Constants for the dispersive longitudinal waves in graphite epoxy composite

Specimen	Propagating Direction	a_1	a_2	a_3
1	<100>	8.188 x 10^5	-3.527 x 10^4	0
3	<100>	8.944	-5.896	0
4	<100>	9.350	-7.420	0
1	<101>	4.870	-3.090	1.062x10^3
2	<010>	5.085	-3.267	1.111
3	<010>	4.967	-2.798	0.356
5	<010>	4.938	-2.679	0.741
6	<011>	3.864	-1.170	0
	<011>	3.734	-0.976	0
7	<101>	6.070	-1.405	0
	<101>	5.887	-1.250	0
8	<110>	7.366	-3.355	0
	<110>	6.927	-2.952	0

Internal consistencies of wave velocities in the graphite epoxy composite for both dispersive and nondispersive modes.

Relation	Frequency (MHz)	Left Hand Side	Right Hand Side	
Nondispersive modes				
24		3.62±0.10	3.615±0.11	$V_2 = V_5$
25		1.68±0.05	1.61±0.02	$V_3 = V_8$
26		1.46±0.03	1.38±0.06	$V_6 = V_9$
28		2.61±0.11	2.36±0.11	$V^2_{12} = 0.5\ (V^2_3 + V^2_6)$
29		7.42±0.41	7.55±0.11	$V^2_{15} = 0.5\ (V^2_2 + V^2_6)$
30		9.00±1.18	7.90±0.09	$V^2_{18} = 0.5\ (V^2_2 + V^2_3)$
Dispersive modes				
31	0.0	55.84±2.4	59.13±3.16	$V^2_{10} + V^2_{11} = V^2_2 + 0.5\ (V^2_1 + V^2_4)$
	0.1	55.42±2.4	57.99±3.1	
	1.0	51.57±2.2	52.52±2.7	
	2.0	47.04±2.0	45.73±2.27	
32	0.0	41.39±0.97	39.51±2.20	$V^2_{13} + V^2_{14} = V^2_3 + 0.5\ (V^2_1 + V^2_7)$
	0.1	41.06±0.97	39.16±2.17	
	1.0	38.09±0.97	35.88±1.92	
	2.0	34.59±0.97	31.98±1.60	
33	0.0	18.03±0.76	17.82±0.87	$V^2_{16} + V^2_{17} = V^2_6 + 0.5\ (V^2_4 + V^2_7)$
	0.1	17.82±0.76	17.52±0.86	
	1.0	15.80±0.67	14.83±0.73	
	2.0	13.26±0.56	11.95±0.59	

Calculation of nine elastic constants:

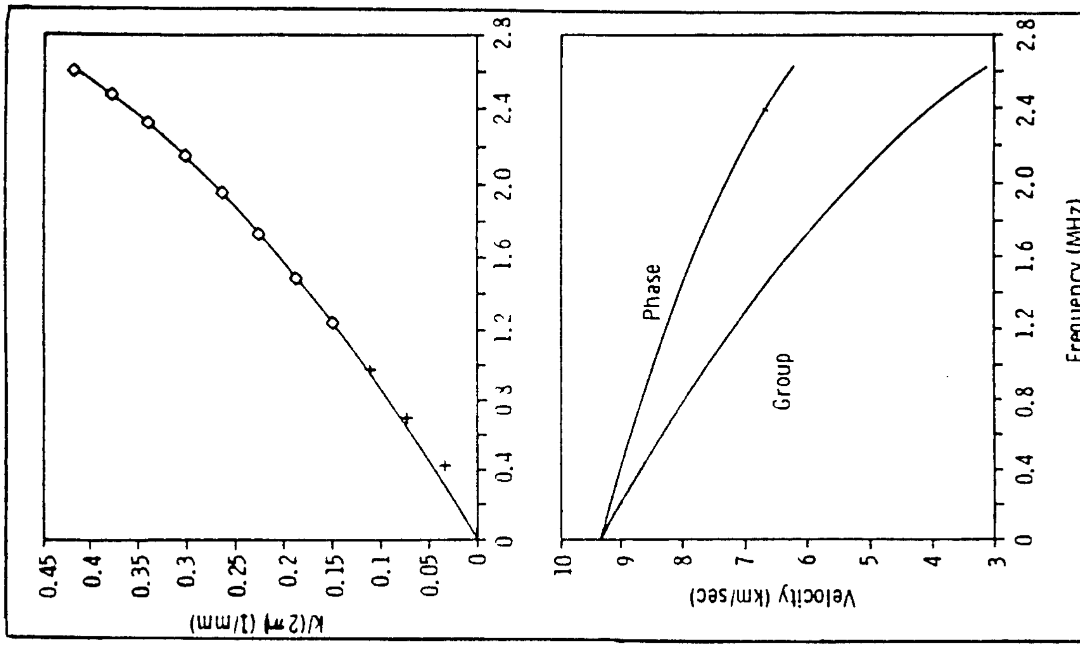
Basis of procedure adopted to calculate the elastic constants

- **Constants must be representative of pertinent velocity measurements**
- **Effect of inordinately large discrepancy as shown in [relation 30] on the elastic constants be minimized**

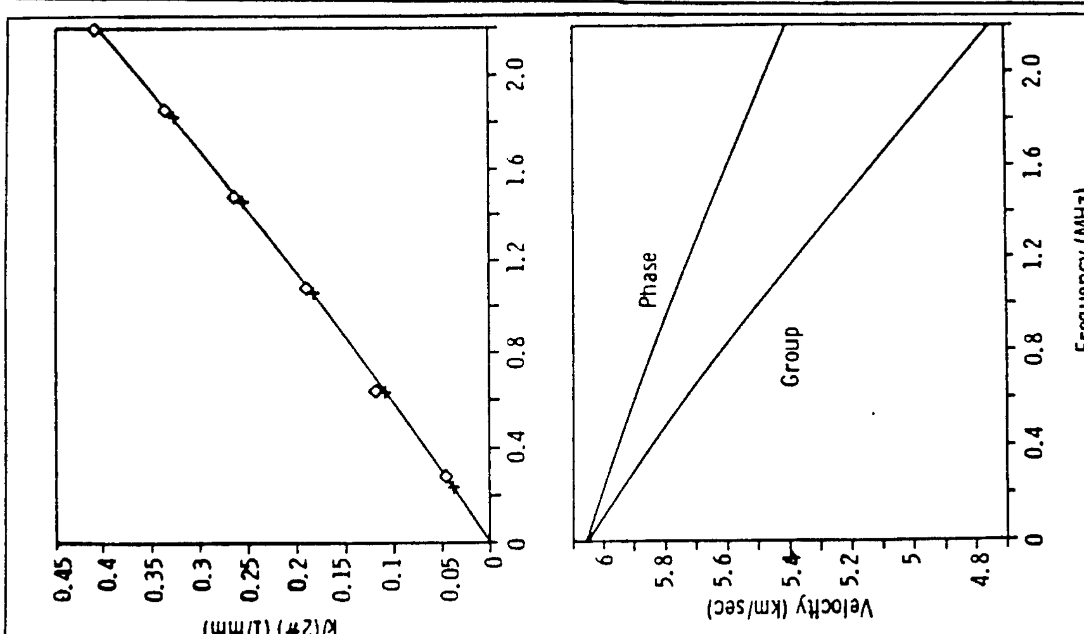
Variation in the values of elastic constants with frequency.

Values of adiabatic elastic constants (C_{ij}) of graphite epoxy in units of GPa.

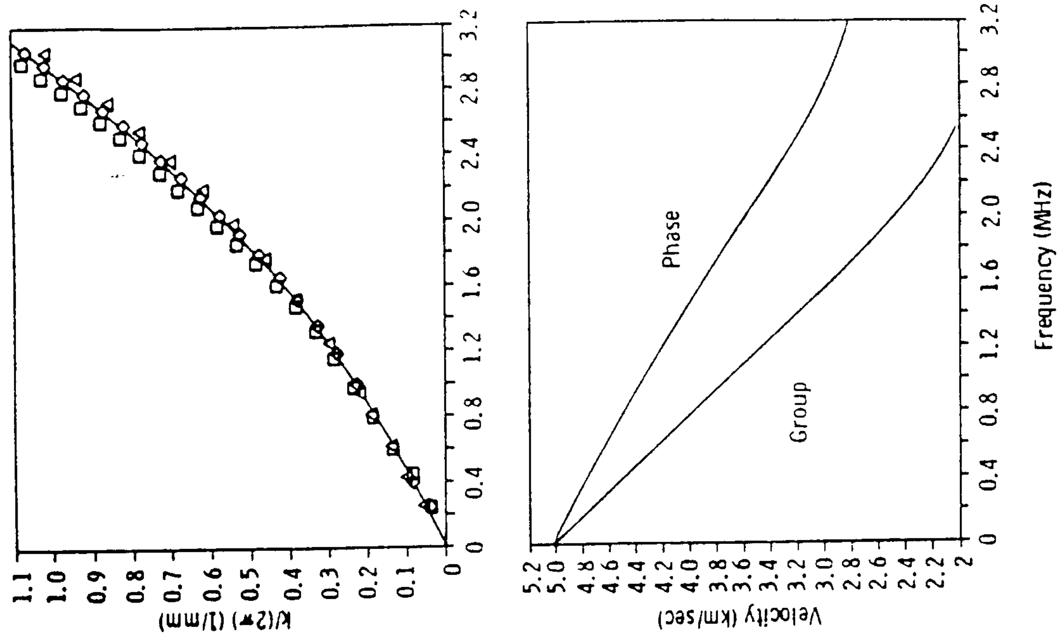
Elastic Constants	Frequency (MHz) 0	0.1	1.0	2.0
C_{11}	102.58	101.50	91.47	79.54
C_{22}	38.33	37.40	29.19	20.36
C_{33}	10.03	10.03	10.03	10.03
C_{44}	3.12	3.12	3.12	3.12
C_{55}	4.23	4.23	4.23	4.23
C_{66}	19.97	19.97	19.97	19.97
C_{12}	26.67	24.80	19.28	11.46
C_{13}	11.87	11.84	12.24	12.60
C_{23}	5.24	5.61	5.69	4.41



DISPERSION OF LONGITUDINAL WAVES IN THE <100> DIRECTION



DISPERSION OF LONGITUDINAL WAVES IN THE <101> DIRECTION



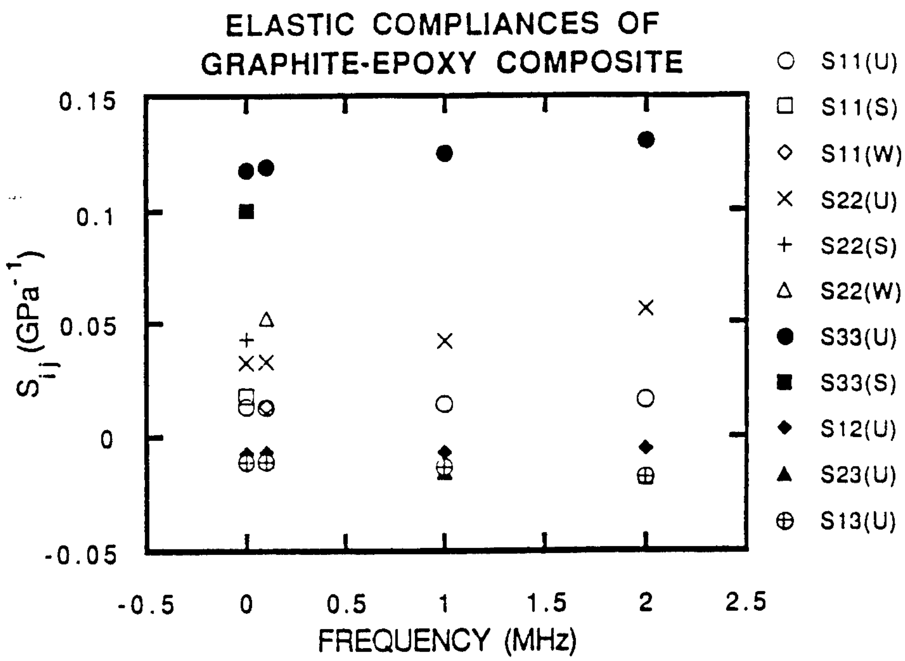
DISPERSION OF LONGITUDINAL WAVES IN THE <010> DIRECTION

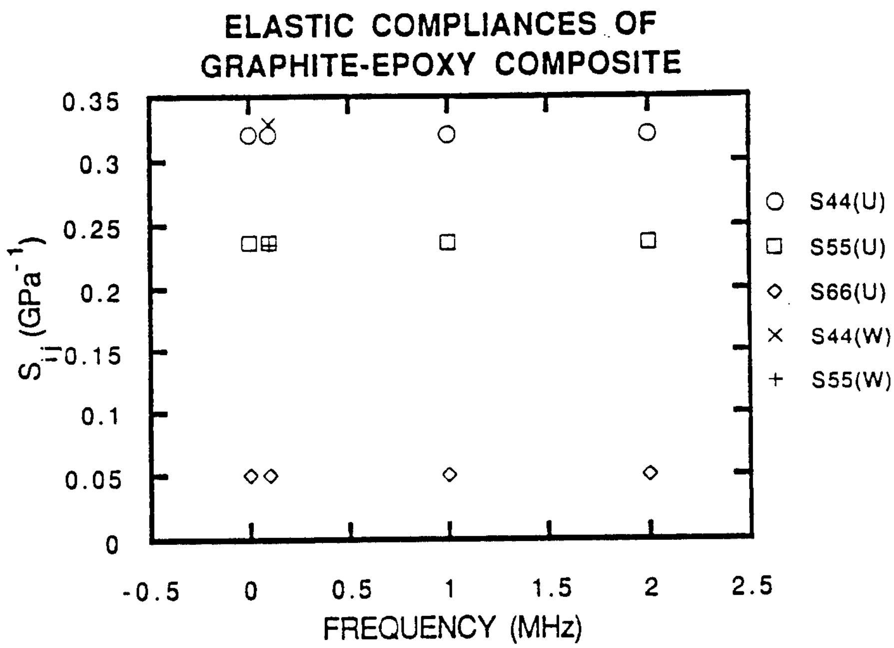
Variability of measured wave velocities at 2 MH3

Orientation	Longitudinal	Velocities (km/σ) Shear (1)	Shear (2)
<100>	7.210-8.921	3.54-3.73	1.65-1.75
<010>	3.07-3.71	3.54-3.74	1.44-1.48
<001>	2.49-2.62	1.59-1.63	1.33-1.37
<110>	5.93-6.30	2.95-3.18	1.58-1.65
<101>	5.43-5.56	2.15-2.18	2.69-2.76
<011>	3.09-3.11	1.90-1.924	2.89-3.11

Comparison with static & 100 KH3 measurement of Young's moduli (in GPa) in various directions of graphite-epoxy composite.

Directions	Calculated Ultrasonic	Experiment Static Compression	Wire Transducer
<100>	76.8	75.4	76.2
<010>	30.8	26.9	19.3
<001>	8.5	10.0	
<110>	49.7	50.3	
<101>	11.6	10.8	
<011>	8.8	9.8	





Conclusions

Sources of variations in the values of elastic constants

- Misorientations of fibers in prepreg
- Misorientations in the (0 / ± 45° / 0°) layups or prepregs
- Density variations in the bar 2.4 percent
- Specimen orientation 0.6 percent
- Measurement of velocity 2 percent

Variations > 5 percent probably due to misorientation of fiber and layups of prepreg.

In spite of some limitations of the material the present measurements provide complete set of elastic constants to test validity of models proposed to predict anisotropicity and dispersions of wave velocities in this type of composite.

On Maximizing The Axial Compressive Strength of Filament Wound Composite Cylinders

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Lawrence Livermore National Laboratory

Mark Garnich
Battelle Pacific Northwest Laboratories

Travis Bogetti, Jim Bender and Bruce Burns
Ballistic Research Laboratory

The high specific strength advantages of fiber composites offer great potential for an advanced artillery projectile. Successful utilization of these materials requires performance of a composite cylinder under predominantly axial compressive loads. In order to achieve design performance levels, three key issues need to be addressed. First, composite tubes exhibiting sufficient compressive strength must be fabricated in a cost-efficient manner. Second, a reliable test method to determine this strength as a function of material and processing changes must be developed. Finally, a method to effectively transfer compressive load into the composite cylinder without degradation of performance must be designed within the restrictions imposed by the application.

A filament winding process was selected to fabricate test specimens and prototype structures for the following reasons; it is a relatively mature process with an extensive experience base, it is ideally suited to the fabrication of cylindrical structures, it is easily scaled-up to large volume production, and both the process and the materials are cost-effective. Because the compressive loads experienced by the composite projectile result from inertial forces, lower density (albeit higher cost) carbon fiber was initially selected over glass fiber. The combined cost of carbon fiber and epoxy resins used in this program is \$10/lb–a significant savings compared to the prepreg material form.

The first phase of the program was restricted to optimizing the compressive performance of cylinders via changes in fiber lay-up, matrix materials and composite quality. This optimization was based on results of compression tests with $^1/_3$-scale cylinders and a simple plug-type fixture which met the design geometry requirements. This plug fixture provided for some shear transfer of axial load across the inner wall of the cylinder, but transferred the bulk of the load through the ends of the cylinder. Although all compressive failures were found to initiate exclusively near a fixture, significant changes in apparent compressive strengths were realized with changes in the both the matrix material and the fiber lay-up. The highest compressive strengths achieved in small-scale static tests were maintained in both static and dynamic tests of full-scale prototypes.In these tests all failures were observed to occur near the ends of cylinders.

The second phase of the program was concentrated on determining the inherent cylinder strength, the effect of fiber lay-up and matrix properties on this strength, and on designing an improved load-transfer method which would minimize end effects. A composite tube test fixture developed at LLNL for multiaxial testing was used to determine "inherent" cylinder strengths. Numerical analysis of the multiaxial fixture shows that it efficiently transfers axial compressive load into the cylinder for the following reasons: load is transferred via both end loading and shear loading thereby reducing the axial compressive stress and the tendency for brooming failures at the very ends of the cylinder, the shear load transfer is gradually reduced into the gage section thereby avoiding stress concentrations, and the entire gripped end of the tube is under radial compression which acts to resist any tendency of the tube to delaminate. Results of tests comparing the strengths of tubes fitted with both the multiaxial fixture and the simple end plug revealed a reduction due to end failures of nearly 30% in the compressive performance of tubes with end plugs. To improve the deliverable design strengths to acceptable levels, a two-prong approach was taken. First, attempts were made to increase the inherent cylinder strength by increasing the percentage of axial (load-bearing) layers and by improving the composite material quality. Second, several new end fixtures were designed to allow a higher percentage of the cylinder strength to be delivered in the application. Successes and failures in these attempts to improve structural compressive strengths will be presented. Lessons learned in testing and predicting the performance of composite cylinders in compression will also be discussed.

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A Thermal/Mechanical Model for Lay-Up Design of Thick-Walled Composite Cylinders

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Abstract

An elasticity solution based analytic model for predicting the thermal and mechanical response of multi-layered composite cylinders is presented. A generalized plane strain axisymmetric approach is taken to model the ply-by-ply stress and strain distributions (as a function of cylinder radius) away from the cylinder ends (center of cylinder) due to thermal and mechanical load configurations. Displacement continuity and force equilibrium are satisfied at the ply interfaces. Thermal residual stress predictions are based on a post-consolidation process. Various lamina failure theories, including progressive ply failure, are incorporated into the analysis. A computer code is developed to facilitate the center of cylinder design of thick-walled filament wound composite cylinders due to manufacturing (thermal residual) stress and axisymmetric mechanical loading. Case studies are presented which demonstrate the utility of the analysis as a design tool for selecting optimum cylinder lay-up constructions for various thermal and mechanical load configurations.

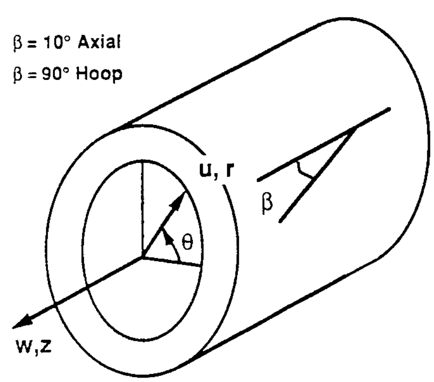
OBJECTIVE

Develop a model to facilitate the design and fabrication of thick-walled composite cylinders loaded in axial compression.

CYLINDER ANALYSIS

- Closed Form Solution
- Generalized Plane Strain
- Multi-Layered Solution
- No End Effects (stress state at the center of cylinder)
- Axial compression loading
- Thermal residual stress
- Progressive ply failure analysis

THEORETICAL DEVELOPMENT



CONSTITUTIVE RELATION FOR A SINGLE LAYER

$$\begin{Bmatrix} \sigma_z \\ \sigma_\theta \\ \sigma_r \\ \tau_{\theta r} \\ \tau_{zr} \\ \tau_{z\theta} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & C_{16} \\ C_{12} & C_{22} & C_{23} & 0 & 0 & C_{26} \\ C_{13} & C_{23} & C_{33} & 0 & 0 & C_{36} \\ 0 & 0 & 0 & C_{44} & C_{45} & 0 \\ 0 & 0 & 0 & C_{45} & C_{55} & 0 \\ C_{16} & C_{26} & C_{36} & 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_z - \alpha_z \Delta T \\ \varepsilon_\theta - \alpha_\theta \Delta T \\ \varepsilon_r - \alpha_r \Delta T \\ \gamma_{\theta r} \\ \gamma_{zr} \\ \gamma_{z\theta} - \alpha_{z\theta} \Delta T \end{Bmatrix}$$

STRAIN-DISPLACEMENT RELATIONS

$$\varepsilon_r = \frac{du}{dr}, \quad \varepsilon_\theta = \frac{u}{r}, \quad \text{and} \quad \varepsilon_z = \frac{dw}{dz}$$

FORCE EQUILIBRIUM IN RADIAL DIRECTION

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_\theta}{r} = 0$$

GOVERNING EQUATION

$$r^2 \frac{d^2u}{dr^2} + r \frac{du}{dr} - m^2 r = f\,(r, \Delta T, \varepsilon_z)$$

SOLUTION TECHNIQUE

- Radial displacement

$$u = A r^m + B r^{-m} + C_1 (r, \Delta T, \varepsilon_z)$$

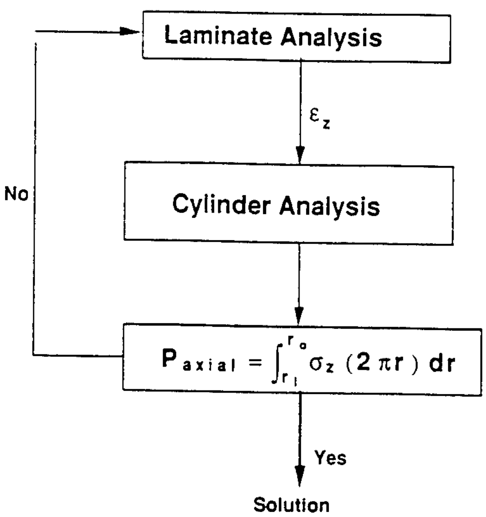
- Radial stress and Hoop stress

$$\sigma_r = AC_2\, r^{m-1} + BC_3\, r^{-m-1} + C_4 \Delta T$$

$$\sigma_\theta = AC_2\, r^{m-1} - BC_3\, r^{-m-1} + C_4 \Delta T$$

COMPUTATION PROCEDURE

- Construct a laminate with the same layup of the cylinder
- Apply the axial load to the laminate and obtain an approximate "axial strain"
- Perform the cylinder analysis and verify boundary condition



NUMERICAL IMPLEMENTATION

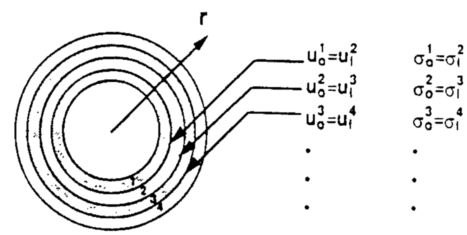
Displacement in the k-th layer

$$\begin{Bmatrix} u_i^k \\ u_o^k \end{Bmatrix} = \begin{bmatrix} f_{11}^k(r) & f_{12}^k(r) \\ f_{21}^k(r) & f_{22}^k(r) \end{bmatrix} \begin{Bmatrix} A^k \\ B^k \end{Bmatrix} + \begin{Bmatrix} p_i^k(\Delta T, r, \varepsilon_z) \\ p_o^k(\Delta T, r, \varepsilon_z) \end{Bmatrix}$$

Radial stress in the k-th layer

$$\begin{bmatrix} \sigma_i^k \\ \sigma_o^k \end{bmatrix} = \begin{bmatrix} g_{11}^k(r, \Delta T, \varepsilon_z) & g_{12}^k(r, \Delta T, \varepsilon_z) \\ g_{21}^k(r, \Delta T, \varepsilon_z) & g_{22}^k(r, \Delta T, \varepsilon_z) \end{bmatrix} \begin{Bmatrix} u_i^k \\ u_o^k \end{Bmatrix} + \begin{Bmatrix} G_i^k(\Delta T, r, \varepsilon_z) \\ G_o^k(\Delta T, r, \varepsilon_z) \end{Bmatrix}$$

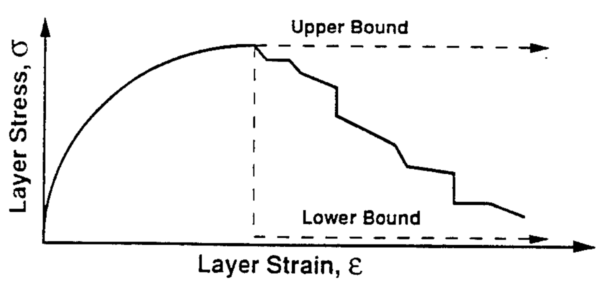
BOUNDARY CONDITIONS

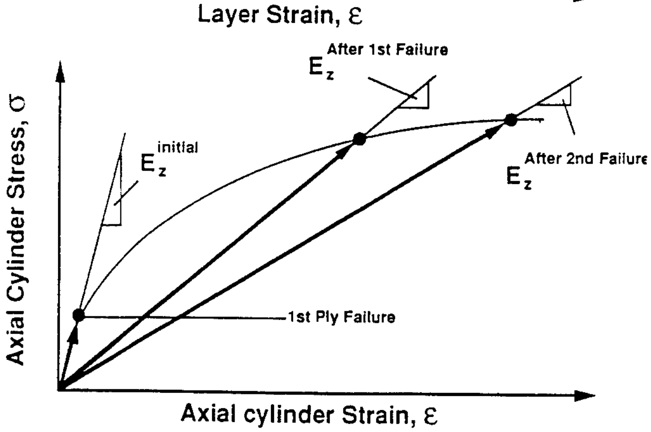


SYSTEM OF N+1 EQUATIONS

$$\begin{bmatrix} K_{11} & K_{12} & K_{13} & \cdots \\ K_{21} & K_{22} & K_{23} & \cdots \\ K_{31} & K_{32} & K_{33} & \cdots \\ \vdots & \vdots & \vdots & \end{bmatrix} \begin{Bmatrix} U_1 \\ U_2 \\ U_3 \\ \vdots \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ \vdots \end{Bmatrix}$$

PROGRESSIVE FAILURE ANALYSIS





PARAMETRIC STUDY

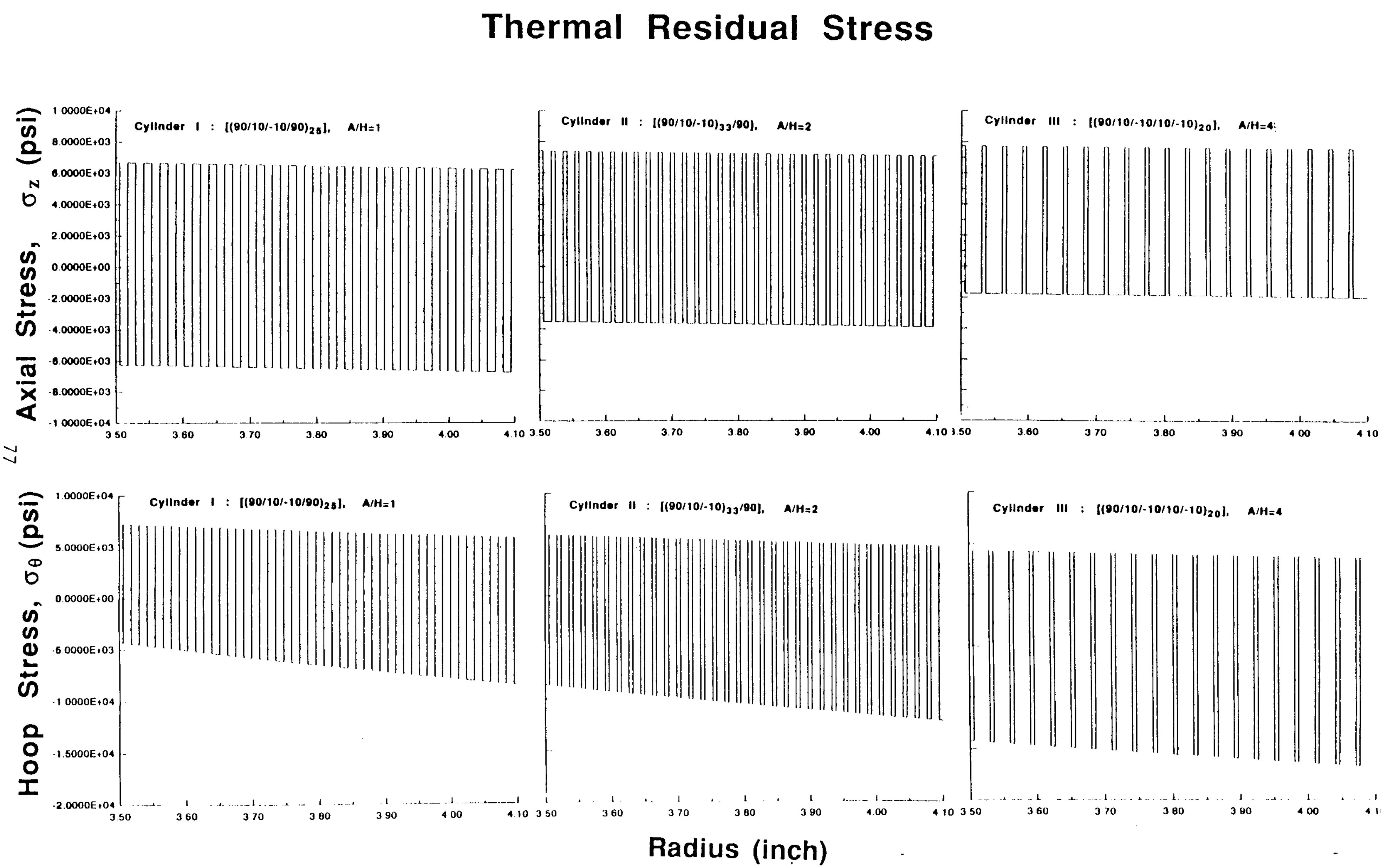
Cylinder of 100 layers, 0.6 inch thick, and 7 inches in diameter of Glass/Epoxy Material

Case Studies

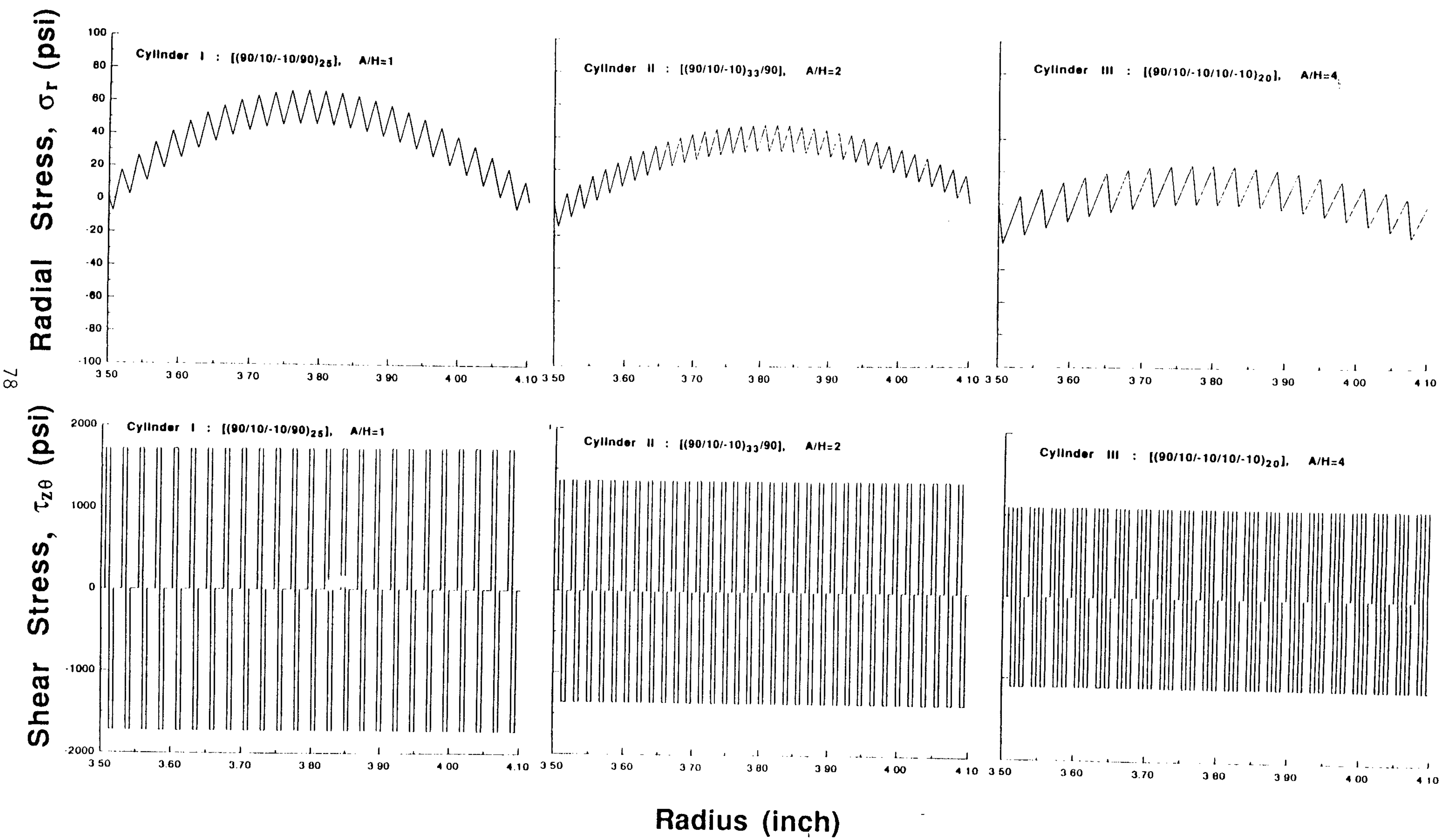
Cylinder	Lay-up	Axial/Hoop Ratio
I	$[(90/10/-10/90)_{25}]$	1
II	$[(90/10/-10)_{33}/90]$	2
III	$[(90/10/-10/10/-10)_{20}]$	4

Typical Material Properties

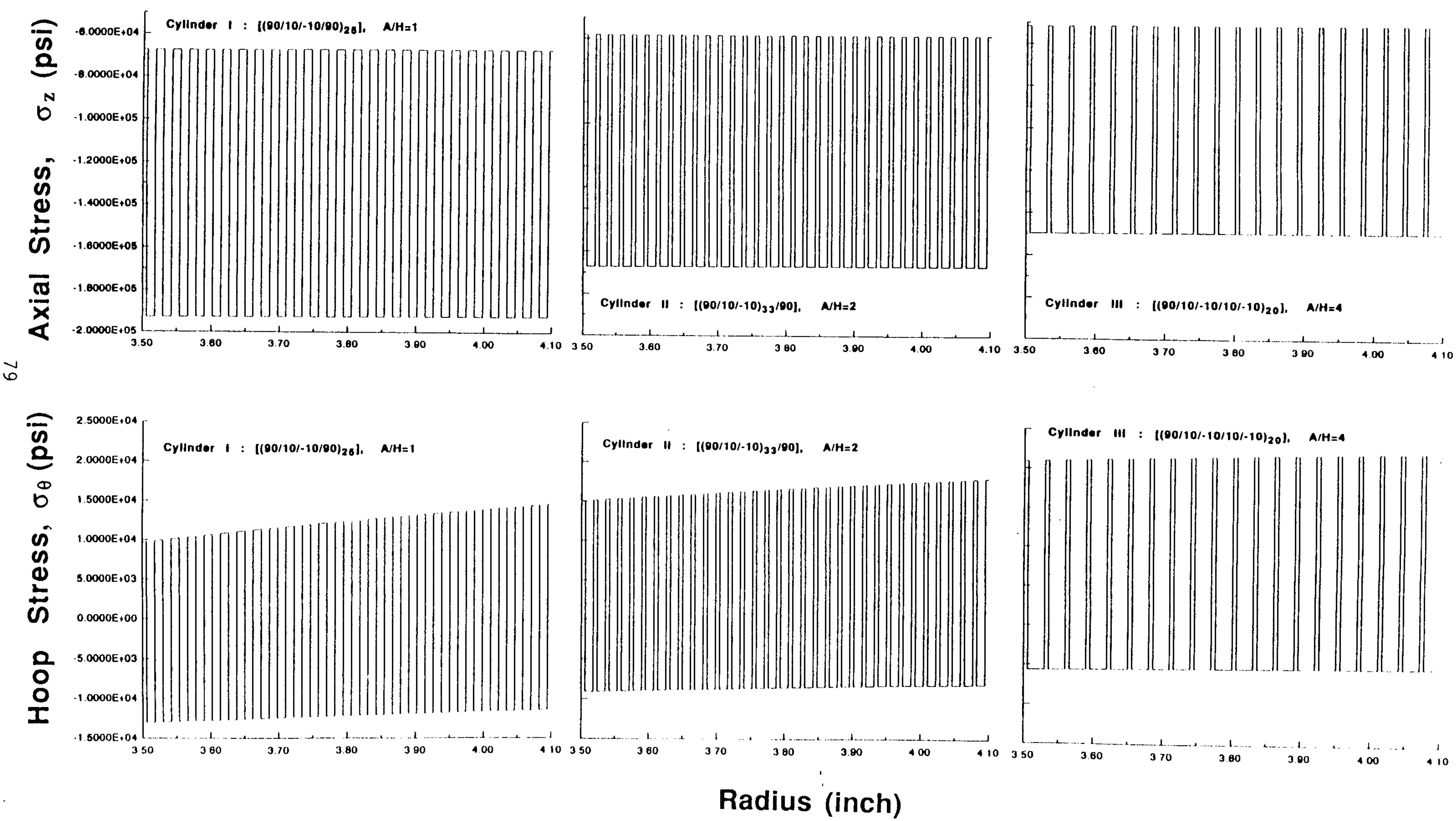
E_{11} = 8.00E+06 psi.	G_{12} = 1.00E+06 psi.
E_{22} = 2.80E+06 psi.	G_{23} = 6.00E+05 psi.
E_{33} = 2.80E+06 psi.	G_{31} = 1.00E+06 psi.
ν_{12} = 0.300	α_1 = 3.50E-06 /°C
ν_{23} = 0.300	α_2 = 30.0E-06 /°C
ν_{31} = 0.100	α_3 = 30.0E-06 /°C


Thermal Residual Stress
Axial Stress, σ_z (psi)
1.0000E+04
8.0000E+03
6.0000E+03
4.0000E+03
2.0000E+03
0.0000E+00
-2.0000E+03
-4.0000E+03
-6.0000E+03
-8.0000E+03
-1.0000E+04
Cylinder I : $[(90/10/-10/90)_{25}]$, A/H=1
Cylinder II : $[(90/10/-10)_{33}/90]$, A/H=2
Cylinder III : $[(90/10/-10/10/-10)_{20}]$, A/H=4
Hoop Stress, σ_θ (psi)
1.0000E+04
5.0000E+03
0.0000E+00
-5.0000E+03
-1.0000E+04
-1.5000E+04
-2.0000E+04
3.50
3.60
3.70
3.80
3.90
4.00
4.10
Radius (inch)

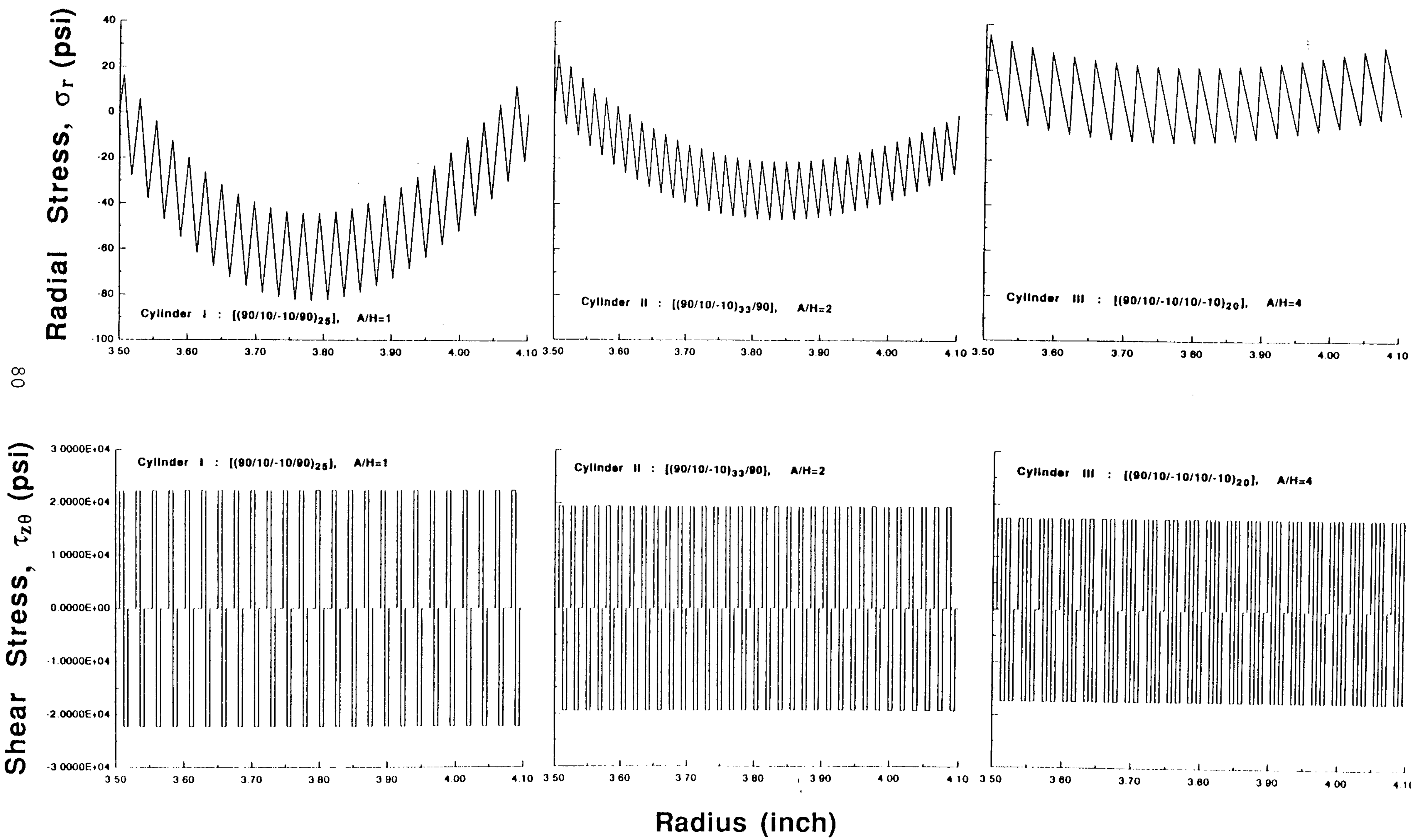
Thermal Residual Stress



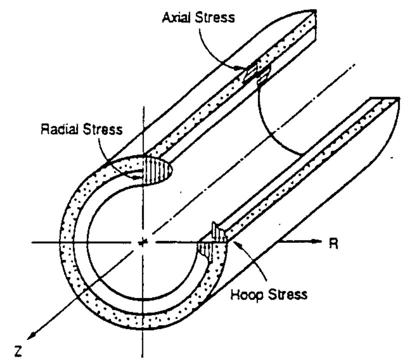
Stress Distribution due to Axial Compression



Stress Distribution due to Axial Compression



STRESS DISTRIBUTIONS



RESULTS SUMMARY

LAMINA STRENGTH ALLOWABLES FOR GLASS/EPOXY

X1C=175 ksi. X1T=245 ksi. (SF) = $\sigma_{Allowable} / \sigma_{Applied}$
X2C=50 ksi. X2T=7 ksi.
S12=12 ksi.

THERMAL STRESS COMPONENTS (ΔT=-150 °C)

Stress	Layer	A/H=1	A/H=2	A/H=4	Mode
σ_z	10°	-6 (29.0)	-4 (44)	-2 (87.5)	X1C
	90°	6 (1.2)	7 (1.0)	8 (0.9)	X2T
σ_θ	10°	7.5 (0.9)	6.5 (1.1)	5.0 (1.4)	X2T
	90°	-8.0 (21.9)	-12 (14.6)	-16 (10.9)	X1C
σ_r	10°		small		
	90°		small		
$\sigma_{z\theta}$	10°	1.8 (6.7)	1.5(12.3)	1.1(11)	S12
	90°				

MECHANICAL STRESS COMPONENTS (P_{Axial}= -130 ksi.)

Stress	Layer	A/H=1	A/H=2	A/H=4	Mode
σ_z	10°	-190 (0.9)	-170 (1.0)	-150 (1.0)	X1C
	90°	-7 (7.1)	-6 (8.3)	-5 (10.0)	X2C
σ_θ	10°	-13 (3.8)	-10 (5.0)	-5 (10.0)	X2C
	90°	15 (16.3)	20 (17.3)	23 (10.6)	X1T
σ_r	10°		small		
	90°		small		
$\sigma_{z\theta}$	10°	22 (0.5)	20 (0.6)	18 (0.7)	S12
	90°				

CONCLUSIONS

- An exact solution model was developed to study layer-by-layer thermal and mechanical response in composite cylinders.
- This basic model can be enhanced to study effects of
  - progressive ply failure
  - material non-linearity
  - high strain rate
  - cure shrinkage residual stress development during processing
- Case Study
  - Thermal residual transverse tensile stress is high enough to cause matrix micro-cracking.
  - Mechanically induced in-plane shear and longitudinal compressive stresses in 10° plies exceed their corresponding allowable strengths and can be reduced by increasing the A/H ratio.

FUTURE RESEARCH

- NON-LINEAR MATERIAL RESPONSE
- HIGH RATE OF STRAIN
  - Constitutive models
  - Failure criteria
- FINITE ELEMENT ANALYSIS
  - Thick structures in compression
  - Three-dimensional capability
  - Arbitrary shapes/loading
  - Progressive failure/damage analysis

An Analysis of the Composite Infantry Fighting Vehicle Roadwheel Housing Attachment

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Materials Reliability Division
Army Materials Technology Laboratory
Watertown, MA 02172-0001

ABSTRACT

Increased mobility and performance requirements of next generation Army hardware systems are presently being met by exploiting the advantages of fiber reinforced composite laminates. The Composite Infantry Fighting Vehicle (CIFV), presently being developed by FMC under the direction of the Army Materials Technology Laboratory (AMTL), is a prime example of such an application. Design engineers have been able to meet both structural and medium caliber ballistic requirements while obtaining increased weight savings, lower fabrication costs, increased operational life, and improved noise and vibration characteristics by using an S2 glass/polyester woven roving to fabricate both hull and turret structures.

The CIFV hull is constructed by joining two composite hull halves along a vertical center line. An aluminum chassis frame with longitudinal box beam supports and transverse torsion bar beam housings is joined between the bottom of both hull halves. Blast protection from land mines is accomplished through a composite bottom plate attached to the chassis. Roadwheel arms are attached to torsion bar assemblies through roadwheel housings which together with the chassis sandwich the lower portion of the both the right and left hull halves. Torsion bar ends are anchored to respective roadwheel housings on opposing hull sides.

Although significant parts consolidation is being achieved with this basic hull design, aluminum and composite components must still be structurally joined. In light of parts consolidation, many of these joints may be termed *design critical* when both structural integrity and repair considerations are taken into account. The roadwheel housing attachment is an example of such design criticality. The joint's function of transmitting severe roadwheel suspension loads to the hull and providing torsion bar anchoring is quite demanding while its failure would necessitate costly localized repair of the surrounding hull structure.

Use of frictional forces generated from the through thickness clamping action of the joint's multiple mechanical fasteners was proposed to counteract suspension loads and avoid potentially damaging bolt bearing stress conditions within the hull. This friction joint concept is however susceptible to obtaining and maintaining minimum friction force values within the roadwheel housing joint. Reductions in bolt preload from through thickness viscoelastic relaxation of the

thick composite hull material could significantly degrade joint performance. Predictive design and analysis techniques are needed to evaluate the friction joint concept and estimate friction joint lifetimes. Furthermore, overall structural integrity of the roadwheel housing joint during bolt bearing conditions need to be investigated. To this end, work was conducted to experimentally investigate single connector phenomenological characteristics and relate them to two proposed multiple connector roadwheel housing configuration to predict friction joint performance [1].

In this work, through thickness viscoelastic relaxation effects of the thick $[(0/90/45)_n]_s$ S2 glass/polyester woven roving CIFV hull material was experimentally obtained under both static and dynamic surface traction fatigue loading conditions for a single connector configuration. Single connector joint slip load as a function of bolt preload was also experimentally determined. Using this single connector information, a computer code was developed to predict friction joint lifetimes for each of the purposed multiple connector roadwheel housing configurations subjected to several Perryman III terrain test conditions. Joint reaction forces and moments used in this code were obtained from CIFV *DADS* suspension modeling results.

Bolt bearing stress state conditions within the hull material resulting from friction joint slippage was predicted for worst case single connector conditions with a 3D nonlinear elastic finite element model using finite element code *Abaqus*. The quarter symmetry model consisted of a bolt washer, a steel cover plate, and a composite plate. Interface elements were used to model contact between the washer and plates. A rigid surface was used to model the bolt. Far field tensile stress boundary conditions were applied to the two plates to produce a maximum bearing load while varying through thickness bolt preloads were introduced by a compressive stress boundary condition applied to the model's bolt washer. Finite element constitutive equations were developed for the S2 woven roving material from mechanical properties obtained from tension, compression, intralaminar shear, and interlaminar shear tests.

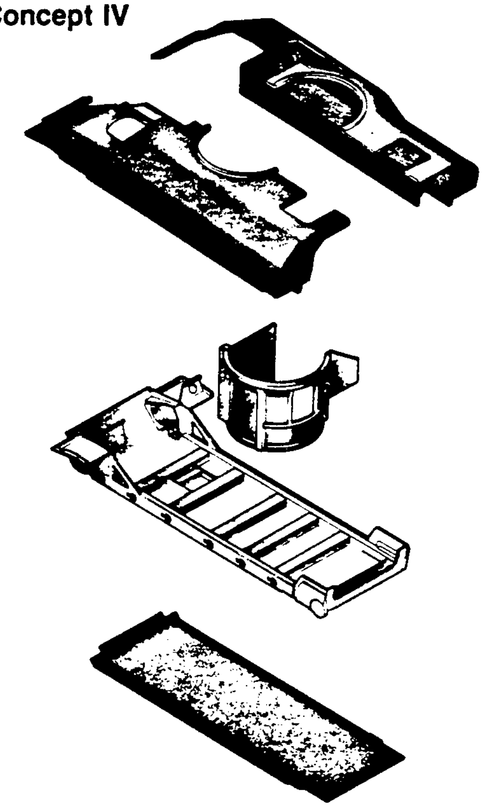
Results indicate that static single connector bolt preload decay was limited to roughly 5% of initial bolt preloads over a 43 day test period. The dynamic surface traction fatigue loading environment did not alter this observation. Single connector slip test results indicated a linear relationship between bolt preload and joint slip load. The shear moment computer analysis predicted that sufficient frictional forces were generated within each of the roadwheel housing configurations to counteract the Perryman III suspension loads. Similar results were predicted when bolt preload relaxation effects were included. Finite element analysis results for the worst case single connector bearing conditions indicated peak in-plane compressive loads just under in-plane compressive strengths obtained from mechanical testing.

REFERENCES

[1] S.M. Serabian, C. Cavallaro, R. Dooley, and K. Weight, "An Assessment of Friction Joint Concepts for the Roadwheel Housing Attachment of the Composite Infantry Fighting Vehicle", AMTL Technical Report, *to be printed*.

COMPOSITE INFANTRY FIGHTING VEHICLE HULL PROGRAM

Hull Exploded — Concept IV

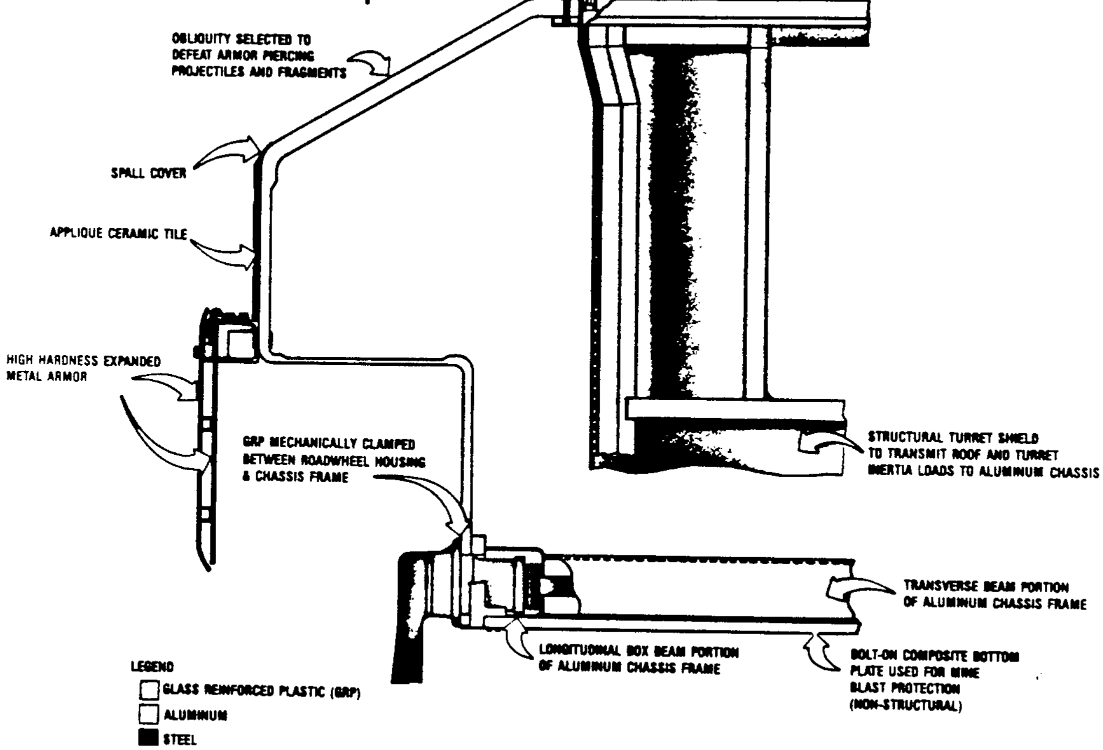


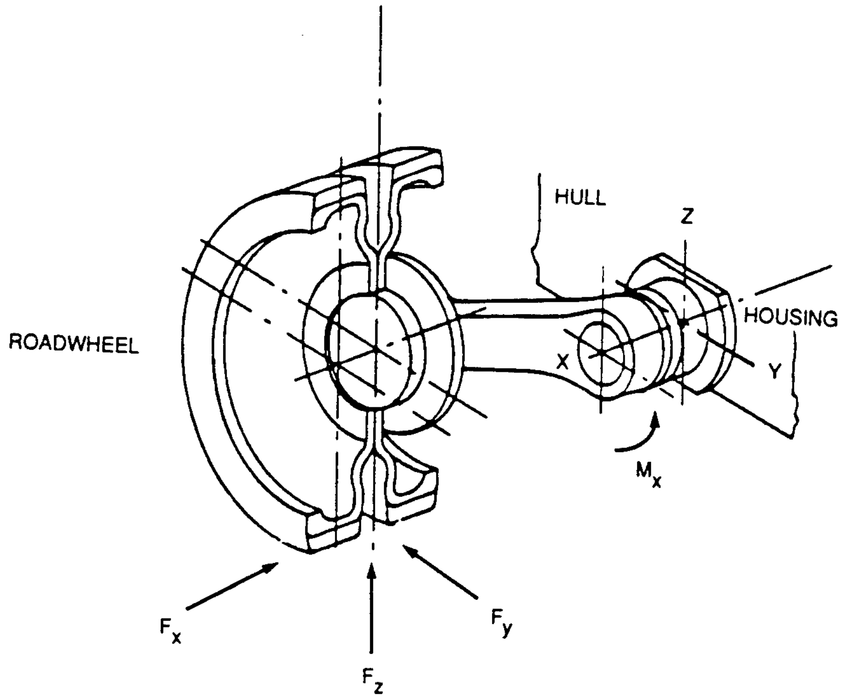
AMTL

FMC

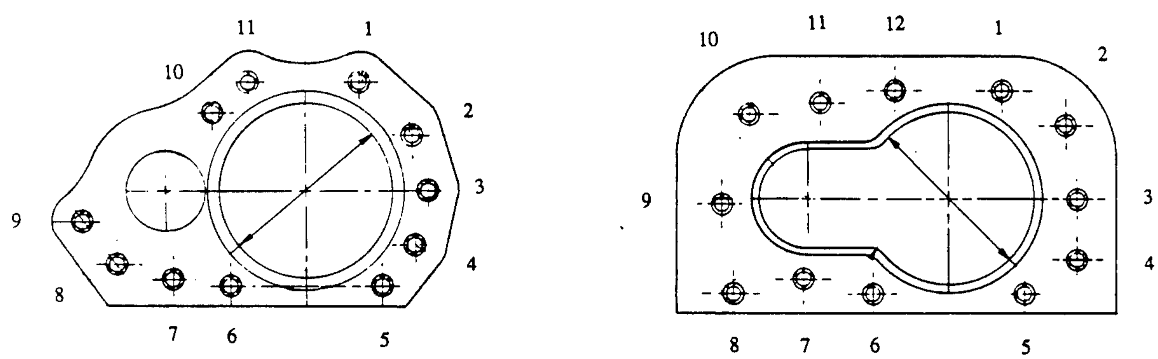
COMPOSITE INFANTRY FIGHTING VEHICLE HULL PROGRAM

Hull Cross Section — Concept IV

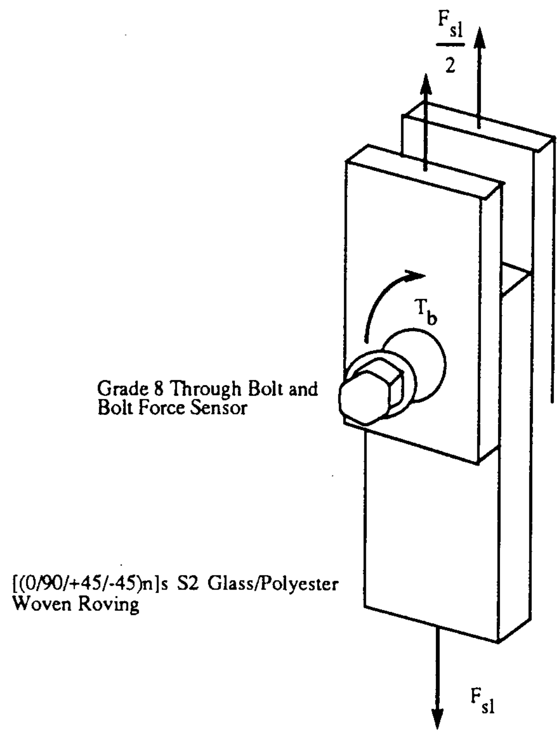




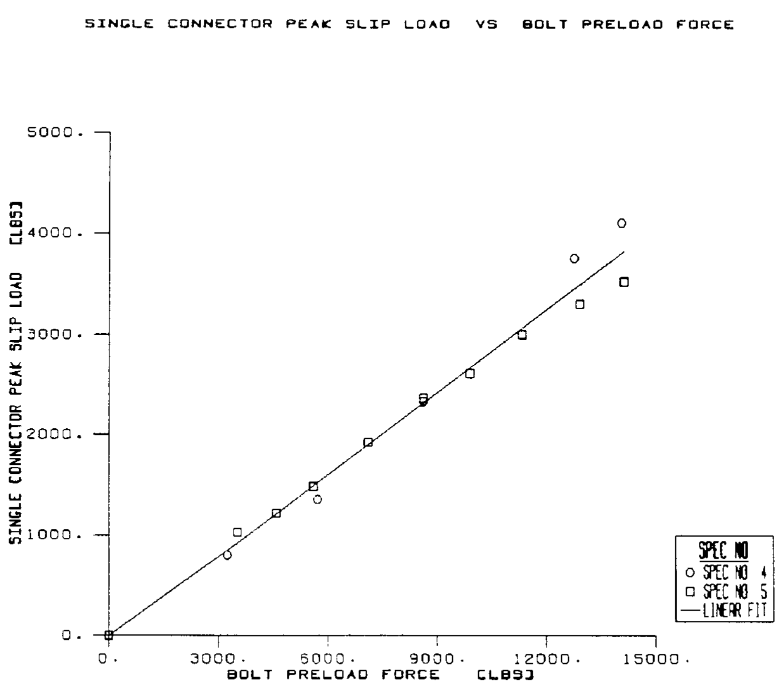
Suspension Loads Coordinate System



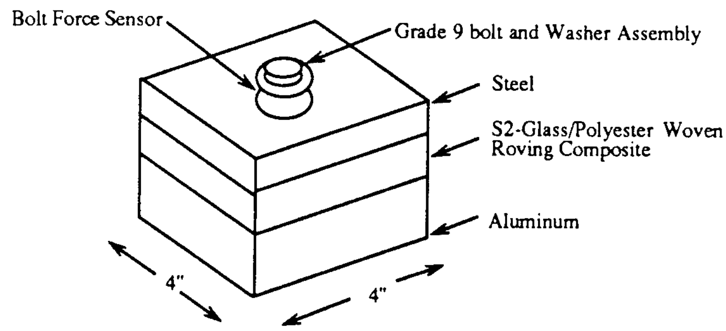
Original and Modified Roadwheel Housing Attachments



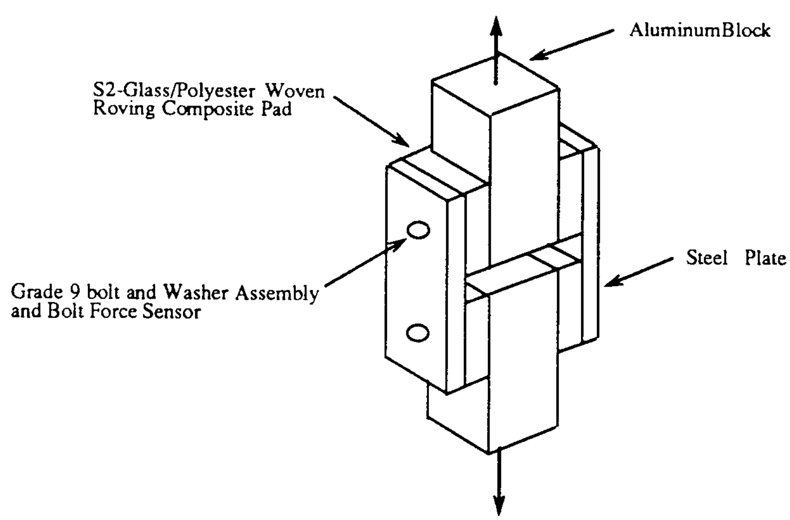
Single Connector Static Slip Test Specimen Configuration



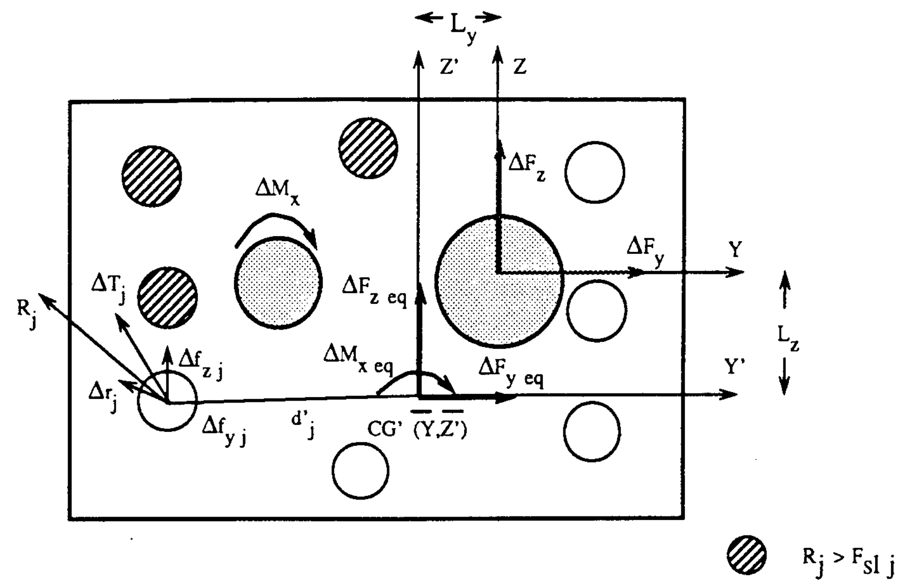
Single Connector Peak Slip Load Vs. Bolt Preload Force



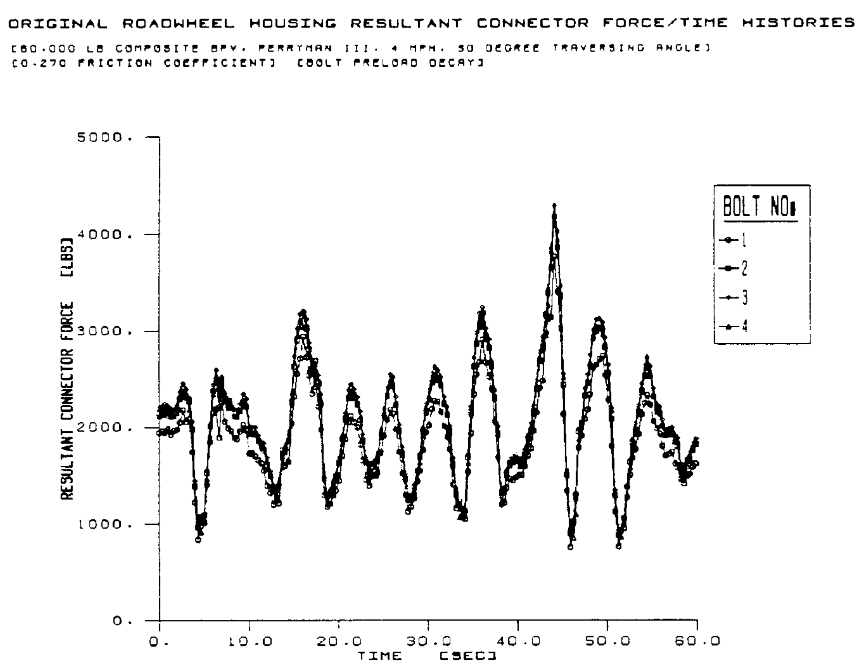
Static Bolt Force Preload Relaxation Specimen



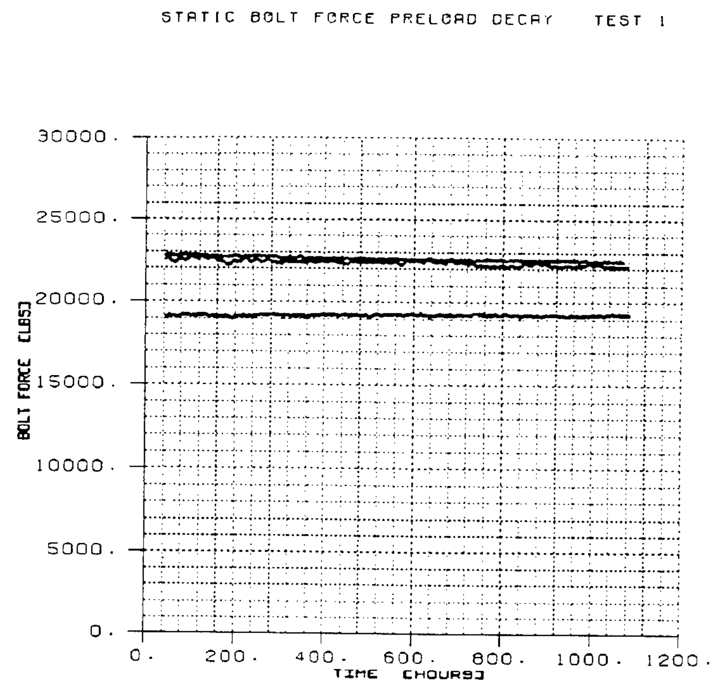
Dynamic Bolt Force Preload Relaxation Specimen



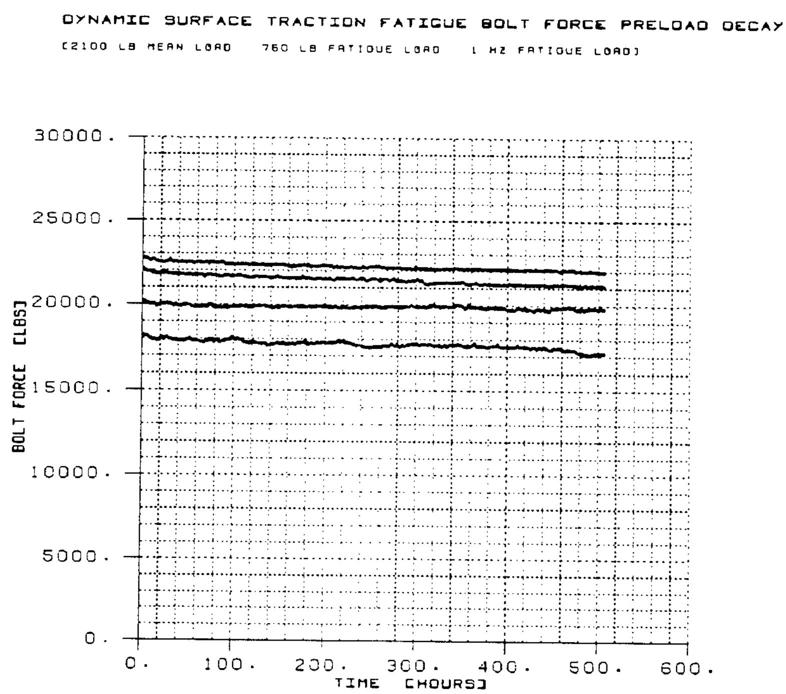
Shear/Moment Slip Analysis of Roadwheel Housing Joint



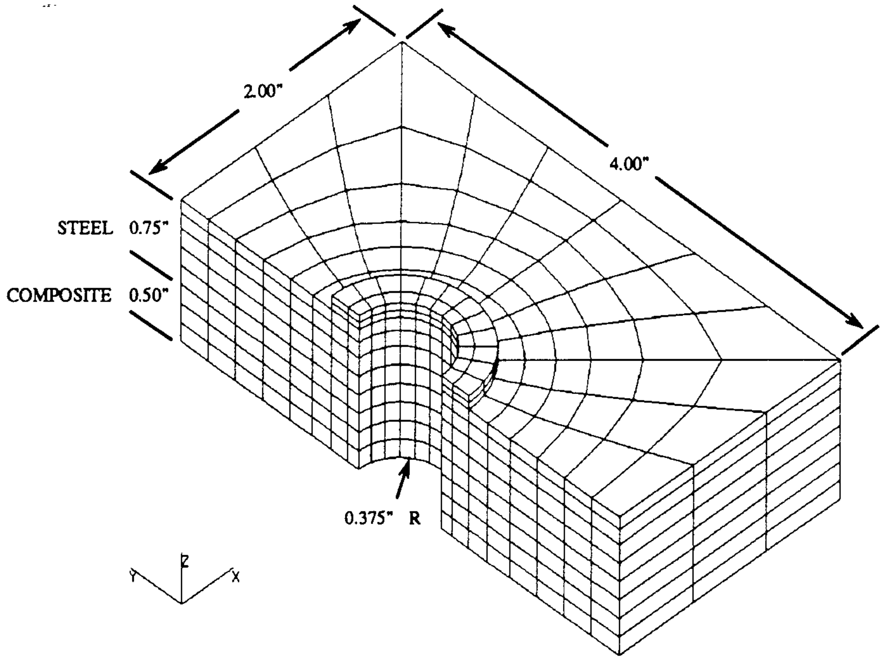
Typical Prediction of Roadwheel Housing Resultant Connector Force-Time Histories [terrain 1] [$\mu_{eff} = 0.270$] [19,000 lb bolt preload] [bolts 1-4]



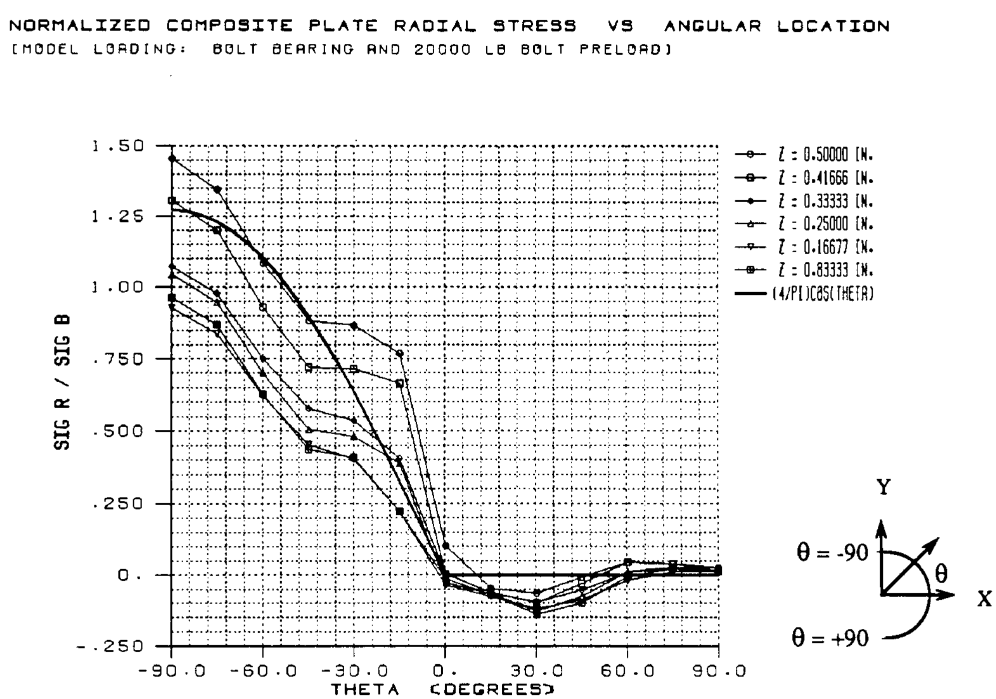
Typical Static Loading Bolt Force Preload Decay Data



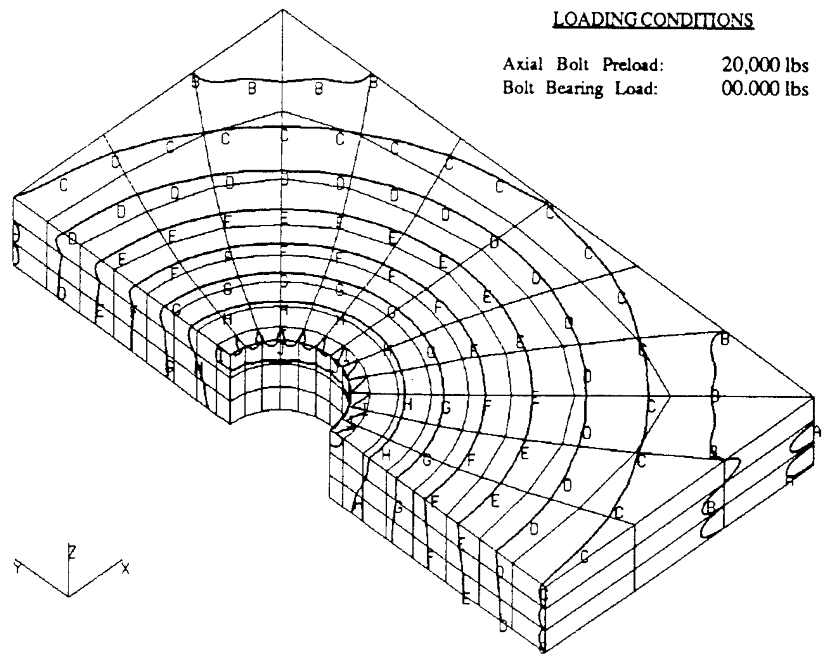
Typical Dynamic Surface Traction Fatigue Bolt Force Preload Decay Data

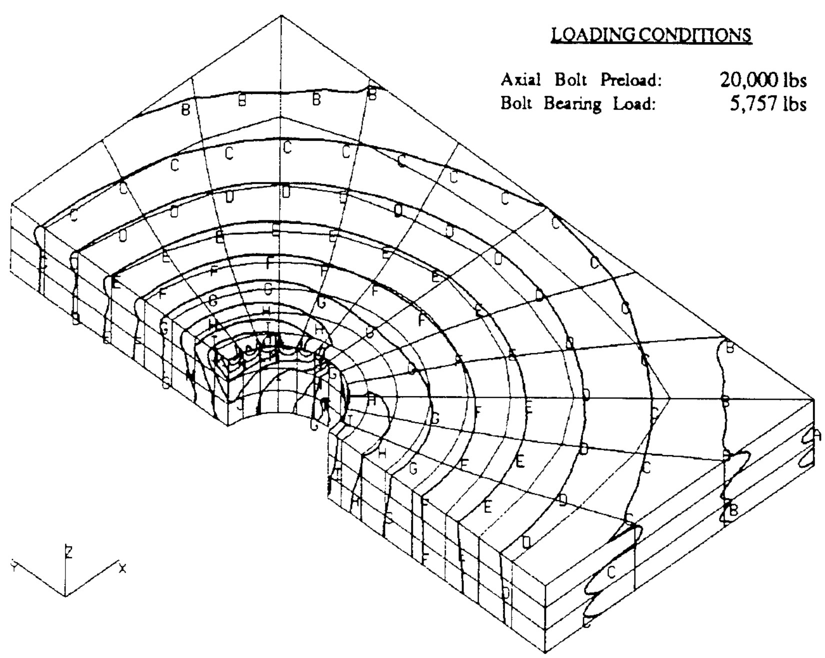


CIFV Friction Joint Finite Element Model



Normalized Composite Plate σ_r Stress vs. Angular Location





SCALE
Psi

A = - 0
B = - 375
C = - 750
D = -1125
E = -1500
F = -1875
G = -2250
H = -2625
I = -3000
J = -3375
K = -3750
L = -4125
M = -4500
N = -4875
O = -5250

Composite Plate σ_z Stress Distribution for Bolt Preload/Bearing Load Cases

CHARACTERIZATION AND ISSUES OF MATERIAL MODELING OF 2-D CARBON-CARBON COMPOSITE LAMINATES

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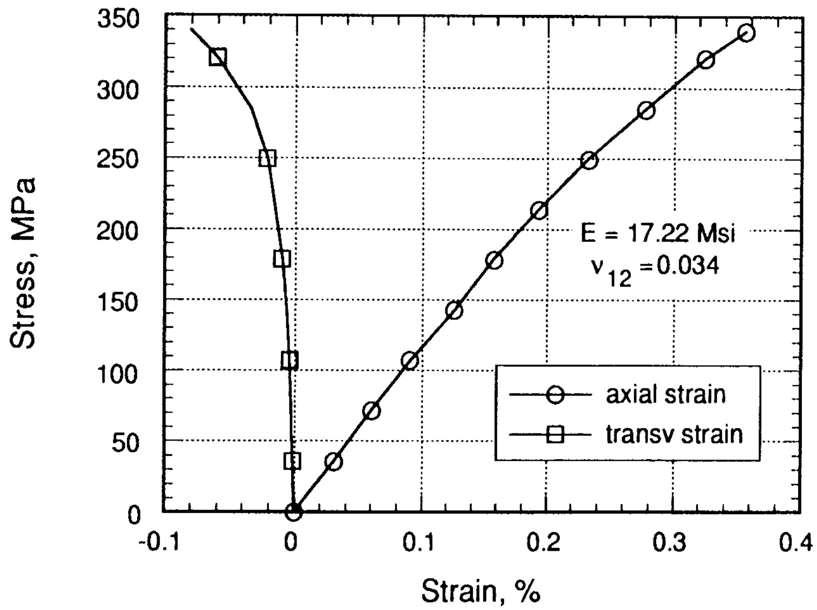
Dayton, OH 45469-0168

ABSTRACT

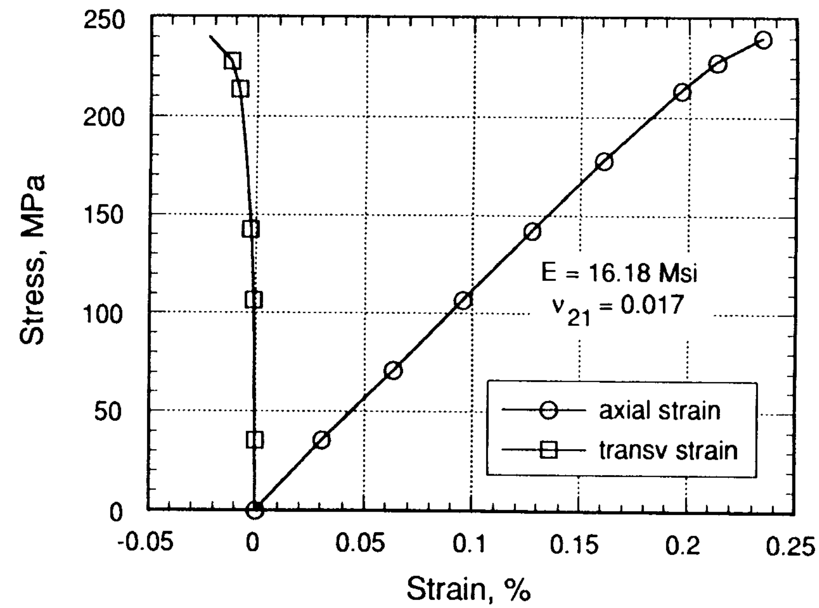
The 2-D carbon-carbon is a cloth woven fabric of fibers embedded in carbon matrix. The fabric weaving architecture (e.g., Plain weave, 8HS, 5HS) is varied to meet the desired stiffness and strength requirements for the composite. Due to the fabric architecture there exist a representative cell size for material modeling of carbon-carbon composites. The cell size changes for different fabric architecture and also for balanced and unbalanced fabrics. The size of the representative cell is also important for the strain measurement. To have several different cell sizes in this study, carbon-carbon of two different fabric architectures has been tested. One is a 8HS balanced fabric, and the other one is a 5HS unbalanced 6:1 fabric carbon-carbon. Here, unbalanced 6:1 fabric means that the yarn tow density in the warp direction is 6 times that in the fill direction.

Due to the presence of voids and cracks, the measurement of strains in carbon-carbon composites requires a special attention. Normally, extensometer is used to measure surface strains over a length large compared to the representative cell size of carbon-carbon. The accuracy of the extensometer strain reading becomes reliable if there is no relative movement between the extensometer clips and the specimen surface. A repeated use of extensometer on a unidirectional graphite/epoxy specimen indicates that the there is about 2-3% variation in extensometer strain reading. Thus such a variation of extensometer strain reading is also expected for carbon-carbon specimens. In some test geometry (for example, in-plane shear by two-rail or three-rail shear) extensometer is difficult to use. Then the use of strain gage is an alternative. Thus to observe whether strain gages can be used to measure strains of carbon-carbon composites, strain gages of different sizes (1/8", 1/4", 1/2", and 1") are also used in this study. The strain gage reading is compared with that of the extensometer to check its accuracy. It is found that the strain readings by 1/4" and larger gages agreed reasonably well with that of the extensometer for these two composite systems.

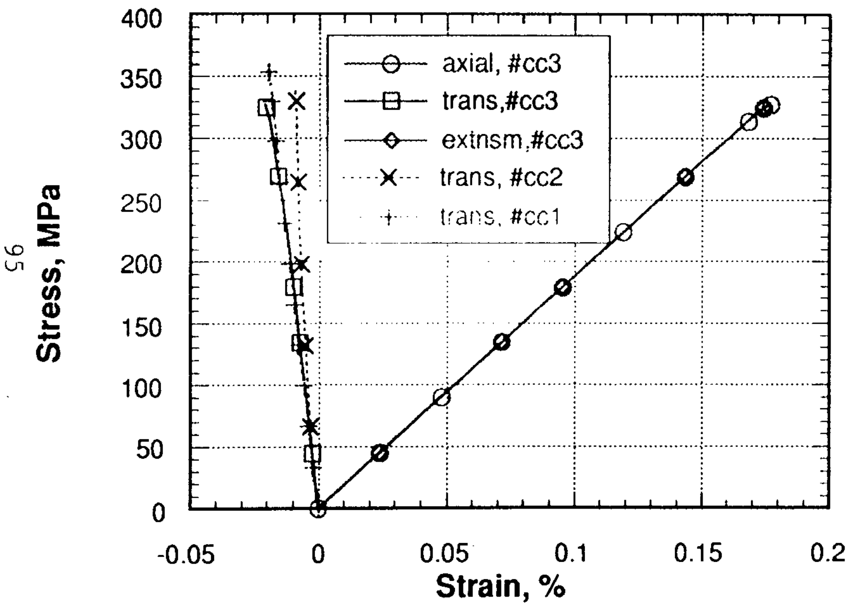
One of the objectives of this work is to generate adequate information for material modeling of 2-D carbon-carbon composites. To develop a reasonably good model, we need the stress-strain curves for all stress components. Here, the tensile stress-strain curves in the warp and fill directions and the in-plane shear stress-strain curves of the two fabric systems are obtained. The stress-strain curves of the unbalanced fabric in the warp direction is found to be almost linear. Whereas in the fill direction the curves are found nonlinear of decreasing modulus. For the balanced fabric, the stress-strain curves in both the directions are found nonlinear with decreasing modulus. The in-plane shear stress-strain curves are obtained by a two-rail shear test. Specimens from the unbalanced fabric aligned in the warp and fill directions are tested. The initial in-plane shear stiffness of the unbalanced fabric measured from the warp and fill specimens are found to be different. Useful information needed for material modeling obtained from these stress-strain curves are reported.



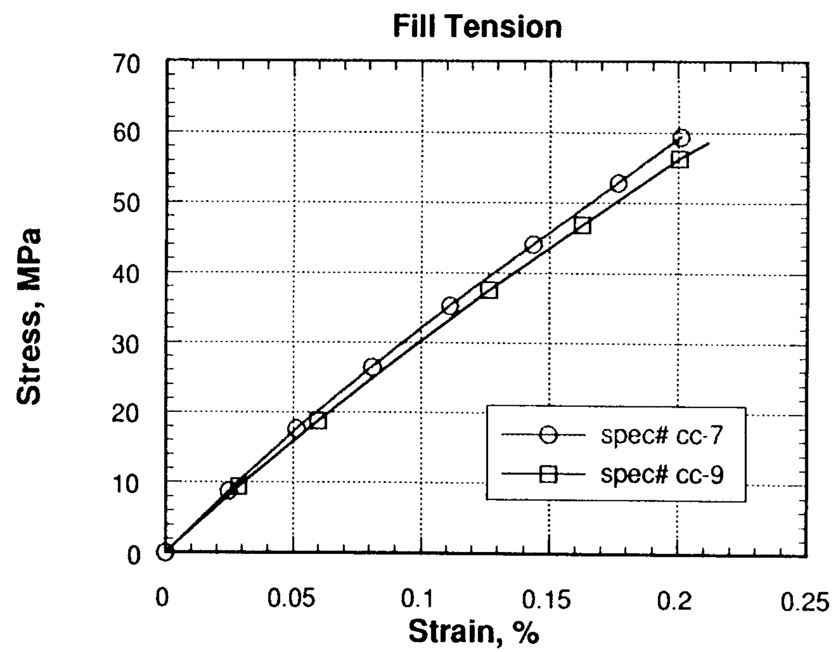
Warp Tension, Balanced



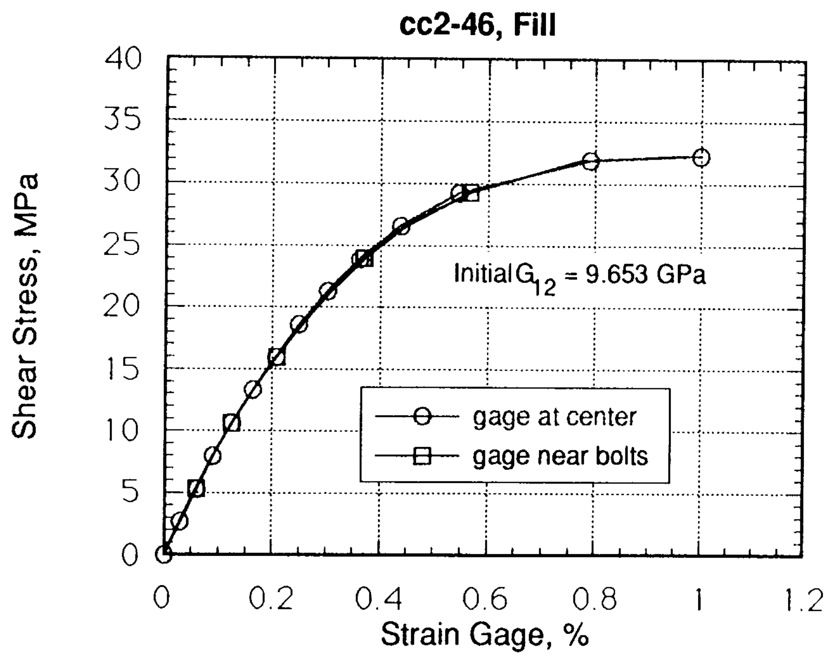
Fill Tension, Balanced



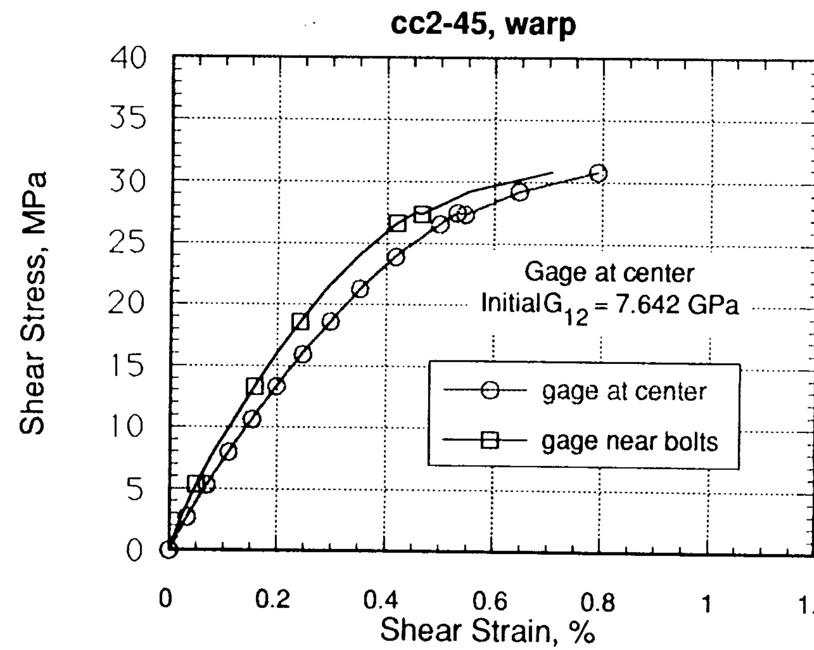
Warp Tension, Unbalanced



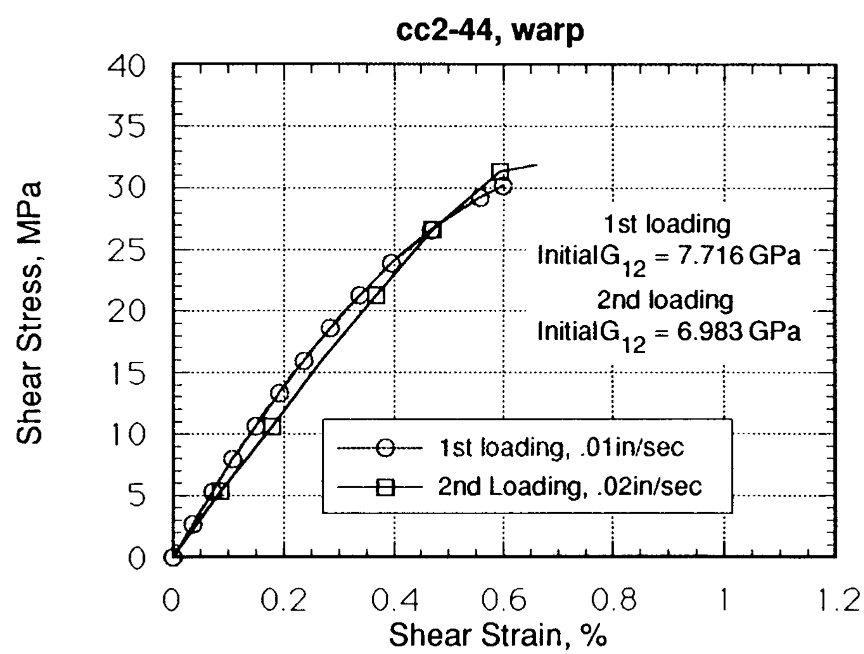
Fill Tension, Unbalanced



In-Plane Shear, Unbalanced, Fill



In-Plane Shear, Unbalanced, Warp



In-Plane Shear, Multiple Loading

Unbalanced, Warp

EFFECTIVE MODULI OF PARTIALLY DEBONDED COMPOSITES

G. P. TANDON and N. J. PAGANO
AdTech Systems Research Inc. WL/MLBM

ABSTRACT

In this work, we have developed an approximate model to examine the effect of an imperfect interface on the elastic response of a unidirectional composite. Specifically, we are treating the case where debonding may occur over a portion of the fiber-matrix interface. The debonded region is being represented by boundary conditions simulating complete separation at the interface. Our theoretical model is defined by combining solutions for the perfectly bonded and fully unbonded interface problems with the solutions of some auxiliary problems (namely, a homogeneous or bimaterial curved bar, subjected to end forces and a couple) such that approximate boundary conditions are satisfied at the juncture between the two regions. The approximations for the boundary conditions involve various combinations of force, moment and displacement continuity equations, including average values over the juncture.

Numerical results are given for a common glass matrix composite material. Stiffnesses calculated based on several definitions of composite strain (such as volume average strain, surface strain and body average strain) and surface displacements have been reported. Peculiarities in the composite stiffness matrix similar to those reported earlier [1], such as the unsymmetric nature of the stiffness tensor, have also been observed here. It is demonstrated that when working with approximate models, such as discussed in this work, one has to be careful about the definition of composite strain to employ to evaluate the effective composite response. Different choices could at times lead to strange and erroneous results. However, this is primarily because of the approximate nature of the solution itself. The composite strain definition, by itself, may be appropriate.

Alternately, the effective moduli can be estimated by matching the boundary displacements of the equivalent homogeneous medium with those of the representative volume element. The use of displacements of three boundary points, namely, points defined by $x_1=1$, $x_2=x_3=0$; $x_2=1$, $x_1=x_3=0$; and $x_3=1$, $x_1=x_2=0$, leads to physically reasonable predictions of the transverse Young's moduli for the entire range of debonding (from 0 to 90 degrees), except for E_{33} at small debonding angles (Here 1 is the fiber direction and 2-3 is the transverse plane with θ being measured from the x_2 axis). Increasing the number of boundary points does not improves the solution very much at small debond angles, whereas, at higher values of debond angle, the solution becomes bad as the lower bound is violated. Finally, some limited comparison to numerical elasticity solutions [2] are also shown.

REFERENCES

1. Pagano, N. J. and Tandon, G. P., " Modeling of Imperfect Bonding in Fiber Reinforced Brittle Matrix Composites ", Mech. of Materials, Vol 9 (1990), pp 49-64
2. Yuan, F. G., " Elastic Moduli of Fiber Reinforced Brittle Matrix Composites with Interfacial Debonding", AFOSR Report (1991)

EFFECTIVE MODULI
OF
PARTIALLY DEBONDED COMPOSITES

G. P. Tandon
AdTech Systems Research Inc.

&

N. J. Pagano
WL/MLBM

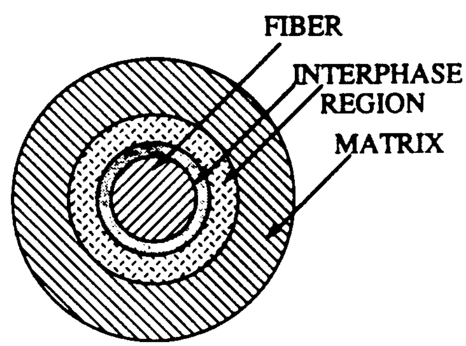
OBJECTIVES

Study behavior of unidirectional composites in the presence of fiber-matrix debonding,which is prevalent in glass- and ceramic-matrix composites.

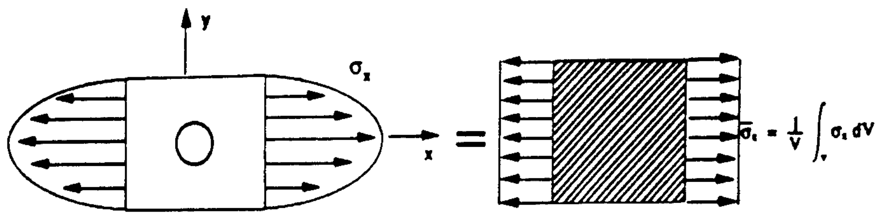
Relate composite performance to fiber, matrix properties and interfacial conditions- Micromechanics

NDSANDS MODEL
(N-Directional Stiffness AND Strength)

* COMPOSITE CYLINDER MODEL
* R, θ DISTRIBUTION
* COATINGS / INTERPHASE REGIONS
* INTERFACIAL CONDITIONS
  * Perfect Bonding (PB)
  * Sliding Interfaces (PS)
  * Separated Interfaces (CS)
* 3 D STATE OF MACRO STRESS
  * Mechanical & Thermal Loading
* CONSTITUENT MATERIAL STRESSES
* ELASTIC STIFFNESS BOUNDS
  * Upper bound close to exact result



EFFECTIVE MODULUS THEORY (EMT)



Micro (R.V.E.) Macro (Homog.)

The composite is modeled as a homogeneous body acted upon by the volume-averaged stresses and strains in the R.V.E.

$$\bar{\sigma} = C^{*}\,\bar{\varepsilon}$$

The procedure is reversible and mathematically rigorous, provided the fiber-matrix interface is perfectly bonded.

VOLUME AVERAGE STRAINS VS. SURFACE STRAINS

Displacement formulation:

$$u_i = \varepsilon^0_{ij}\, x_j \quad \text{on } S_c, \quad i, j = 1, 2, 3$$

Letting $\Delta u_i = u_i^{(m)} - u_i^{(f)}$ on S_{12}, we get

$$\bar{\varepsilon}_{\alpha\beta} = \varepsilon^0_{\alpha\beta} - \frac{1}{2V}\int_{S_{12}} (\Delta u_\alpha n_\beta + \Delta u_\beta n_\alpha)\, dS \qquad \alpha, \beta = 2, 3$$

$$2\,\bar{\varepsilon}_{\alpha 1}\, V = \varepsilon^0_{\alpha 1}\, V - \int_{S_{12}} \Delta u_1\, n_\alpha\, dS + \int_{S_1} u_\alpha\, dS - \int_{S_2} u_\alpha\, dS \qquad \alpha, \beta = 2, 3$$

$$\bar{\varepsilon}_{11}\, V = \int_{S_1} u_1\, dS - \int_{S_2} u_1\, dS$$

If $\Delta u_i = 0$, we get $\bar{\varepsilon}_{ij} = \varepsilon^0_{ij}$

COMPOSITE RESPONSE

$$\sigma_i = C_{ij}\, \varepsilon_j \qquad i, j = 1, 2, \ldots 6$$

▲ Consider alternative strain measures to represent composite behavior

- Volume average (mathematical)
- Surface (physical) strains

  ε_2 and ε_6 defined by their surface values at $\theta = \pi/2$; ε_3 and ε_5 by their values at $\theta = 0$ degree; ε_1 is constant.

  -Lead to correct boundary displacement of an element;
  -Experimental measurements are based on surface strains.

- Body Average strains (Benveniste, 1985)

$$\varepsilon_{ij} = \frac{1}{2V}\int_S (u_i n_j + u_j n_i)\, dS$$

Material	E (GPa)	G (GPa)	α (μmm/mm/^{0}C)
Nicalon	200.0	77.0	3.2
1723 Glass	88.0	36.0	5.2

SOME SIGNIFICANT RESULTS

▲ Unsymmetric stiffness matrix, SIX independent coefficients
$C_{12} = C_{13} \neq C_{21} = C_{31}$

Material System	Interfacial conditions	Using surface strains		Using volume averaged strains	
		$C_{12} = C_{13}$ (GPa)	$C_{21} = C_{31}$ (GPa)	$C_{12} = C_{13}$ (GPa)	$C_{21} = C_{31}$ (GPa)
Nicalon / 1723 Glass	PB	48.306	48.306	48.306	48.306
	PS, k = 0	48.306	22.226	48.306	37.047

Using displacement boundary conditions, $v_f = 0.4$
[PB: perfect bond; PS: perfectly smooth ; $k = (\varepsilon_z)f / (\varepsilon_z)m$]

Transverse Young's modulus, E_{22}, (in GPa) of unidirectional composite, $v_f = 0.4$

[PB: perfect bond; CS: complete separation; $k = (\varepsilon_z)f / (\varepsilon_z)m$]

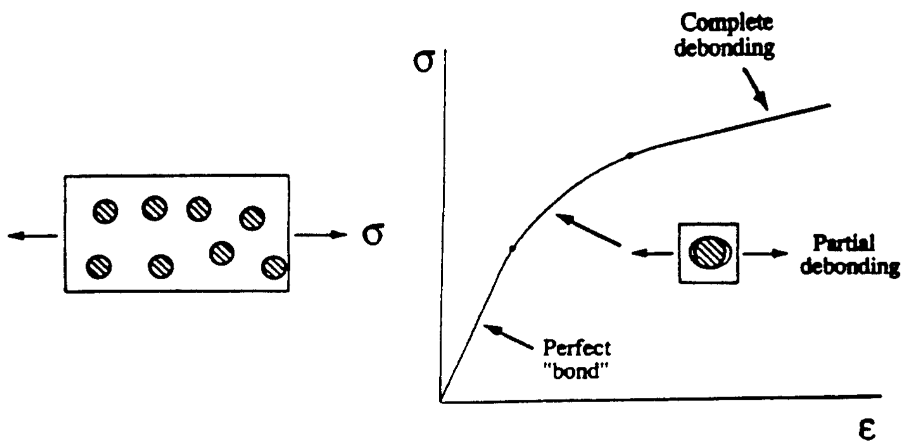
Material System	Interfacial conditions	Displacement boundary conditions		Traction boundary conditions	
		Using surface strains	Using volume averaged strains	Using surface strains	Using volume averaged strains
Nicalon/ 1723 Glass	PB	119.09	119.09	89.13	116.47
	CS, k = 0	33.60	88.0	-	88.0
' Void '/ 1723 Glass	PB	33.60	33.60	-	12.29

- States of PS, CS and ' void ' are extreme cases

- May not be realized in <u>actual</u> composites;

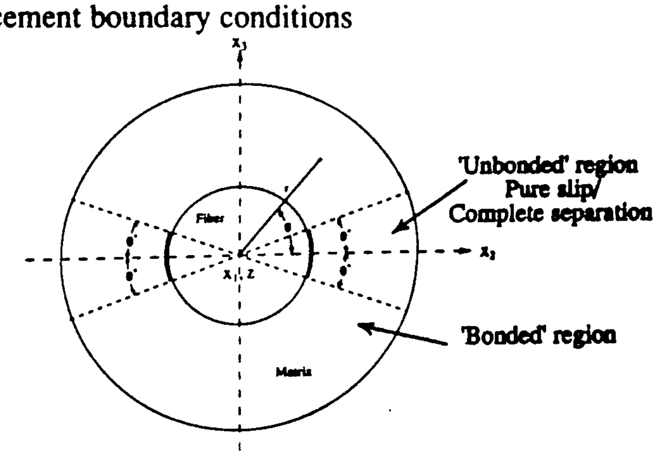
- Provide lower 'bounds' on composite moduli with respect to interfacial conditions

TRANSVERSE STRESS-STRAIN CURVE

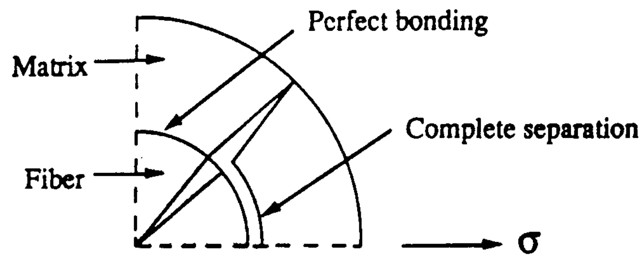


APPROXIMATE MODEL

▲ Combination of analyses for bonded and unbonded interface conditions
- Satisfies field equations of elasticity
- Displacement boundary conditions

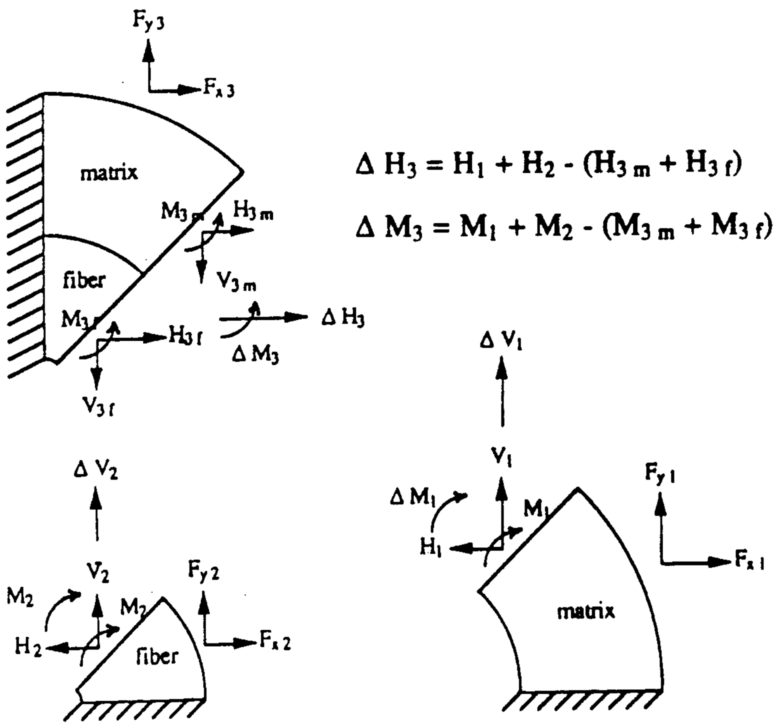


- Leads to traction and displacement discontinuities on the lines $\theta = \pm\theta^*, \pi \pm \theta^*$



Schematic of the displacement gap along the the fiber-matrix interface

<u>Solution</u>: Apply a system of forces and moments along the planes of discontinuity to fully/partially close the predicted gap and monitor the resultant traction/displacement discontinuities along those planes



$$\Delta H_3 = H_1 + H_2 - (H_{3m} + H_{3f})$$

$$\Delta M_3 = M_1 + M_2 - (M_{3m} + M_{3f})$$

$$\Delta V_2 = V_{3f} - V_2$$

$$\Delta M_2 = M_{3f} - M_2$$

$$\Delta V_1 = V_{3m} - V_1$$

$$\Delta M_1 = M_{3m} - M_1$$

THE SOLUTION APPROACH

The solution technique consists of combining the solutions for fully bonded and completely unbonded interface problems with the auxiliary solutions of a curved bar (homogeneous or bimaterial) loaded by an end force and a concentrated moment such that approximate boundary conditions are satisfied at the juncture between the two sections (namely bonded and unbonded region).

e.g., Satisfy force equilibrium
Satisfy moment equilibrium
Match the average slope of the two sections
Specify displacement at some points, e.g., at $\theta = 0^o$ and 90^o

Effective Transverse Young's Moduli of Nicalon/1723 Glass Composite Using Various Composite Strain Definitions;
(Fiber volume fraction = 0.4; $\theta^* = 15$ degrees)

Moduli (GPa)	Using Volume Average Strain	Using Surface Strain	Using Body Average Strain
E_{22}	120.05	103.95	-22.82
E_{33}	119.30	188.56	124.63

▲ Neither one of the three definitions seems to be completely unambigious. However, this is not to suggest that all definition are "bad", but rather its the approximate nature of the solution itself which leads to the wrong result.

▲ Application of additional forces and moments in the auxiliary solutions distorts the displacement field $u_i = \varepsilon^0_{ij} x_j$ drastically.

▲ These results are not necessarily " composite properties ".

ALTERNATE APPROACH

The effective moduli can be estimated by matching the boundary displacements of the equivalent homogeneous medium with those of the representative volume element (e.g., Roy and Tsai, 1991)

$$u_i(S) = S_{ijkl} \bar{\sigma}_{kl} x_j$$

Choose three points defined by

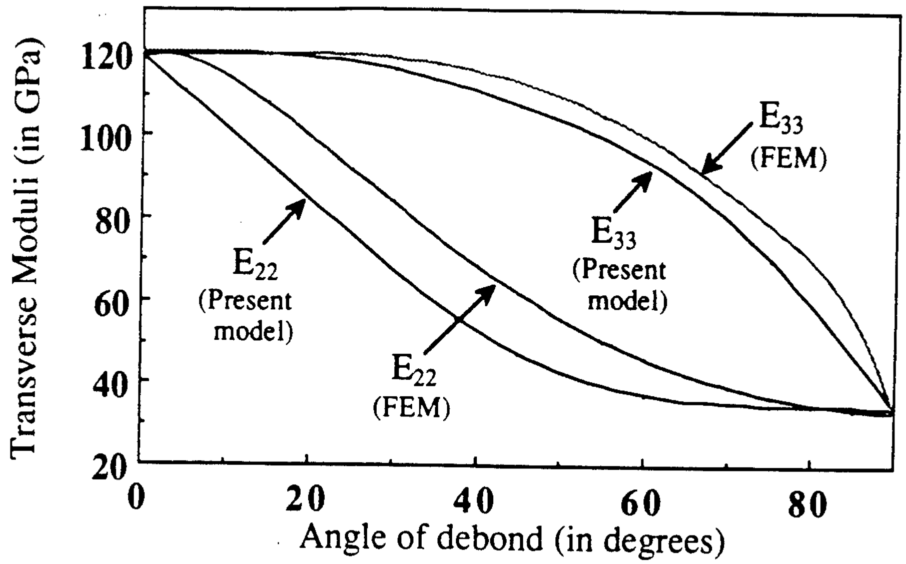
$x_1=1, x_2=x_3=0;$ $x_2=1, x_1=x_3=0;$ $x_3=1, x_1=x_2=0.$

since the boundary displacements are being matched at $\theta = 0$ and 90 degrees.

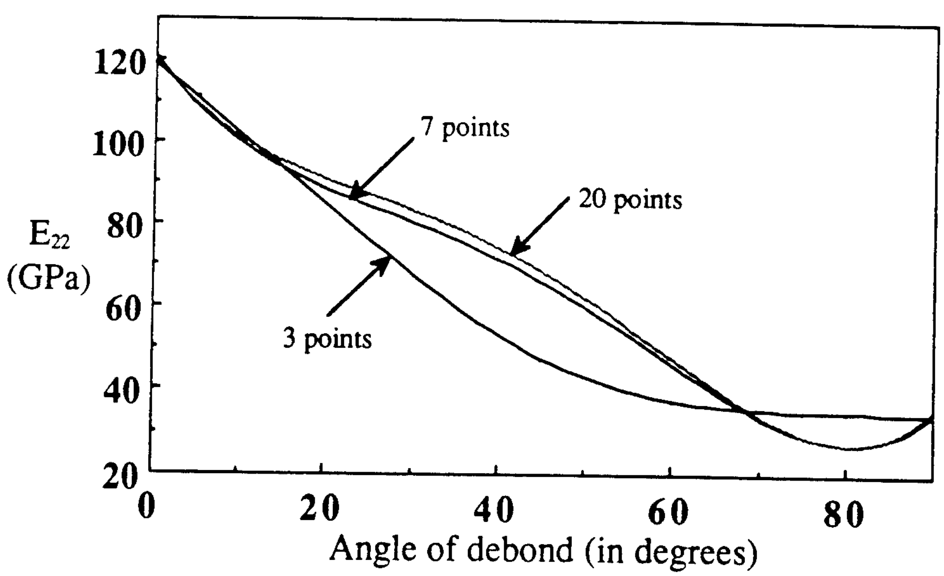
Effective Compliance Coefficients of Nicalon/1723 Glass Unidirectional Composite ($\theta^* = 15$ degrees)

Compliance Coefficient $(Pa)^{-1}$	Using Displacement of 3 Boundary Points	Finite Element Solution (CCM)
S_{11}	7.5213E-12	7.5956E-12
S_{12}	-1.9595E-12	-1.9429E-12
S_{13}	-1.9141E-12	-1.9663E-12
S_{14}	7.9843E-15	-
S_{21}	-1.8993E-12	-1.9474E-12
S_{22}	1.0715E-11	9.292E-12
S_{23}	-1.8850E-12	-2.0501E-12
S_{24}	-1.4682E-12	-
S_{31}	-1.9519E-12	-1.9623E-12
S_{32}	-2.8083E-12	-2.062E-12
S_{33}	8.3765E-12	8.3584E-12
S_{34}	4.7693E-13	-
S_{44}	2.3697E-11	2.1635E-11
S_{55}	2.2148E-11	
S_{66}	2.4772E-11	

$S_{12} \neq S_{21} \neq S_{13} \neq S_{31}$, $S_{23} \neq S_{32}$, $S_{22} \neq S_{33}$,
$S_{24} \neq S_{34}$, $S_{44} \neq 2\,(S_{22} - S_{23})$ and $S_{55} \neq S_{66}$



- Comarison of FEM solution with the present model employing displacement values at 3 points



- 3 points result is obtained using direct point matching (determined system)
- 7 and 20 points results are obtained using least squares approach (overdetermined system)

SUMMARY

▲ Micromechanical damage modeling

- Significant breakdown of classical EMT displayed
- Unsymmetric stiffness tensor

▲ Concepts for alternate formulations established

- Use of surface strains & body average strains as measures of composite strain
- Use of surface displacements to evaluate composite response

▲ CAUTION - Use of different measures of composite strain to evaluate effective response when working with approximate models such as discussed here

▲ Different interfacial conditions lead to boundary value problems with vastly different 'composite properties ' (DIAGNOSTIC)

WORK-in-PROGRESS

▲ Comparison to Finite Element Solution Using Gap Elements

▲ Alternate Approach Using Reissner's Variational Principle

Analysis of a Novel Compression Test Specimen: a Miniature Sandwich Beam

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Dayton, OH 45469-0168.

ABSTRACT

Existing test methods underestimate the longitudinal compressive strengths of unidirectional composites due to premature specimen failure. These failures arise primarily from eccentric loading and consequent specimen buckling, or stress concentrations at the ends of the gage section. To obtain more reliable estimates of this composite property, a test specimen was designed to minimize or completely eliminate the instability which leads to specimen buckling. This specimen is a miniature sandwich beam in which the honeycomb core of the traditional sandwich specimen is replaced with a core of neat resin similar to the matrix of the composite to be tested. This substitution of core materials reduces the difference in Poisson's expansions between the face sheet (skin) and core under an applied load and consequently suppresses the separation of skin from core, a problem commonly observed with the traditional sandwich specimen. The sandwich panel is fabricated by laying composite prepreg tape on either side of a partially-cured resin plaque and curing this assembly in an autoclave with the standard composite cure cycle [1]. Specimens cut from this panel have the same dimensions as standard test coupons (ASTM D3410) and are tested in axial compression in an IITRI test fixture.

A stress analysis was conducted to calculate the interlaminar stresses at the specimen free edges using the global-local model developed by Pagano and Soni [2]. The interlaminar normal stress is highest at the midplane (center of the core) and is tensile, whereas the interlaminar shear stress is highest at the interface between resin core and composite skin. The largest interlaminar stresses for graphite/epoxy (AS4/3501-6) are 17 MPa (normal) and 13 MPa (shear) at an applied strain of 0.025, which is approximately failure strain of this material system. These stresses are not large enough to induce interlaminar failure prior to ultimate failure of the specimen in compression. The close match of Poisson's ratios of skin and core is primarily responsible for these insignificant interlaminar stress components in the free-edge region. Similar results were obtained for AS4/PEEK and S2-Glass/epoxy composites.

A finite element method was employed to determine the stress distribution at the ends of the gage sections of a miniature sandwich specimen (with 2-ply AS4/3501-6 skins) and a conventional 24-ply all-composite AS4/3501-6 test coupon [3]. The sandwich core has a thickness of 3.18 mm while both specimens are 6.35 mm wide and have tapered (15°), 1.59 mm thick, bonded glass/epoxy tabs at the ends of a 12.7 mm gage section. A four-noded quadrilateral isoparametric finite element mesh containing 1285 elements and 1378 nodes was used in the analysis. The stress distribution along the x-direction was determined for the outer surface of the skin from the center of the gage section, and in the z-direction, from the midplane to the skin surface at the end of the gage section. The out-of-plane stresses σ_z and τ_{xz} were found to be too small to influence the compressive strength. The maximum axial stress, σ_x, occurs on the outermost surface at the end of the gage section (or tapered end of the tab) for both specimen types, with corresponding stress concentration factors of 1.15 and 1.24, for the sandwich and all-composite specimen, respectively.

To optimize the geometry of the miniature sandwich specimen with respect to stress concentrations, the influence of parameters such as thickness of skin and core, thickness of the intermediate adhesive layer, and tab material, thickness, and taper angle, were investigated. Preliminary results from these parametric studies indicate no remarkable influence of adhesive layer

thickness on the stress distribution. Variations in skin and core thickness (used in this analysis) also produce negligible changes in the stress concentrations. A reduction in the taper at the end of the tab, from 90° to 15°, considerably reduces the stress concentration; however, the resultant increase in the ungripped specimen length also reduces the critical buckling load.

The significant advantage of the miniature sandwich specimen over all-composite test specimens is the improvement of premature failure through the reduction of stress concentration at a critical location, and the complete elimination of overall specimen buckling.

REFERENCES

1. A. S. Crasto and R. Y. Kim, "Compression Strengths of Advanced Composites from a Novel Mini-Sandwich Beam," Int. SAMPE Tech. Conf., 22, 264 (1990).

2. N.J. Pagano and S.R. Soni, "Global-Local Laminate Variational Model," Int. J. Solids Structures, 19(3), 207-228 (1983).

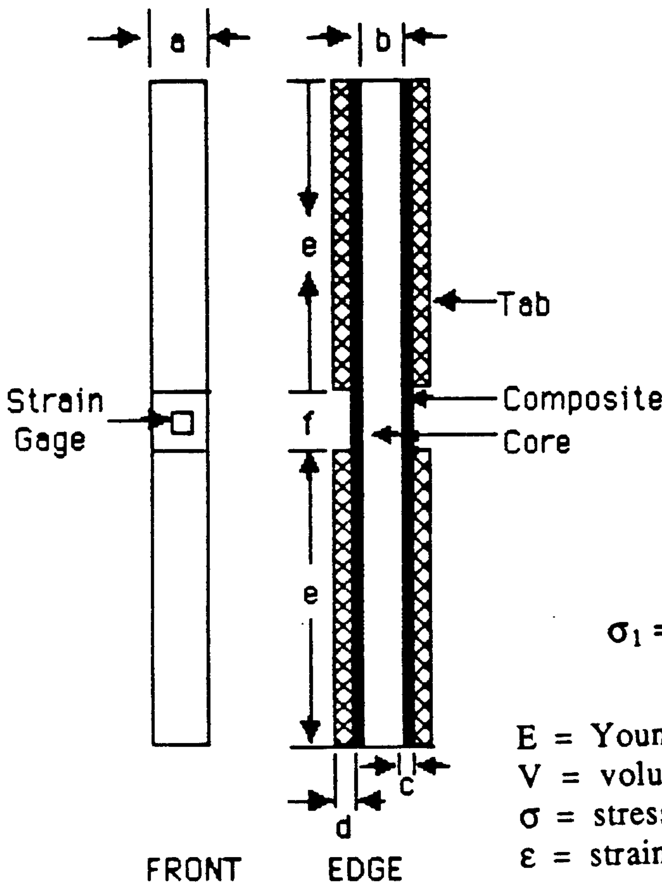
3. S.C. Tan, "Analysis of ASTM 3410 Compression Test Specimens," AIAA Journal, May 1991.

OBJECTIVE

- **To compare the performance of the mini-sandwich with conventional all-composite coupons**

- **To opimize the geometry and dimension of the mini-sandwich compression specimen**

Sandwich specimen



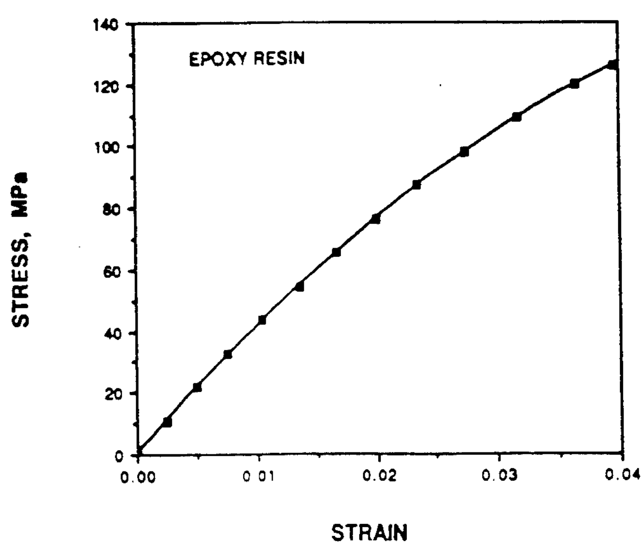
Dimensions, mm

a: 6.35
b: 3.175
c: 0.254-0.508
d: 1.58
e: 63.5
f: 12.7

$$\sigma_1 = \frac{1}{V_1}(\sigma_a - \varepsilon_a E_2 V_2)$$

E = Young's modulus
V = volume fraction
σ = stress
ε = strain

a = entire specimen
1 = skin
2 = core

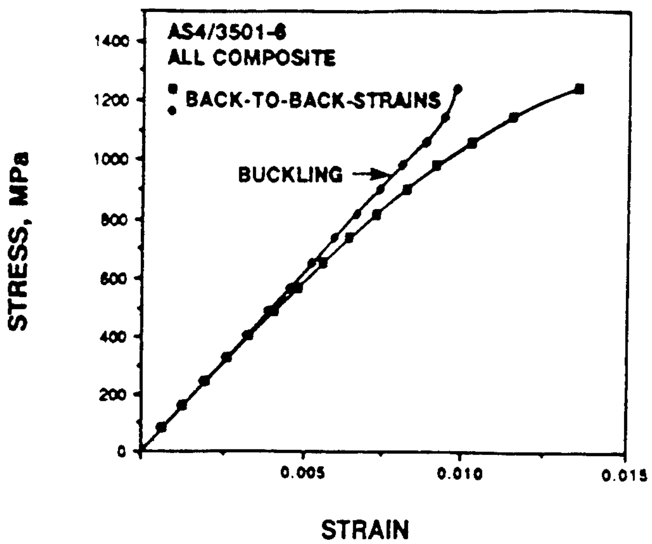


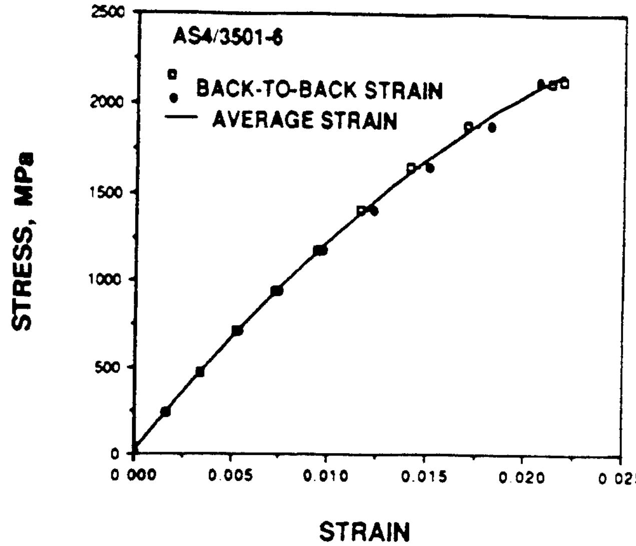
Compressive strengths of sandwich and all-composite specimens

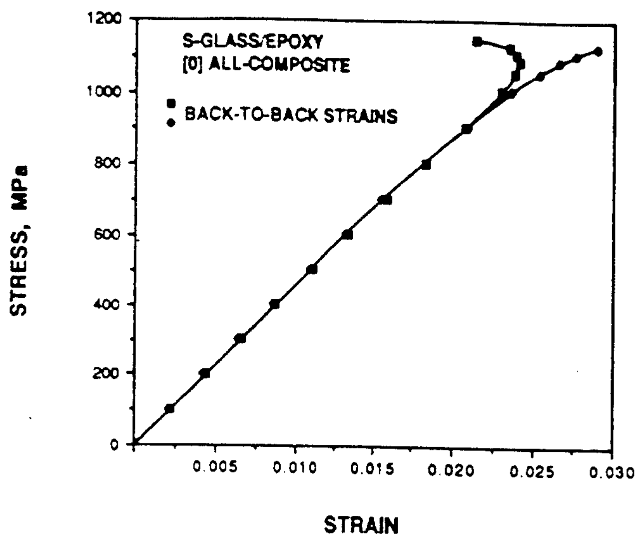
Material system	Fiber volume %	Sandwich IITRI			All-composite IITRI
		Modulus, GPa	Strength,MPa	Cv, %	Strength,MPa
E-glass/epoxy	62	44	1085	6.4	806
S2-glass/1034	60	58	2238	4.5	1400
AS4/3501-6	62	137	2020	3.1	1260
AS4/APC-2	57	129	1573	3.4	1100
IM8/3501-6	65	x	2270	x	1380
Boron/epoxy	50	x	3625	x	2930

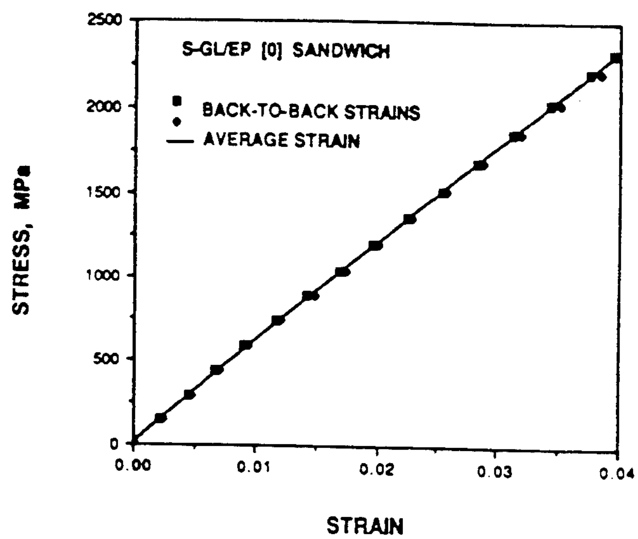
Cv: Coefficient of variation

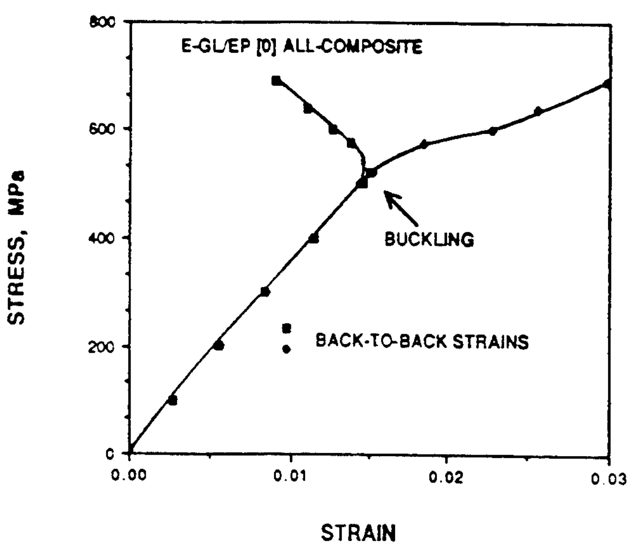
Compressive stress-strain curves for unidirectional composites

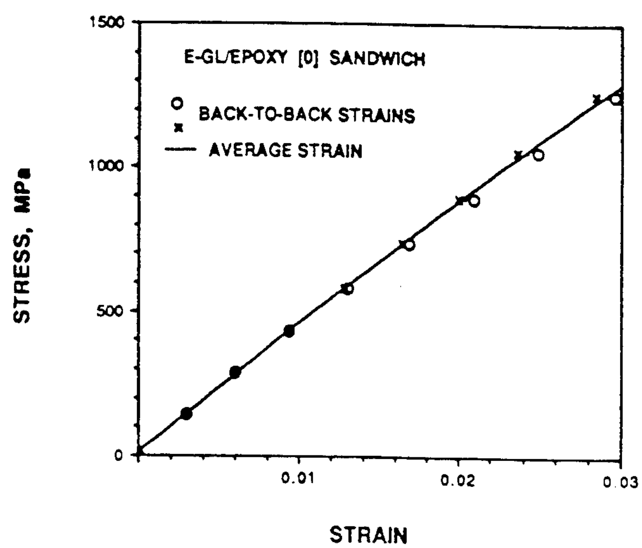




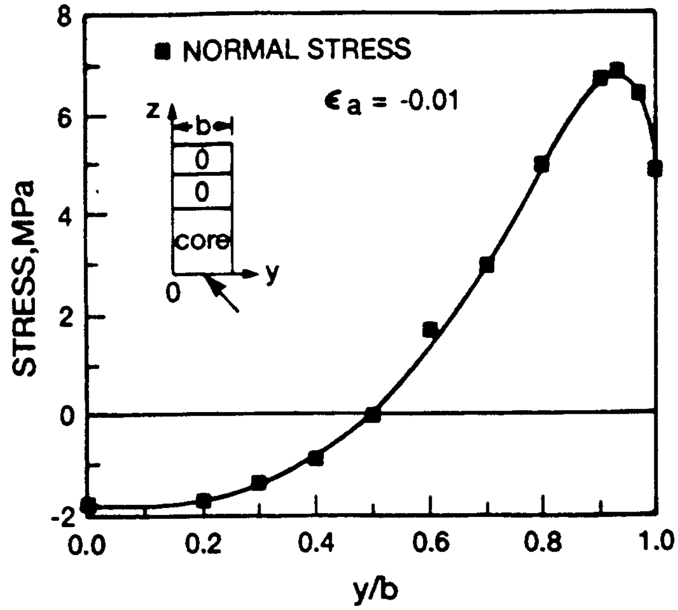


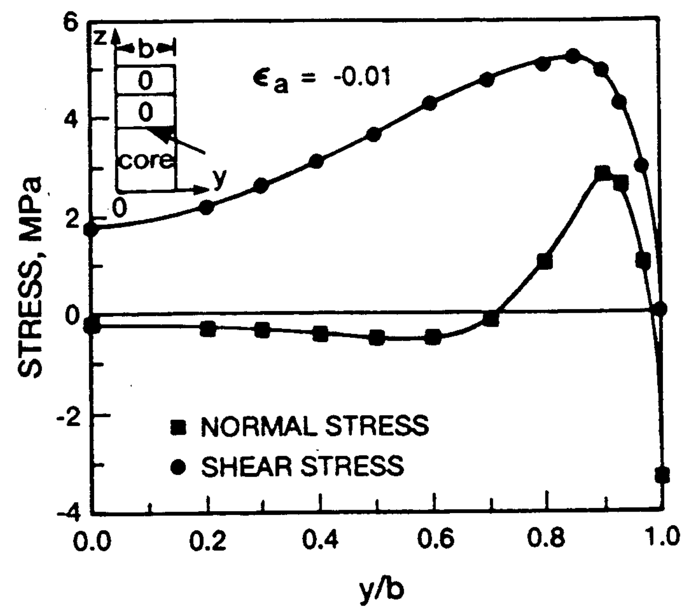


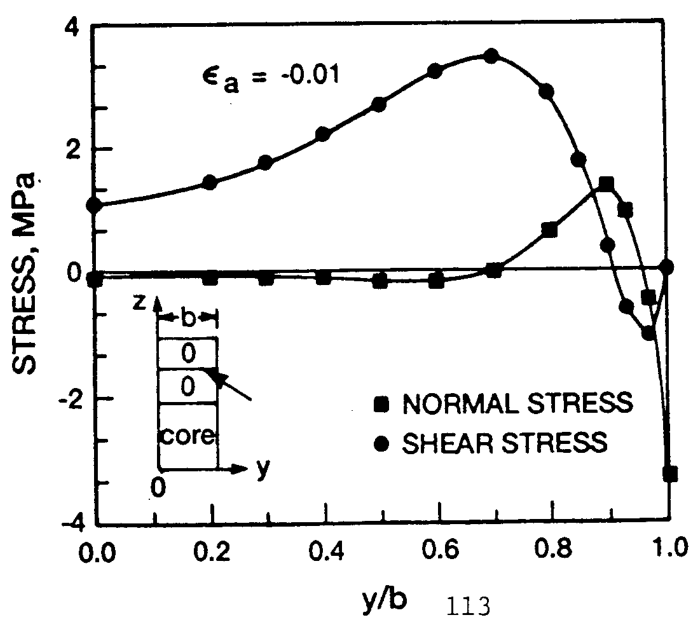


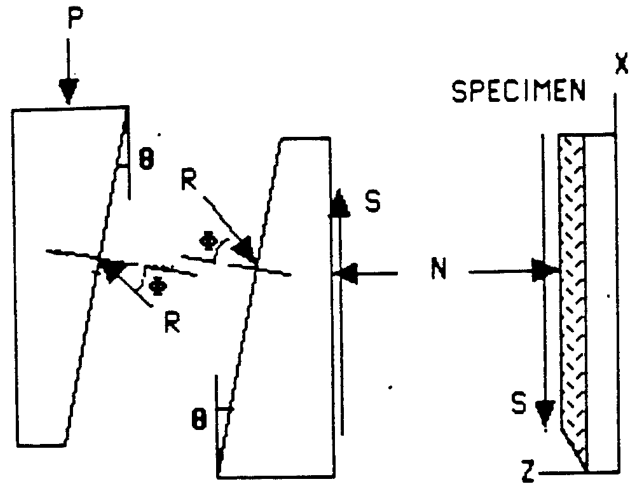


FREE-EDGE STRESSES





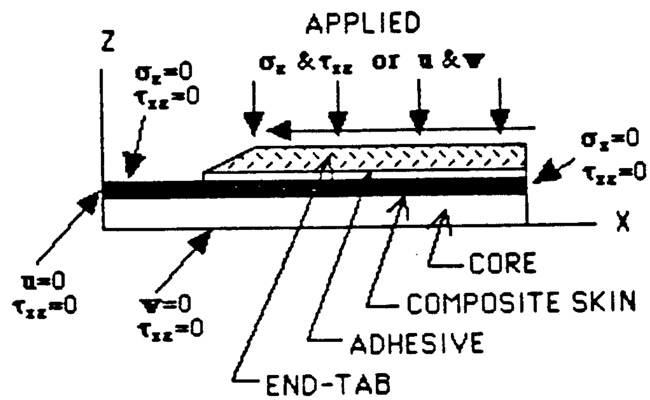




$$S = R \sin(\theta + \Phi) = P$$

$$N = R \cos(\theta + \Phi)$$

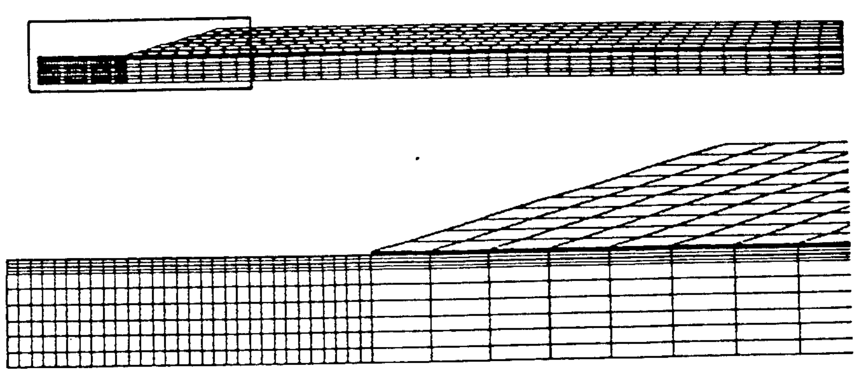
Free body diagram of the IITRI wedge grip and the sandwich specimen

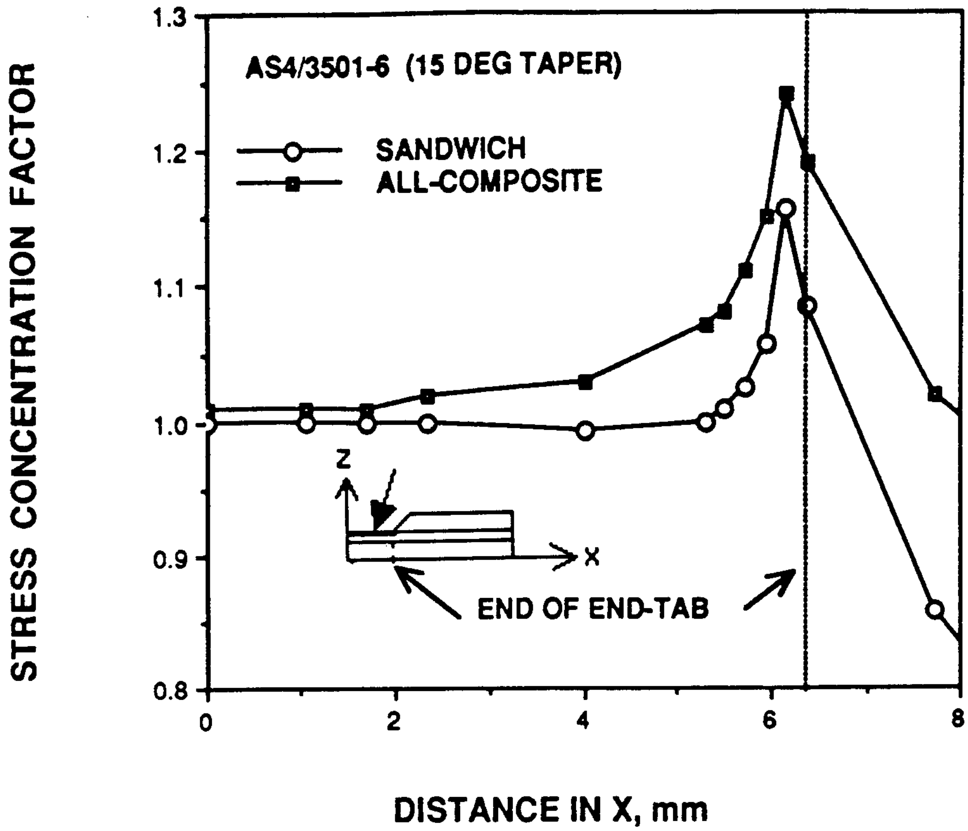


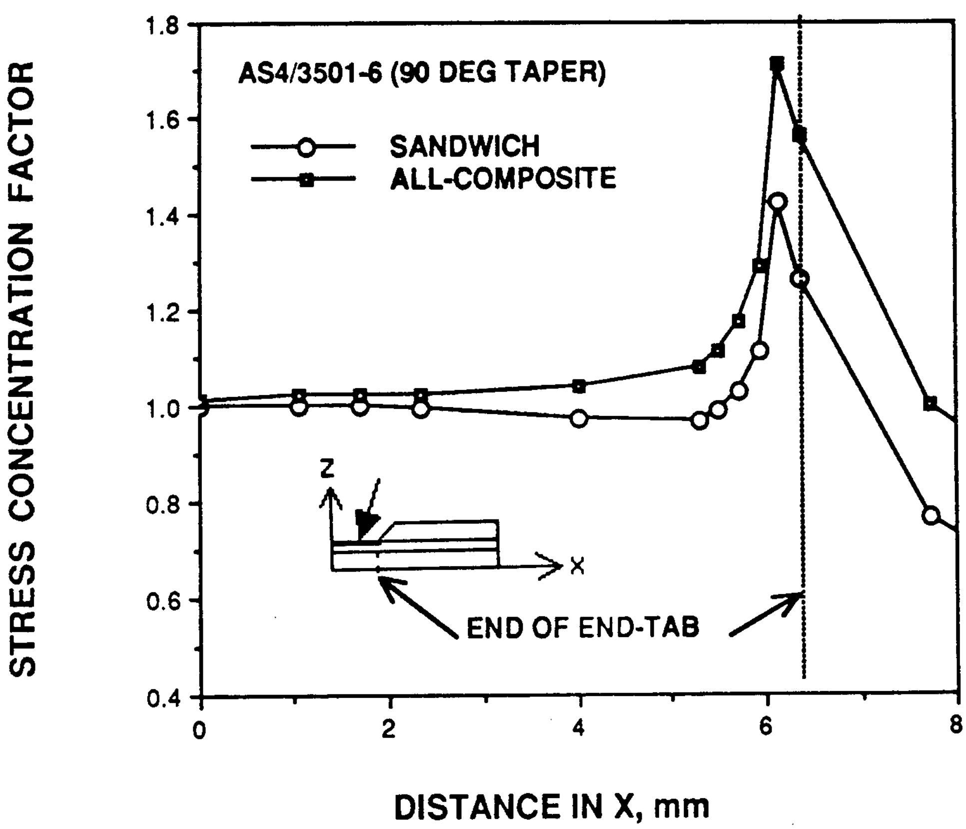
One-quarter of the sandwich specimen and boundary conditions

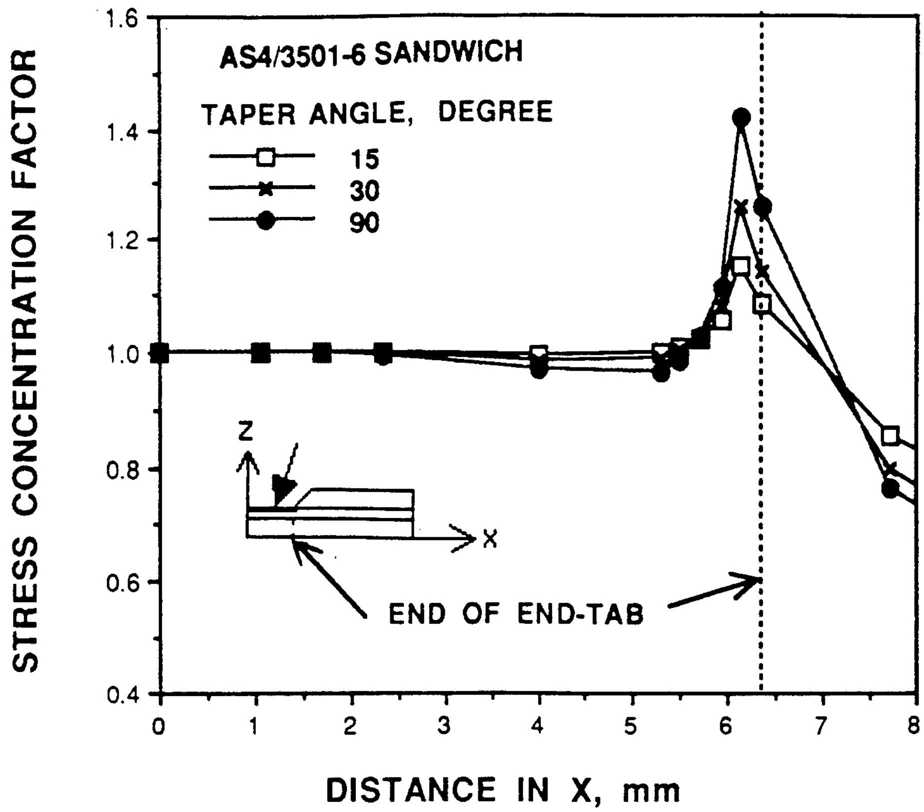
Finite element mesh

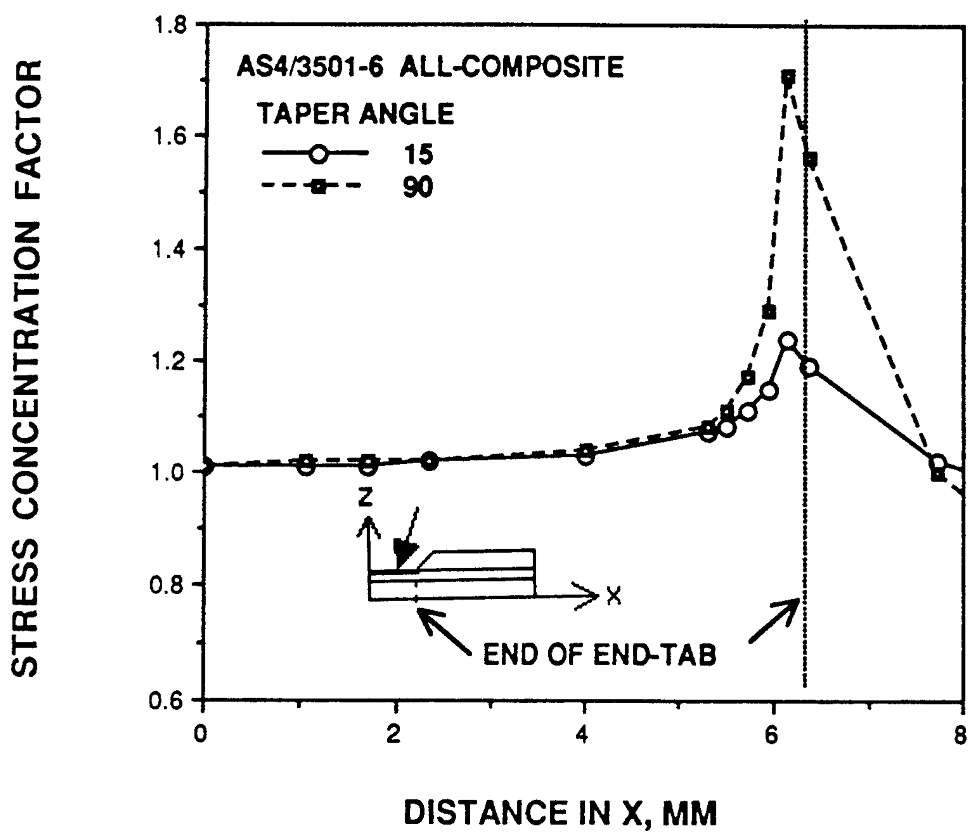
1285 ELEMENTS AND 1378 NODES

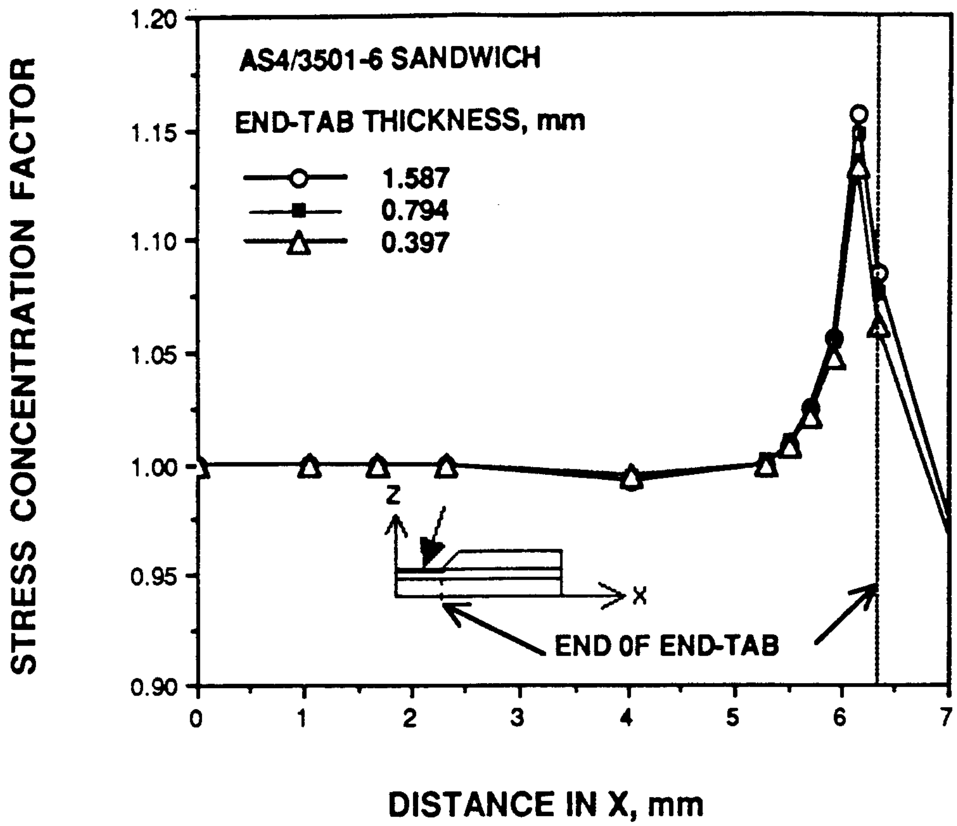


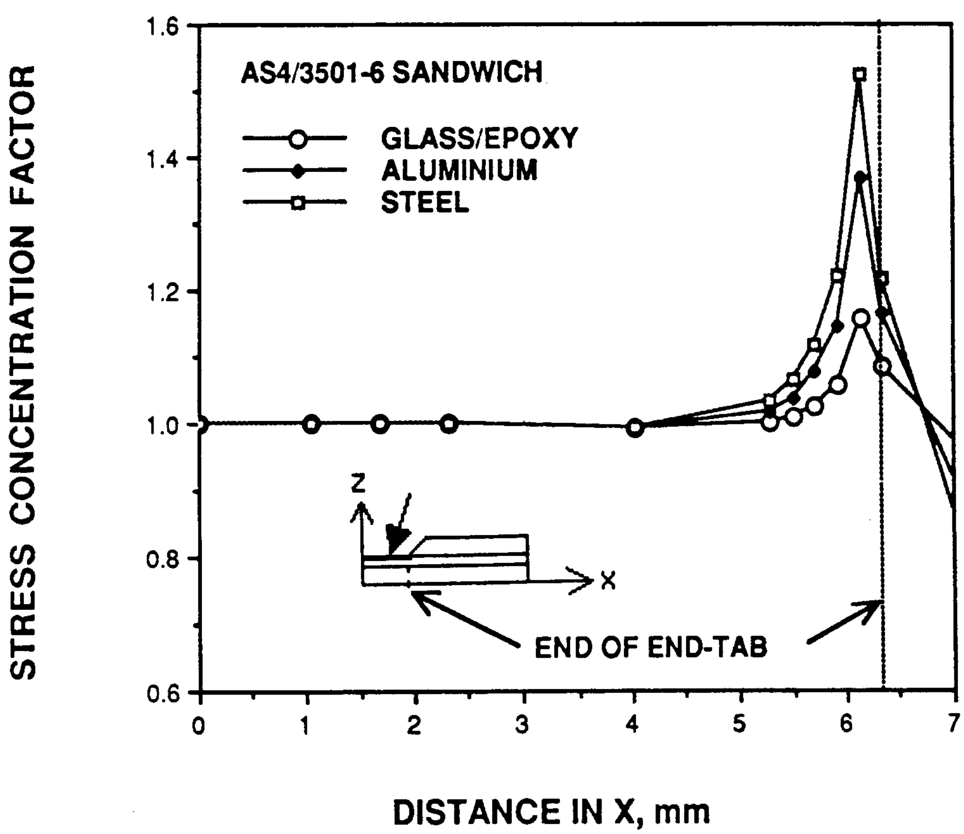

AS4/3501-6 (15 DEG TAPER)
SANDWICH
ALL-COMPOSITE
END OF END-TAB
STRESS CONCENTRATION FACTOR
DISTANCE IN X, mm
Z
X


AS4/3501-6 (90 DEG TAPER)
SANDWICH
ALL-COMPOSITE
END OF END-TAB
STRESS CONCENTRATION FACTOR
DISTANCE IN X, mm
Z
X


AS4/3501-6 SANDWICH
TAPER ANGLE, DEGREE
15
30
90
Z
X
END OF END-TAB
STRESS CONCENTRATION FACTOR
DISTANCE IN X, mm

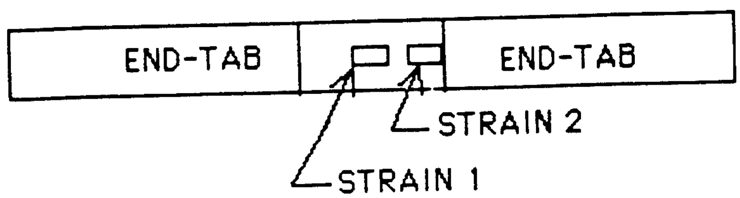

AS4/3501-6 ALL-COMPOSITE
TAPER ANGLE
15
90
Z
X
END OF END-TAB
STRESS CONCENTRATION FACTOR
DISTANCE IN X, MM


AS4/3501-6 SANDWICH
END-TAB THICKNESS, mm
1.587
0.794
0.397
END OF END-TAB
STRESS CONCENTRATION FACTOR
DISTANCE IN X, mm


AS4/3501-6 SANDWICH
GLASS/EPOXY
ALUMINIUM
STEEL
END OF END-TAB
STRESS CONCENTRATION FACTOR
DISTANCE IN X, mm

Stress concentration at end of end-tab
(1.587 mm thick glass/epoxy fabric end-tab)

Taper angle degree	Sandwich		All-composite	
	FEM	Experiment	FEM	Experiment
15	1.06	1.06	1.12	1.16
90	1.2	1.2	1.38	1.37



STRAIN GAGE LENGTH: 0.81 mm

SCF= STRAIN 2/STRAIN 1

CONCLUSIONS

- Significant reduction of stress concentration
- Elimination of specimen buckling
- Free-edge stresses are insignificant
- Optimization needs for improvement of specimen design

TORSION OF LAMINATED ORTHOTROPIC PLATES

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ABSTRACT

Torsion is a fundamental problem in engineering design and the exact solution for the case of homogeneous, isotropic bars and rectangular plates can be found in any textbook on classical theory of elasticity. Lekhnitskii [1] has extended the classical solution to the case of homogeneous bars and rectangular plates. A solution for the torsion of symmetric laminates containing layers with orthotropic properties relative the the plate axes has been presented by Kurtz and Whitney [2]. This solution has been extended to the case of unsymmetric laminates containing orthotropic layers [3].

In the current paper example problems are presented for both symmetric and unsymmetric laminates. A comparison is made between solutions generated from the exact elasticity analysis (ELAS) and two laminated plate theories incorporating transverse shear deformation. With the inclusion of shear deformation the twisting moment and transverse shear force resultant can be prescribed independently on the boundary. In classical laminated plate theory these two boundary conditions are replaced with the Kirchoff condition, leading to a membrane type solution in which the interlaminar shear stress vanishes. The two shear deformation theories differ in the manner in which the transverse shear constitutive relations are developed. In one case (SDT) these relations are developed directly from kinematic considerations in the usual manner [4] with shear correction factors being introduced. A modified shear deformation theory (MSDT) in which the transverse shear constitutive relations are developed from Reissner's principle [5] is also considered. This approach requires the use of an assumed through-the-thickness distribution of the transverse shear stresses. Example problems are based on an assumed parabolic interlaminar shear stress distribution in the same manner as in a homogeneous plate.

Numerical results are based on laminates constructed of graphite/epoxy unidirectional composites and homogeneous isotropic steel. Laminate geometry includes $[0°_{GR}/STEEL]_S$, $[0°_{GR}/STEEL]_T$, $[0°/90°]_S$, and $[0°/90°]_T$. The graphite/epoxy and steel layers provide a drastic difference in shear properties for comparison of the approximate theories with exact elasticity solutions, while the all graphite/epoxy composites represent state-of-the-art engineering laminates. Comparisons include distribution of the inplane shear stress, τ_{xy}, the interlaminar shear stress, τ_{xz}, and the relationship between torque and angle of twist. For the shear deformation laminated plate theories, the interlaminar shear stress distribution, τ_{xz}, is determined from integration of the first equation of equilibrium from classical theory of elasticity.

Accuracy of the shear deformation theories for predicting torque as a function of angle of twist depends on the plate width-to-thickness ratio, b/h. Excellent agreement between the approximate theories and the elasticity solution are obtained for the inplane shear stress

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distribution, τ_{xy}, while the accuracy of the interlaminar shear stress distribution, τ_{xz}, depends on the laminate. In particular, the approximate theories are much more accurate for the all graphite composite plates than for the hybrid graphite/steel laminates.

REFERENCES

1. S. G. Leknitskii, *Theory of Elasticity of an Anisotropic Body*, Mir Publishers, USSR, 1981.

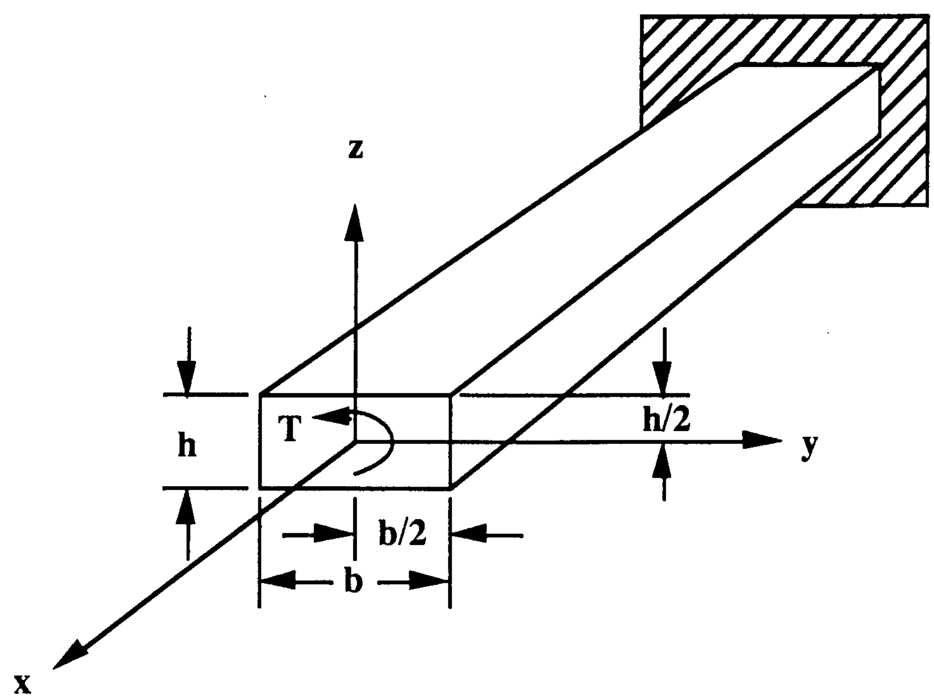
2. R. D. Kurtz and J. M. Whitney, Torsion of Laminates Containing Orthotropic Layers, *Proceedings of the American Society for Composites, Third Technical Conference*, Technomic Publishing Co., Lancaster, PA, 1988, pp. 115-124.

3. J. M. Whitney and R. D. Kurtz, "Exact Elasticity Solution for the Torsion of Rectangular Laminated Plates Containing Orthotropic Layers," in preparation.

4. J. M. Whitney and N. J. Pagano, "Shear Deformation in Heterogeneous Anisotropic Plates," *Journal of Applied Mechanics*, Vol. 37, 1970, pp. 1031-1036.

5. J. M. Whitney, "A Modified Shear Deformation Theory for Laminated Anisotropic Plates," *Proceedings of the American Society for Composites, Fiftj Technical Conference*, Technomic Publishing Co., Lancaster, PA, 1990, pp. 469-478.

NOMENCLATURE FOR TORSIONAL LOADING



NUMERICAL RESULTS

<u>Graphite/Epoxy</u>: $G_{LT} = G_{L3} = 0.8 \times 10^6$ PSI

$G_{T3} = 0.48 \times 10^6$ PSI

<u>Steel</u>: $G = 12 \times 10^6$ PSI

TORQUE VERSUS ANGLE OF TWIST

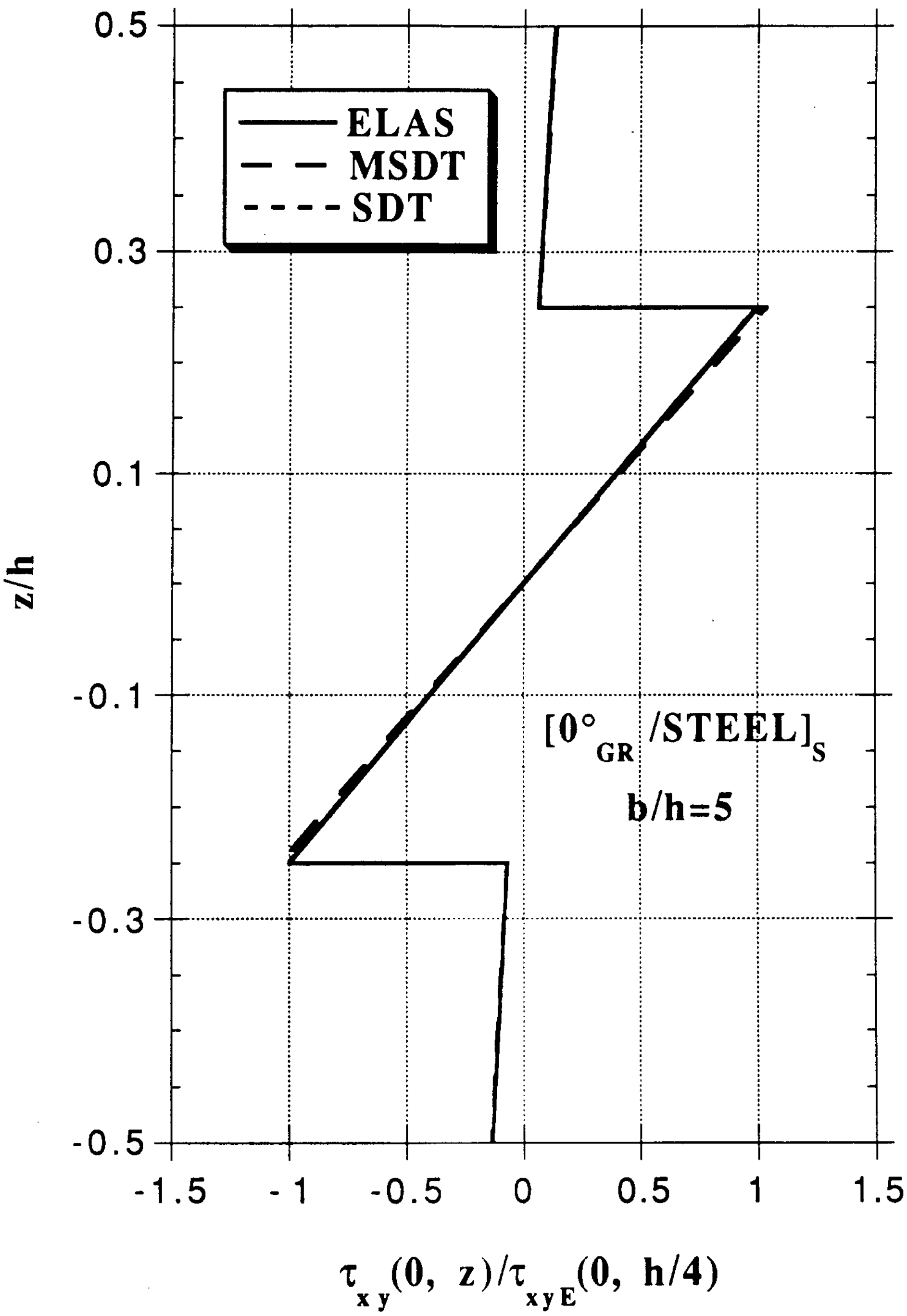
$$T = (K_E, K_{MSDT}, K_{SDT})\,\beta$$

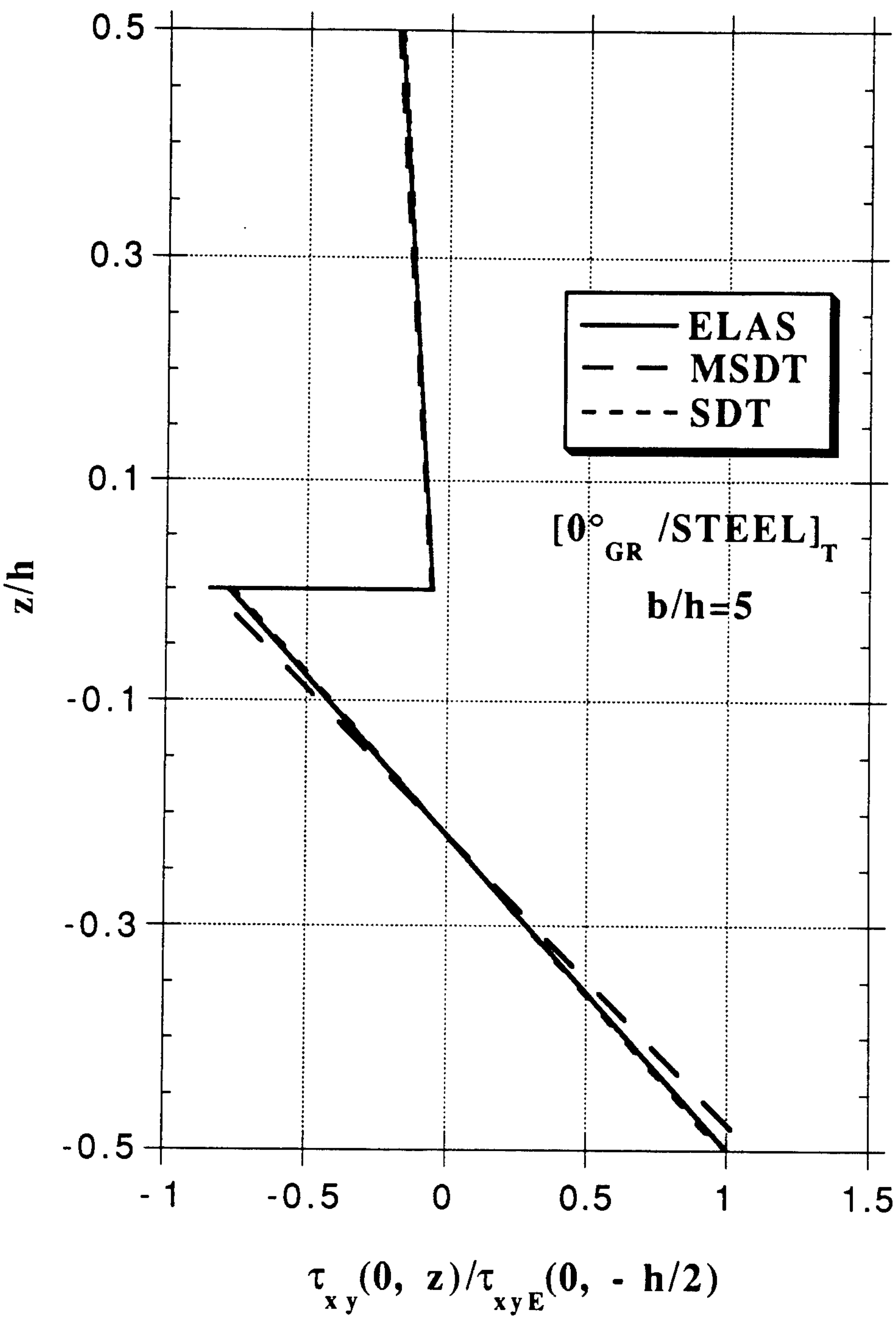
$$(K_{MSDT}, K_{SDT}) = 4bD_{66}^{*}\left(1 - \frac{2h}{\lambda b}\tanh \lambda \frac{b}{2h}\right)$$

$$D_{66}^{*} = \left(D_{66} - \frac{B_{26}^{2}}{A_{66}}\right),\quad \lambda(MSDT) = h\sqrt{\frac{F_{55}}{D_{66}^{*}}},\ \lambda(SDT) = h\sqrt{\frac{kA_{55}}{D_{66}^{*}}}$$

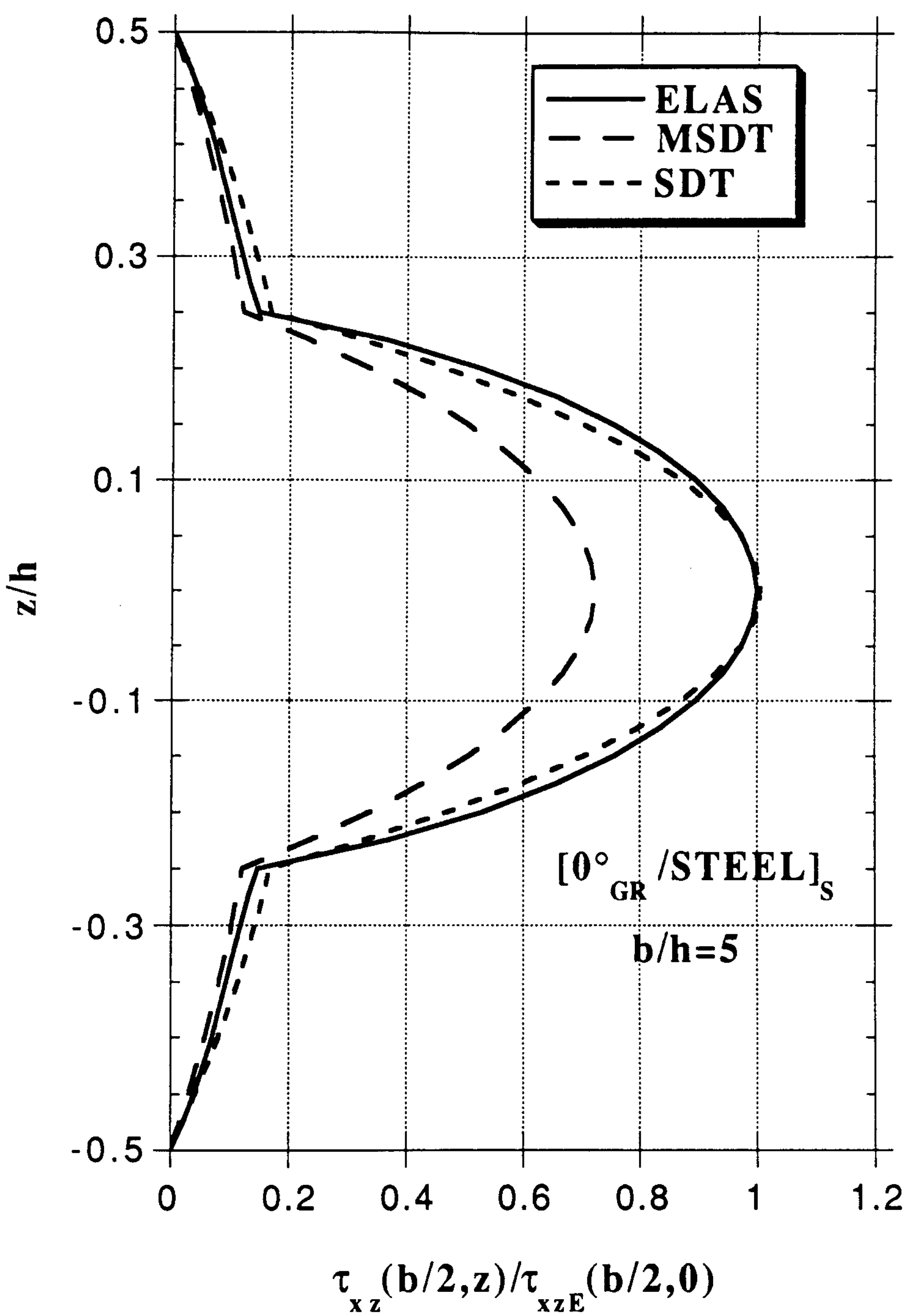
TORQUE FACTOR, K x 10^{-6}

LAMINATE	b/h	K_E	K_{MSTD}	K_{SDT}
$[0°_{GR}$ /STEEL$]_S$	5	3.396	3.275	3.395
	10	7.063	6.935	7.061
$[0°_{GR}$ /STEEL$]_T$	5	4.098	3.767	4.167
	10	8.639	8.310	8.709
$[0°/90°]_S$	5	1.127	1.075	1.093
	10	2.460	2.459	2.479
$[0°/90°]_T$	5	1.140	1.139	1.093
	10	2.474	2.473	2.479

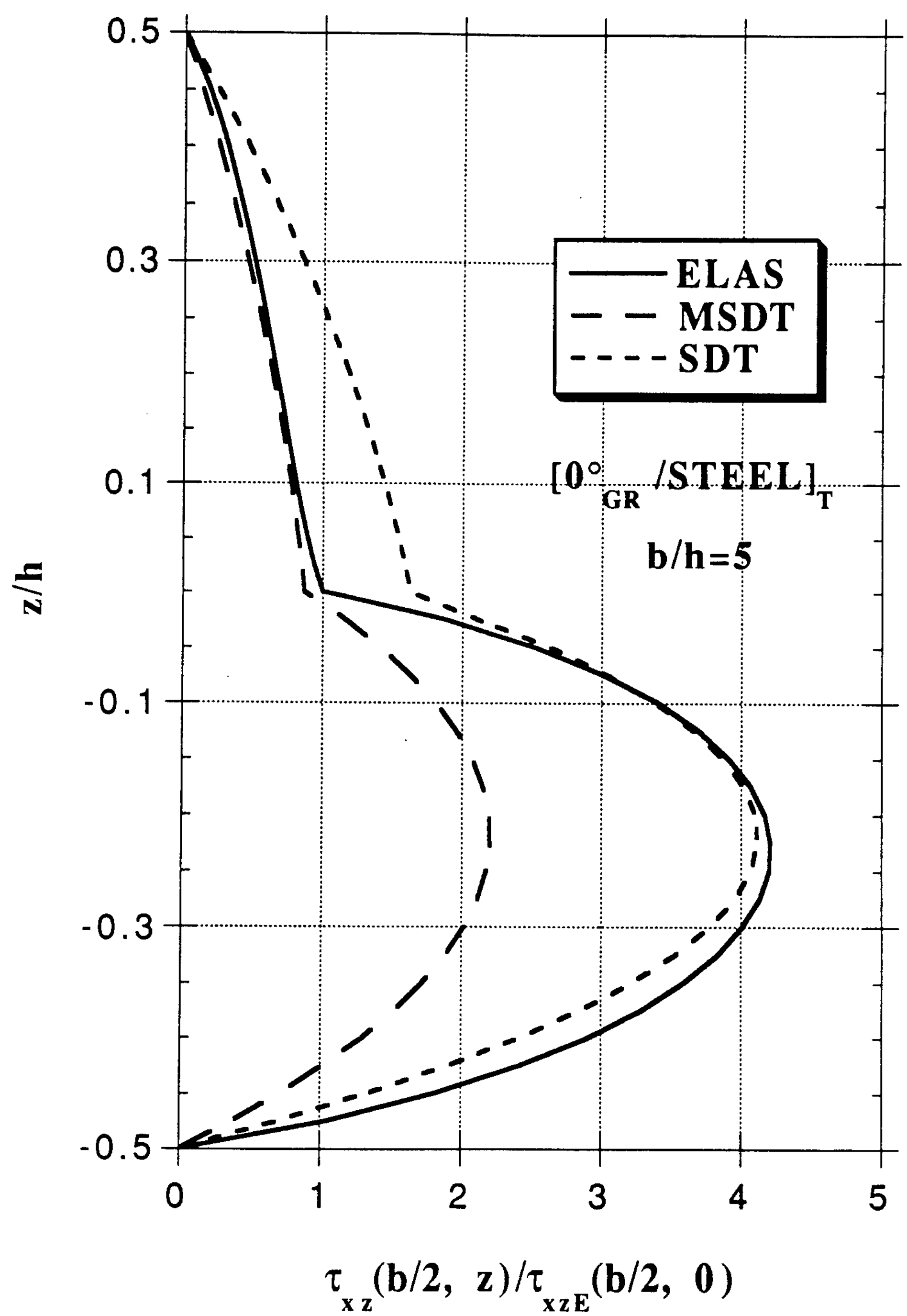

ELAS
MSDT
SDT
0.5
0.3
0.1
-0.1
-0.3
-0.5
z/h
[0°$_{GR}$ /STEEL]$_S$
b/h=5
-1.5
-1
-0.5
0
0.5
1
1.5
$\tau_{xy}(0, z)/\tau_{xyE}(0, h/4)$



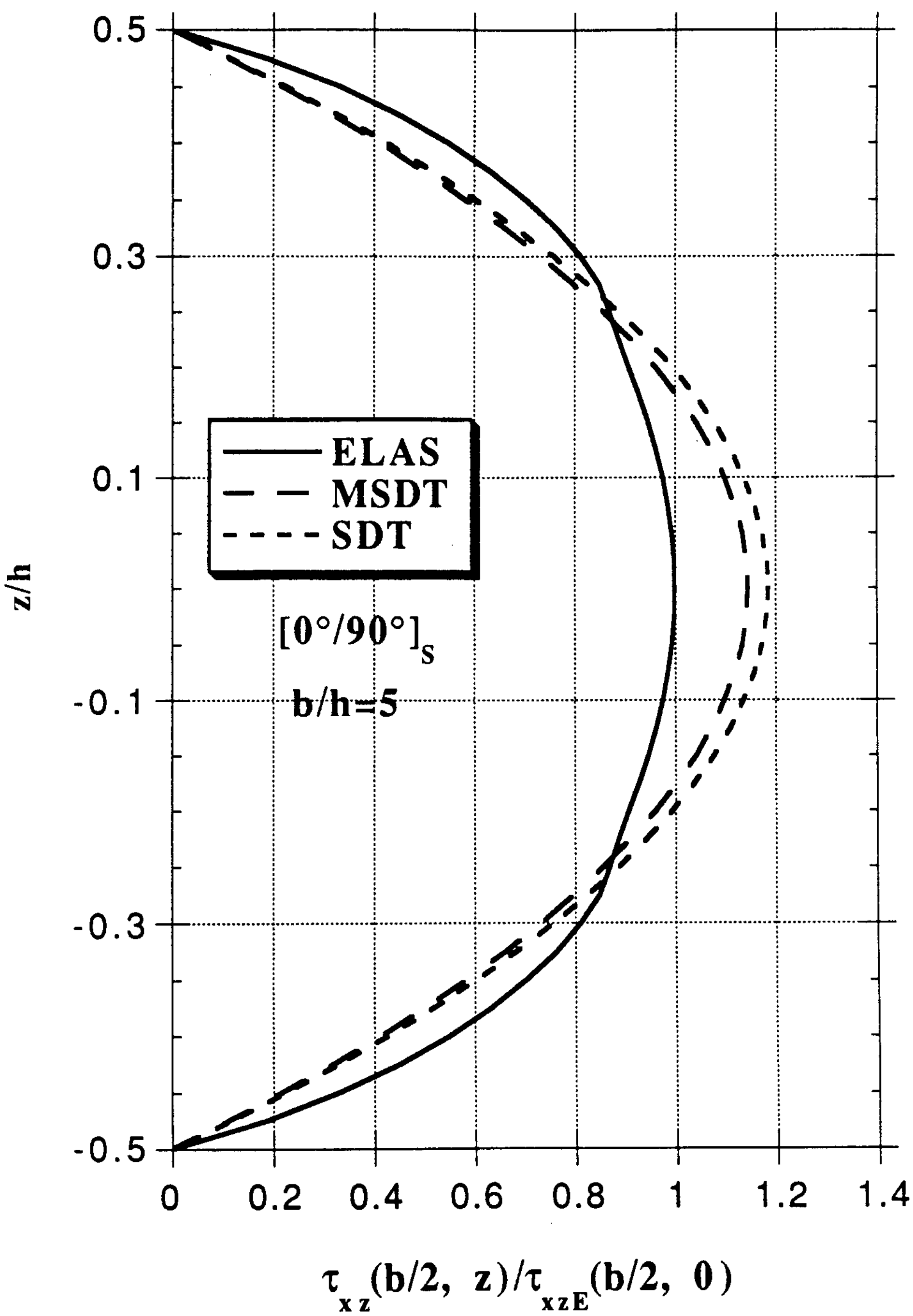
0.5
0.3
0.1
-0.1
-0.3
-0.5
z/h
-1
-0.5
0
0.5
1
1.5
ELAS
MSDT
SDT
[0°GR /STEEL]T
b/h=5
τxy(0, z)/τxyE(0, - h/2)

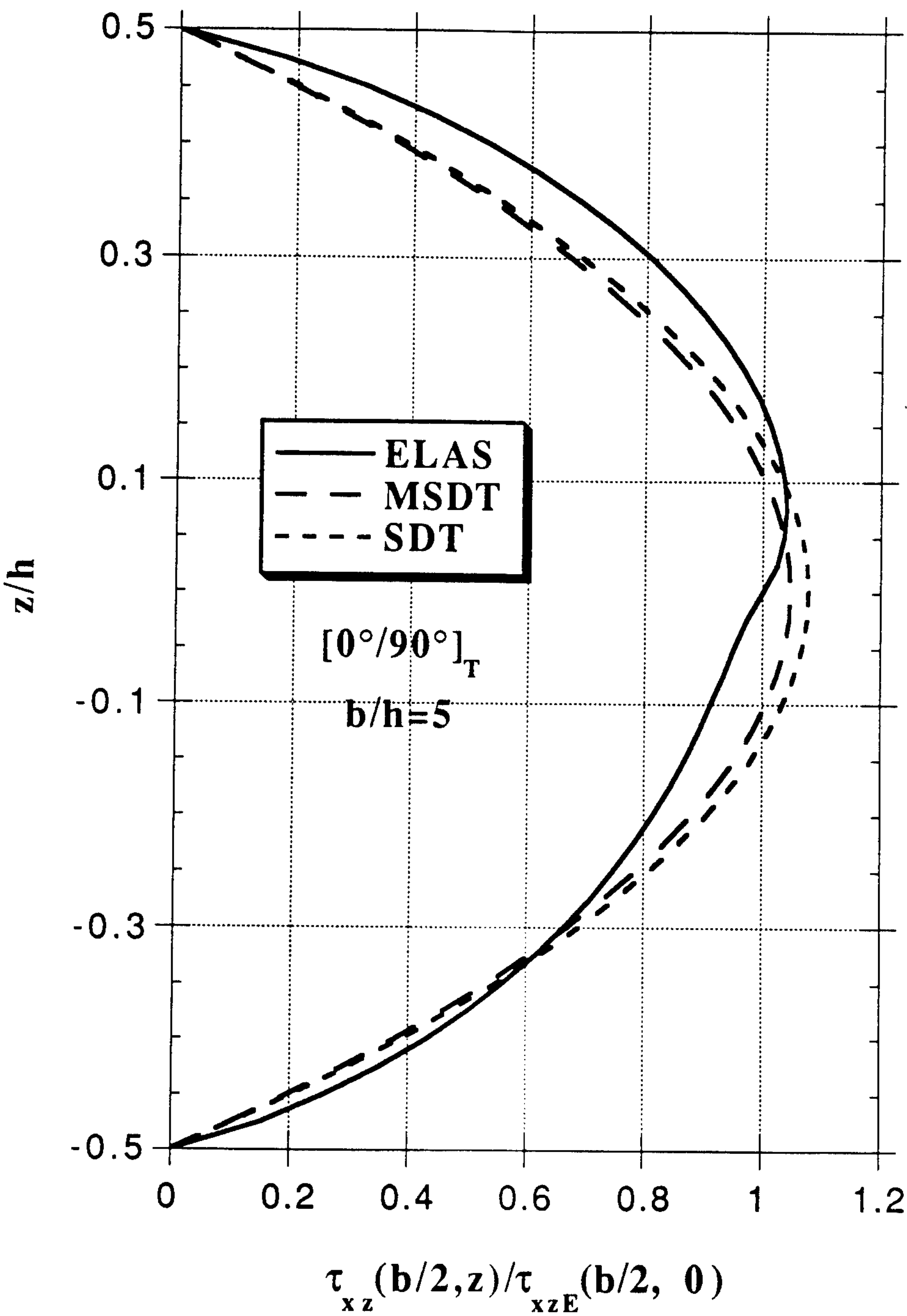


ELAS
MSDT
SDT
[0°$_{GR}$ /STEEL]$_S$
b/h=5
z/h
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
0.2
0.4
0.6
0.8
1
1.2
$\tau_{xz}(b/2,z)/\tau_{xzE}(b/2,0)$



ELAS
MSDT
SDT
[0°GR/STEEL]T
b/h=5
z/h
0.5
0.3
0.1
-0.1
-0.3
-0.5
0
1
2
3
4
5
τxz(b/2, z)/τxzE(b/2, 0)


0.5
0.3
0.1
-0.1
-0.3
-0.5
z/h
0
0.2
0.4
0.6
0.8
1
1.2
1.4
ELAS
MSDT
SDT
[0°/90°]S
b/h=5
τxz(b/2, z)/τxzE(b/2, 0)



0.5
0.3
0.1
-0.1
-0.3
-0.5
z/h
0
0.2
0.4
0.6
0.8
1
1.2
ELAS
MSDT
SDT
[0°/90°]T
b/h=5
τxz(b/2,z)/τxzE(b/2, 0)

Failure Prediction in Composite Shell Structures*

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Two important issues associated with structural integrity of composite shells are the prediction of the conditions for the loss of stability and the question of accurately assessing the influence of defects such as delaminations on the compressive response of the structure.

In the first part of this review, the phenomenon of delamination buckling is modelled as a first approximation by considering a two-dimensional geometry (ring approximation) and a thin delaminated layer. Growth is studied by a fracture mechanics-based energy release rate criterion. Closed form expressions for the critical pressure and growth conditions are derived, as well as for the cutoff level of the delamination range below which delamination buckling cannot take place.

The second part presents an exact elasticity solution to the problem of buckling of thick composite cylindrical orthotropic shells subjected to external pressure. The results will show that the shell theory predictions can produce highly non-conservative results on the critical load of composite shells with moderately thick construction.

Modelling of Delamination Buckling in Laminated Cylindrical Shells.

The delamination is symmetrically located over the range $-\theta_0 < \theta < \theta_0$. Over this region, the structure consists of the part above the delamination, of thickness h_I, referred to as the part I, and the part below the delamination, of thickness h_{II} referred to as the part II. The remaining part of the structure which is intact and of thickness h_s is referred to as the "base shell" and the subscript "s" is used.

Denote by $w_i(\theta)$ the radial, $v_i(\theta)$ the circumferential displacements of the mid-surface of each part. The pre-buckling state of uniform external compression p is characterized by the displacement field:

$$v_i^0(\theta) = 0 \;, \quad w_i^0(\theta) = w_0 = -\frac{R^2 p(1-\nu_{12}\nu_{21})}{E_2 h_s} \;; \;\; \beta_i^0(\theta) = 0 \;, \qquad i = I, II, s$$

The post-buckled shape of the film is now represented by the displacement field (where the superscript "a" represents the additional (to the pre-buckled state) quantities:

$$w_I^a(\theta) = A\cos\frac{\pi}{\theta_0}\theta \;: \qquad v_I^a(\theta) = B\sin\frac{\pi}{\theta_0}\theta \;.$$

Since the postbuckled shape is a perturbation of the pre-buckling state, the additional quantities are of first order (can be infinitesimally close to the initial state). Therefore, substituting the expressions for the resultant force and moment into the nonlinear differential equations of equilibrium (nonlinear Donnell shell theory) and retaining first order terms we can finally obtain the critical pressure:

$$p_{cr} = \frac{E_2}{12(1-\nu_{12}\nu_{21})}\frac{h_I^2 h_s}{R^3}\left(\frac{\pi^2}{\theta_0^2} - 1\right) \;.$$

* Sponsored by the Office of Naval Research, Mechanics Division, Grant Monitor: Dr. Y. Rajapakse

Since the incremental delamination growth is $Rd\theta_0$, the energy release rate is $G = -d\Pi/(Rd\theta_0)$ where Π is the total potential energy and can be obtained from the previous solution in a closed form.

Depending on the delamination size and location through the thickness, local buckling of the delaminated layer may not always occur before buckling of the entire shell. The cutoff angle θ_{0c} below which delamination buckling does not occur is found to be:

$$\theta_{0c} = \frac{\pi h_I}{\sqrt{3h_s^2 + h_I^2}}$$

Buckling of Thick Orthotropic Cylindrical Shells Under External Pressure.

The equations of equilibrium are taken in terms of the second Piola-Kirchhoff stress tensor $\mathbf{\Sigma}$ the form

$$\operatorname{div}\left(\mathbf{\Sigma}.\mathbf{F}^{\mathbf{T}}\right) = 0 \ ,$$

where $\mathbf{F}$ is the deformation gradient defined by

$$\mathbf{F} = \mathbf{I} + \operatorname{grad}\vec{V} \ ,$$

where $\vec{V}$ is the displacement vector and $\mathbf{I}$ is the identity tensor. The strain tensor is defined by

$$\mathbf{E} = \frac{1}{2}\left(\mathbf{F}^{\mathbf{T}}.\mathbf{F} - \mathbf{I}\right) \ .$$

From the above expressions, with appropriate order of magnitude arguments, the buckling equations can be obtained.

The boundary conditions can be expressed as:

$$\left(\mathbf{F}.\mathbf{\Sigma}^{\mathbf{T}}\right).\hat{n} = \vec{t}(\vec{V}) \ ,$$

where $\vec{t}$ is the traction vector on the surface which has outward unit normal $\hat{n}$ before any deformation. The traction vector $\vec{t}$ depends on the displacement field $\vec{V}$. Indeed, because of the hydrostatic pressure loading, the magnitude of the surface load remains invariant under deformation, but its direction changes (since hydrostatic pressure is always directed along the normal to the surface on which it acts).

The problem at hands is that of a hollow cylinder rigidly fixed at its end and deformed by uniformly distributed external pressure p. For such a case, the stress field can be found from Lekhnitskii. Integration of the above stress field through linear strain-displacement relations gives the pre-buckling state of deformation.

In the petrurbed position we seek plane equilibrium modes as follows:

$$u_1(r,\theta) = A_n(r)\cos n\theta \ ; \quad v_1(r,\theta) = B_n(r)\sin n\theta \ ; \quad w_1(r,\theta) = 0 \ .$$

In this manner an eigenvalue problem is formed, which can be solved for the critical pressure.

It is seen that the buckling load predicted by shell theory is 35% higher than the exact solution for $R_2/R_1 = 1.3$ and is more than two times the exact solution for $R_2/R_1 = 1.7$. Therefore, this exact three-dimensional elasticity solution can be used to assess the limitations of shell theories in predicting loss of stability when the applications involve composites with moderately thick construction.

Delamination Buckling in Composite Shells

- pre-buckling state

$$v_i^0(\theta) = 0 \ , \qquad w_i^0(\theta) = w_0 = -\frac{R^2 p(1-\nu_{12}\nu_{21})}{E_2 h_s} \ ; \quad \beta_i^0(\theta) = 0 \ , \qquad i = I, II, s$$

$$\beta_i = \frac{1}{R}(v_i - w_{i,\theta})$$

- displacements

$$w_i = w_i^0 + w_i^a \ ; \qquad v_i = v_i^0 + v_i^a$$

- post-buckled shape ("a" = additional quantities):

$$w_I^a(\theta) = A\cos\frac{\pi}{\theta_0}\theta \ ; \qquad v_I^a(\theta) = B\sin\frac{\pi}{\theta_0}\theta$$

Delamination Buckling , Cont.

- retaining first order terms in nonlinear Donnell shell theory

$$w^a_{,\theta} + v^a_{,\theta\theta} + \frac{h_i^2}{12R^2}\left(v^a_{,\theta\theta} - w^a_{,\theta\theta\theta}\right) = 0$$

$$\frac{h_i^2}{12R^2}\left(v^a_{,\theta\theta\theta} - w^a_{,\theta\theta\theta\theta}\right) - \left(w^a + v^a_{,\theta}\right) - \frac{w_0}{R}\left(v^a_{,\theta} - w^a_{,\theta\theta}\right) = 0$$

- "eigenvector"

$$A = -B\left(1 + \frac{h_I^2}{12R^2}\right)\frac{\pi}{\theta_0} \Big/ \left(1 + \frac{h_I^2}{12R^2}\frac{\pi^2}{\theta_0^2}\right)$$

- critical pressure ("eigenvalue"):

$$p_{cr} = \frac{E_2}{12(1-\nu_{12}\nu_{21})}\frac{h_I^2 h_s}{R^3}\left(\frac{\pi^2}{\theta_0^2} - 1\right)$$

Delamination Buckling , Cont.

- strain energy

$$U_I = \frac{(1-\nu_{12}\nu_{21})}{2Eh_I}\int_{-\theta_0}^{\theta_0} T_{\theta\theta}^2(\theta)R_I d\theta + \frac{12(1-\nu_{12}\nu_{21})}{2Eh_I^3}\int_{-\theta_0}^{\theta_0} M_{\theta\theta}^2(\theta)R_I d\theta$$

- energy release rate

$$G = -\frac{1}{R}\frac{d\Pi}{d\theta_0}$$

- Set

$$t_i = \frac{h_i^2}{12R^2} \qquad i = I, II, s$$

- energy release rate

$$G = \frac{Eh_I}{2(1-\nu_{12}\nu_{21})R^2}A^2\left[\frac{t_I}{1+t_I}\left(\frac{\pi^2}{\theta_0^2}-1\right)\left(1+3\frac{\pi^2}{\theta_0^2}\right)+2\right]$$

Delamination Buckling , Cont.

- cutoff angle θ_{0c} below which delamination buckling does not occur

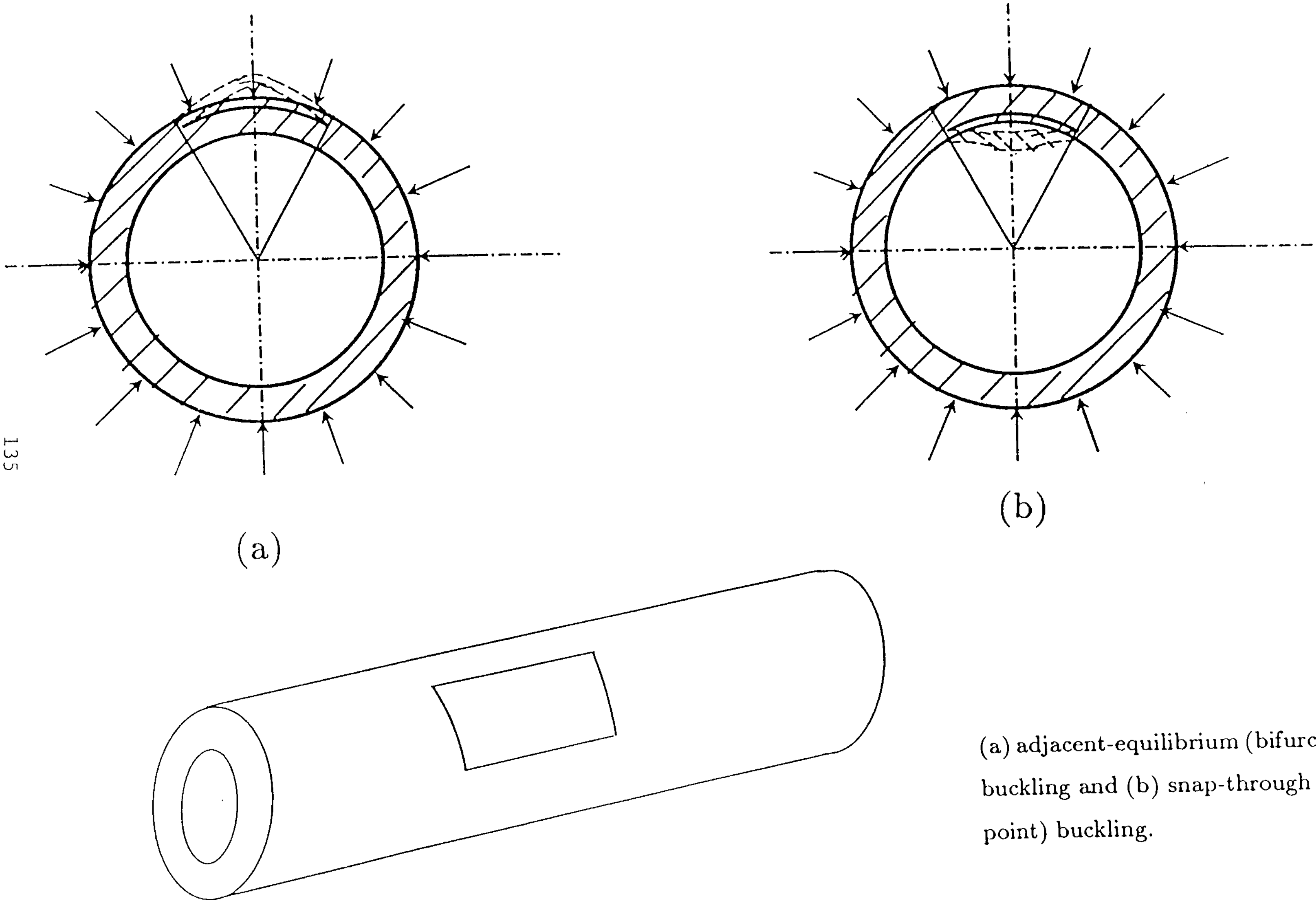
$$\theta_{0c} = \frac{\pi h_I}{\sqrt{3h_s^2 + h_I^2}}$$

- Transverse Shear Effects by first order shear deformation theory:

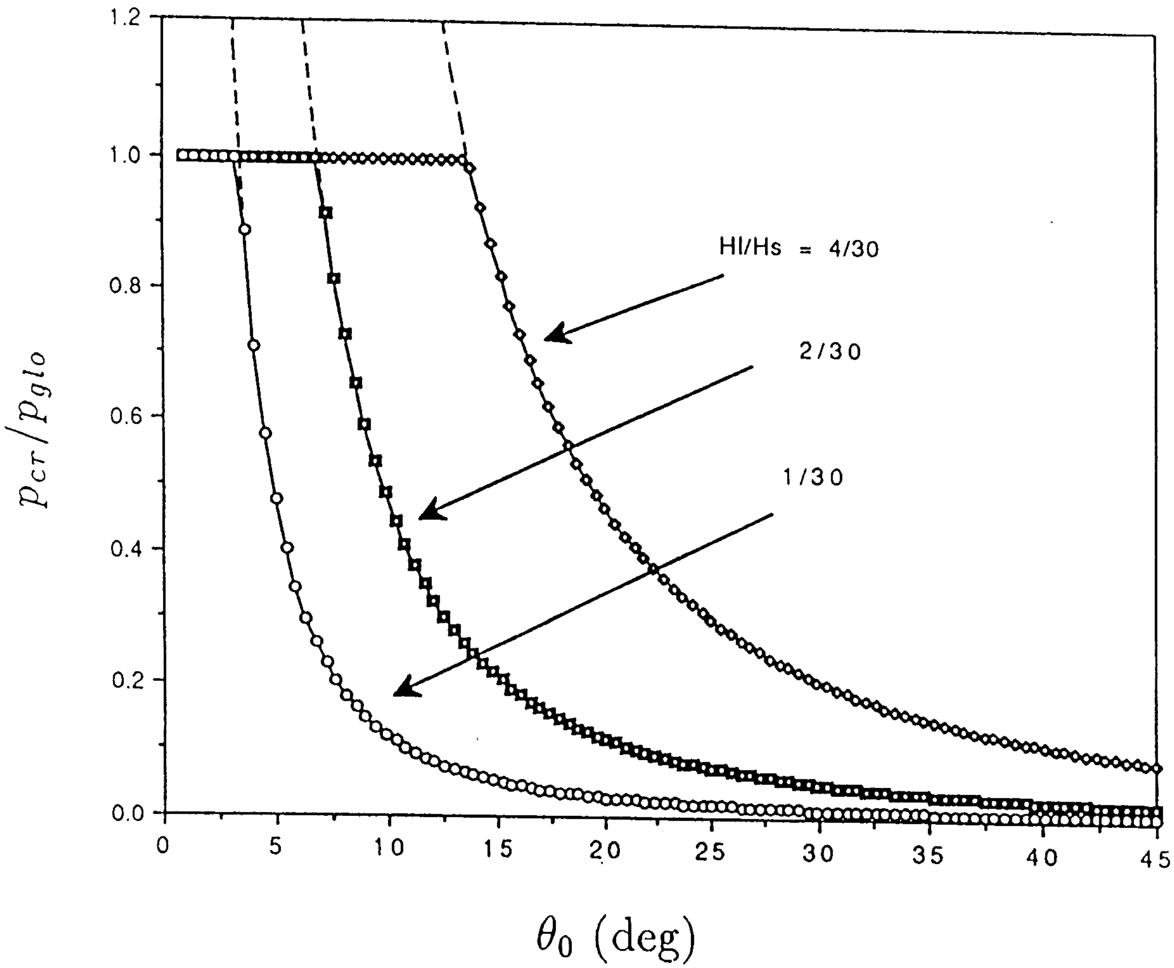
$$p_{cr} = -\frac{E_2 h_s}{(1-\nu_{12}\nu_{21})Rh_I}\left(\frac{\pi^2}{\theta_0^2}-1\right)\left(1-\frac{h_I^2}{4R^2}\right)\frac{(h_I - Rq)}{\left[1-\frac{E_2\pi^2}{G_{12}(1-\nu_{12}\nu_{21})\theta_0^2 Rq}(h_I - Rq)\right]}$$

where

$$q = \ln\frac{R + h_I/2}{R - h_I/2}$$



(a) adjacent-equilibrium (bifurcational) buckling and (b) snap-through (limit point) buckling.



Delamination buckling pressure versus delamination size θ_0 (angular range of the delamination: $|\theta| < \theta_0$) for several values of delamination depth over shell thickness h_I/h_s; p_{glo} is the (global) buckling load for the entire shell.

Stability Loss in Thick Composite Shells

- primary position u_0, v_0, w_0
- perturbed position

$$u = u_0 + \alpha u_1 \ ; \qquad v = v_0 + \alpha v_1 \ ; \qquad w = w_0 + \alpha w_1$$

- nonlinear strain displacement equations, e.g.:

$$\epsilon_{rr} = \frac{\partial u}{\partial r} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial r}\right)^2 + \left(\frac{\partial v}{\partial r}\right)^2 + \left(\frac{\partial w}{\partial r}\right)^2\right]$$

- strain components in the perturbed configuration, e.g.

$$\epsilon_{rr} = \epsilon^0_{rr} + \alpha\epsilon'_{rr} + \alpha^2\epsilon''_{rr} \qquad \gamma_{r\theta} = \gamma^0_{r\theta} + \alpha\gamma'_{r\theta} + \alpha^2\gamma''_{r\theta}$$

Buckling of Thick Composite Shells, Cont.

- stress-strain relations

$$\begin{bmatrix} \sigma_{rr} \\ \sigma_{\theta\theta} \\ \sigma_{zz} \\ \tau_{\theta z} \\ \tau_{rz} \\ \tau_{r\theta} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{bmatrix} \begin{bmatrix} \epsilon_{rr} \\ \epsilon_{\theta\theta} \\ \epsilon_{zz} \\ \gamma_{\theta z} \\ \gamma_{rz} \\ \gamma_{r\theta} \end{bmatrix}$$

- stresses, e.g.

$$\sigma_{rr} = \sigma^0_{rr} + \alpha\sigma'_{rr} + \alpha^2\sigma''_{rr} \qquad \tau_{r\theta} = \tau^0_{r\theta} + \alpha\tau'_{r\theta} + \alpha^2\tau''_{r\theta}$$

$$\sigma_{\theta\theta} = \sigma^0_{\theta\theta} + \alpha\sigma'_{\theta\theta} + \alpha^2\epsilon''_{\theta\theta} \qquad \tau_{rz} = \tau^0_{rz} + \alpha\tau'_{rz} + \alpha^2\tau''_{rz}$$

Buckling of Thick Composite Shells, Cont.

- equations of equilibrium in terms of the second Piola-Kirchhoff stress tensor Σ

$$\text{div}\left(\mathbf{\Sigma}.\mathbf{F}^{\mathbf{T}}\right) = 0$$

- F is the deformation gradient

$$\mathbf{F} = \mathbf{I} + \text{grad}\vec{V}$$

where $\vec{V}$ is the displacement vector and I is the identity tensor.

- strain tensor

$$\mathbf{E} = \frac{1}{2}\left(\mathbf{F}^{\mathbf{T}}.\mathbf{F} - \mathbf{I}\right)$$

Buckling of Thick Composite Shells, Cont.

- boundary conditions

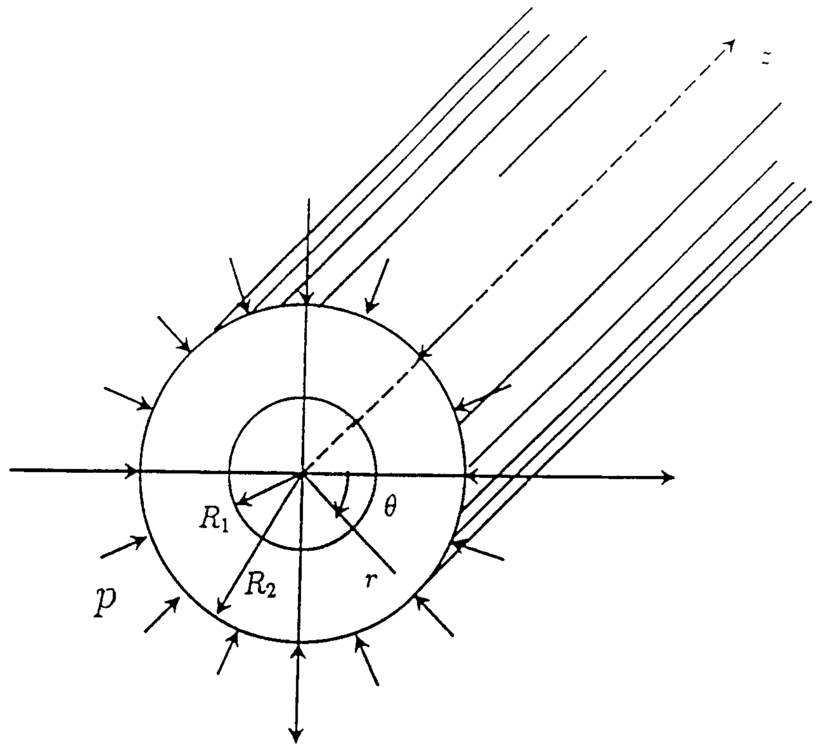
$$\left(\mathbf{F}.\mathbf{\Sigma}^{\mathbf{T}}\right).\hat{n} = \vec{t}(\vec{V})$$

- $\vec{t}$ is the traction vector on the surface which has outward unit normal $\hat{n} = (l, m, n)$ before any deformation
- Pre-buckling State

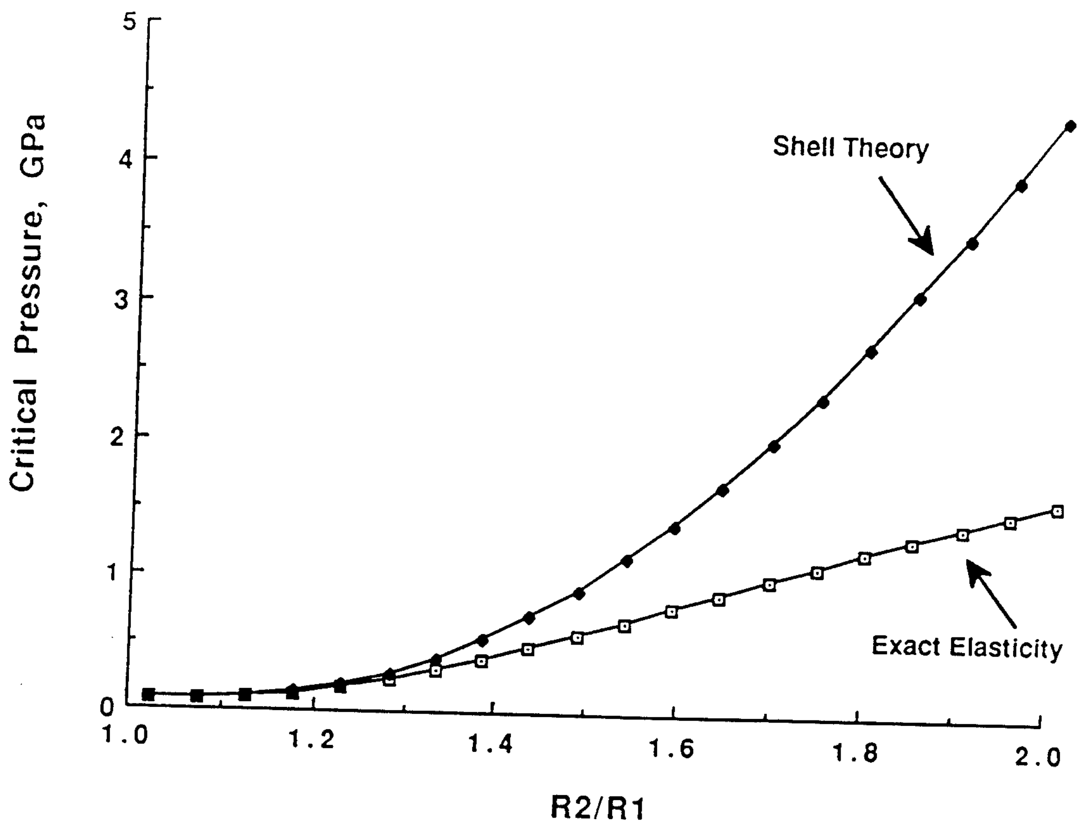
$$u_0(r) = C_1 p r^k + C_2 p r^{-k} \ , \qquad v_0 = w_0 = 0$$

- Perturbed State / equilibrium modes

$$u_1(r,\theta) = A_n(r)\cos n\theta \ ; \qquad v_1(r,\theta) = B_n(r)\sin n\theta \ ; \qquad w_1(r,\theta) = 0$$



Cylindrical shell under external pressure



Critical pressure, p_{cr} vs ratio of outside/inside radius, R_2/R_1. Comparison of the exact three-dimensional elasticity and the shell theory predictions.

EDGE EFFECTS, SHEAR TESTS, MICROSCOPIC DISPLACEMENT FIELDS

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Edge effects in thick laminates were investigated on a ply-by-ply basis along straight boundaries and curved boundaries at holes. Figure 1 illustrates results from moire interferometry measurements, i.e., measurements of in-plane U and V displacements; the ply-by-ply deformations are clearly delineated. The symbols indicate 90°, 0°, +45° and –45° fiber directions. Large transverse tensile strains occur in 45° plies and very large interlaminar shears occur between +45° and –45° plies [1]. An extensive series of tests on laminated plates with central holes is reported in Figs. 2–7. Figure 4 shows that the strains are essentially the same along the straight boundaries for specimens with and without holes. Accordingly, the strains at straight boundaries that are used as normalizing factors represent both cases. Figure 5 shows that tangential strains at the hole differ dramatically from the corresponding strains at the straight boundary, both in magnitude and distribution. Amplification by the hole reaches a factor of 7.5 for the cross-ply laminate. Figure 6 shows that the transverse strains are markedly different at the curved and straight boundaries, both in magnitude and distribution. The results are reasonably systematic, but exceptions are attributed to variations of properties of nominally equivalent plies. Figure 7 is an example depicting extraordinarily rapid changes of interlaminar shear strains with angle θ around the hole. Additional results, including strains at $\theta = 0°$ and 45°, are presented in Ref. [2].

Figures 8–10 illustrate (a) a new electrical resistance strain gage for measuring the average of the shear strains occurring in the entire test zone of a shear specimen, and (b) a compact specimen geometry with special attributes. Both developments are intended to improve the reliability and ease of measurements to determine shear stress–strain properties of composites[3].

Figures 11–15 describe and demonstrate a special capability for micromechanics measurements. Within a small field of view, the relative displacements are small even when the strains are not small. Thus, greater sensitivity is required to produce enough contour lines for a reliable analysis. Enhanced sensitivity and a contour interval of 17nm per fringe contour has been achieved with the system of Fig. 11 and the fringe multiplication scheme outlined in Fig. 12[4]. The method is applied to interlaminar compression in Fig. 13, which reveals an extremely strong ϵ_y strain gradient across the interface region of a cross-ply composite. In Fig. 14 the method is applied to a silicon-carbide/aluminum cross-ply specimen in interlaminar compression. The distribution of plastic deformation in the aluminum matrix is clearly identified. Figure 15 illustrates the method applied to the measurement of thermal strains in a microelectronic subassembly. The results show the beneficial effect of the epoxy binder which drastically reduces shear strains that otherwise would be induced in the solder balls. The microscopic moire interferometry technique offers promise for diverse micromechanics applications.

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[3] P. Ifju and D. Post, "A Special Strain Gage for Shear Testing of Composite Materials," *Proc. SEM Spring Conference on Experimental Mechanics*, Milwaukee (1991).

[4] B. Han, "Higher Sensitivity Moire Interferometry for Micromechanics Studies," *Optical Engineering* (submitted Aug. 1991)

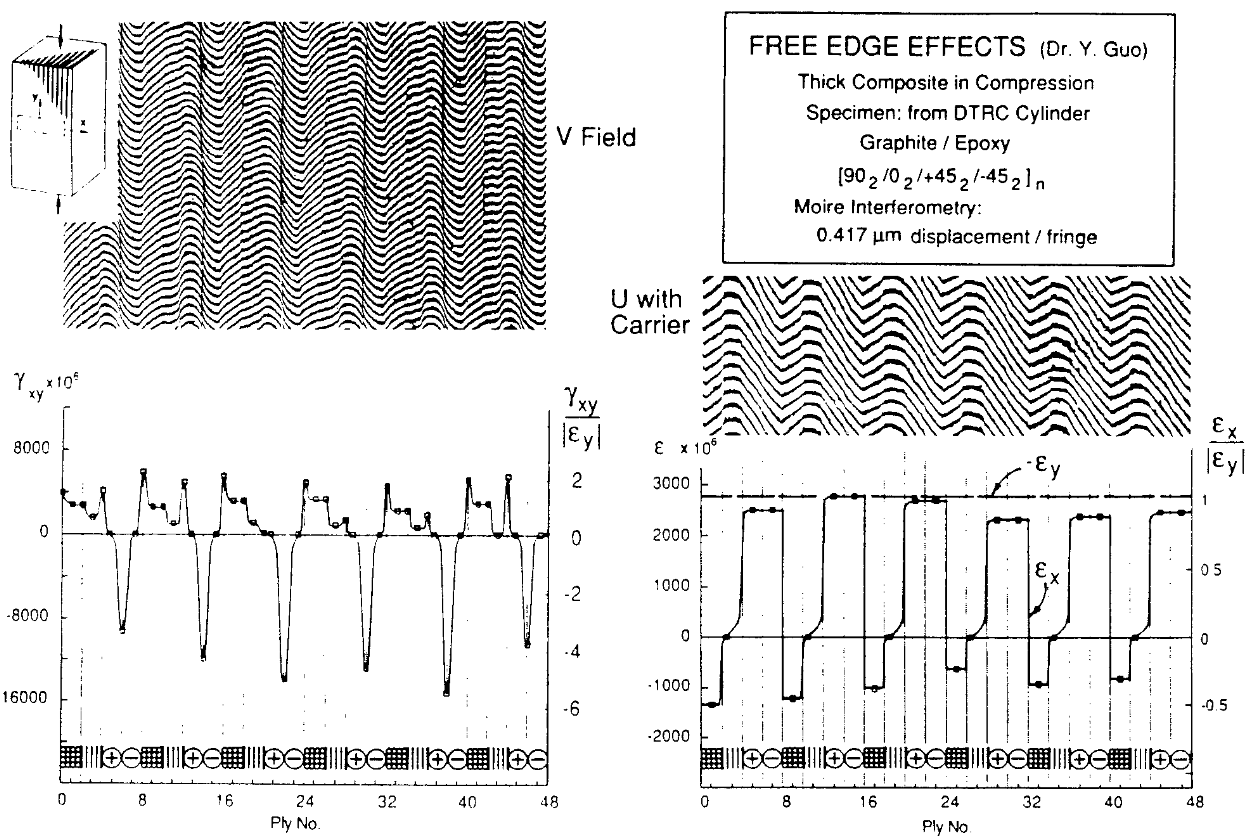
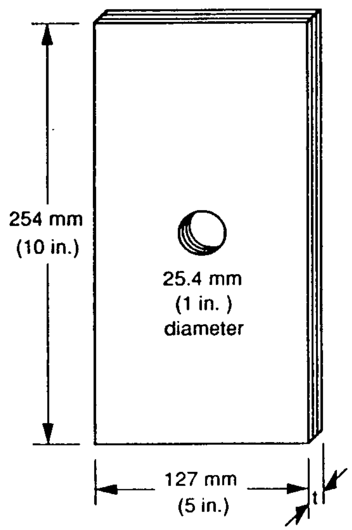


Fig. 1

Free Edge Effects



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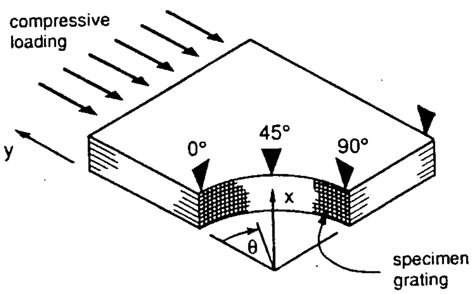
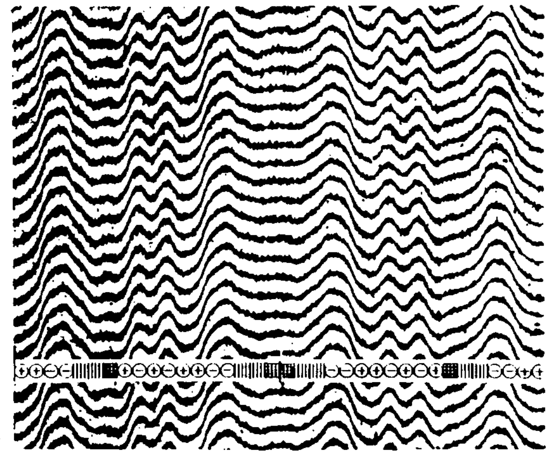


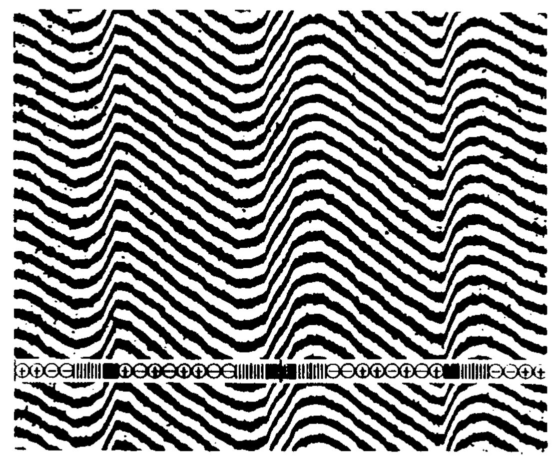
▼ denotes the data site

Specimen	Material	Stacking Sequence	t, mm
B1, B1H	T800H/ 3900-2	$[45_2/-45_2/0_2/90/\pm45_2/ 45_2/-45_2/0_2/90]_s$	7.11 mm
B2, B2H	T800H/ 3900-2	$[45/90/-45/0_3/45/0_4/ -45/0_2/45/0/-45/90]_s$	7.11 mm
N1	AS4/ 3502	$[90_3/45_3/0_3/-45_3]_{2s}$	6.73 mm
N2	AS4/ 3502	$[90_2/0_4]_{4s}$	6.73 mm

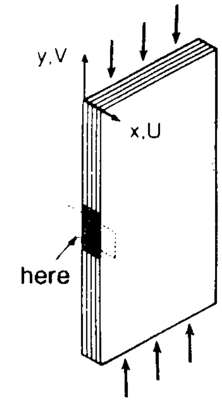
Fig. 2



N_y or V Displacement Field



N_x or U Field with Carrier Fringes of Rotation



Specimen B1

Moire Interferometry
f = 2400 lines/mm

U,V displacement =
0.417 μm/fringe

Patterns show
ply-by-ply
variations

Fig. 3

$\varepsilon_x, \varepsilon_y, \gamma_{xy}$ along Straight Edge

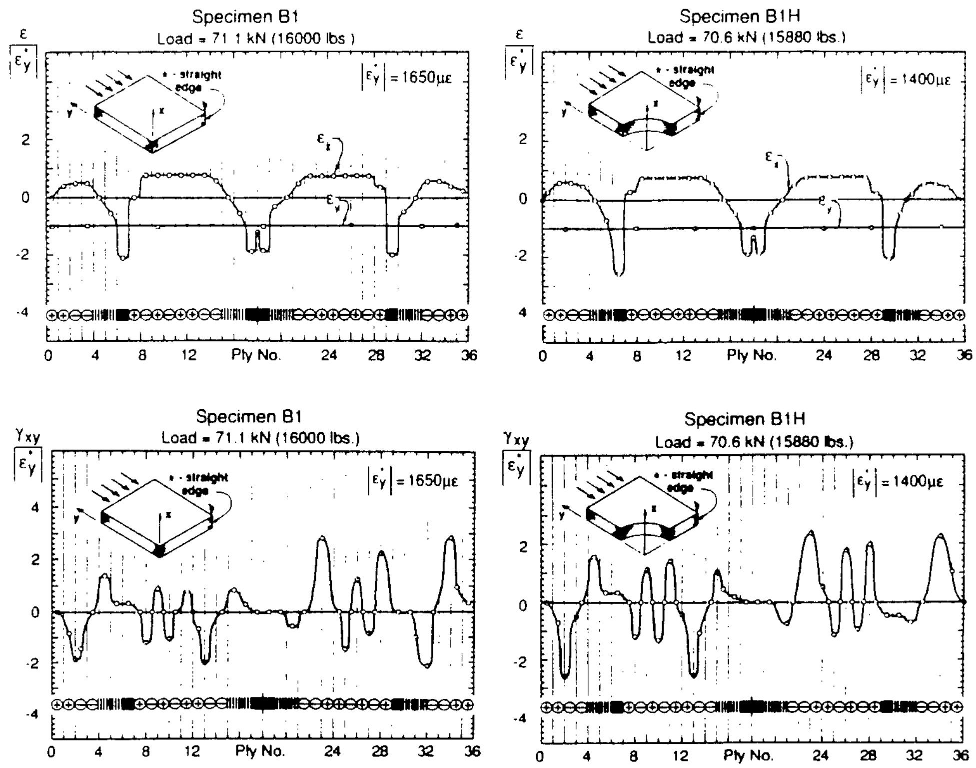
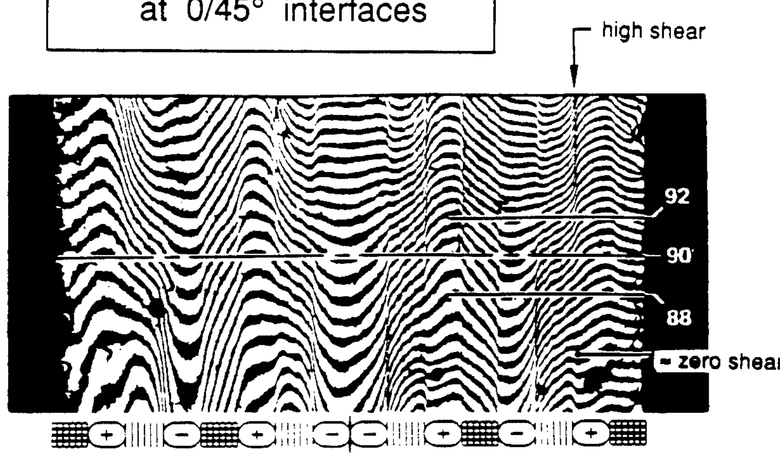


Fig. 4

Variation of $\gamma_{r\theta}$ with θ is EXTREMELY RAPID at 0/45° interfaces



U_θ Displacement Field

Specimen N1

Fig. 7

Tangential Strain in Hole at θ = 90°

$\frac{\varepsilon_\theta}{\varepsilon_y^\bullet}$ is a STRAIN AMPLIFICATION FACTOR caused by the hole

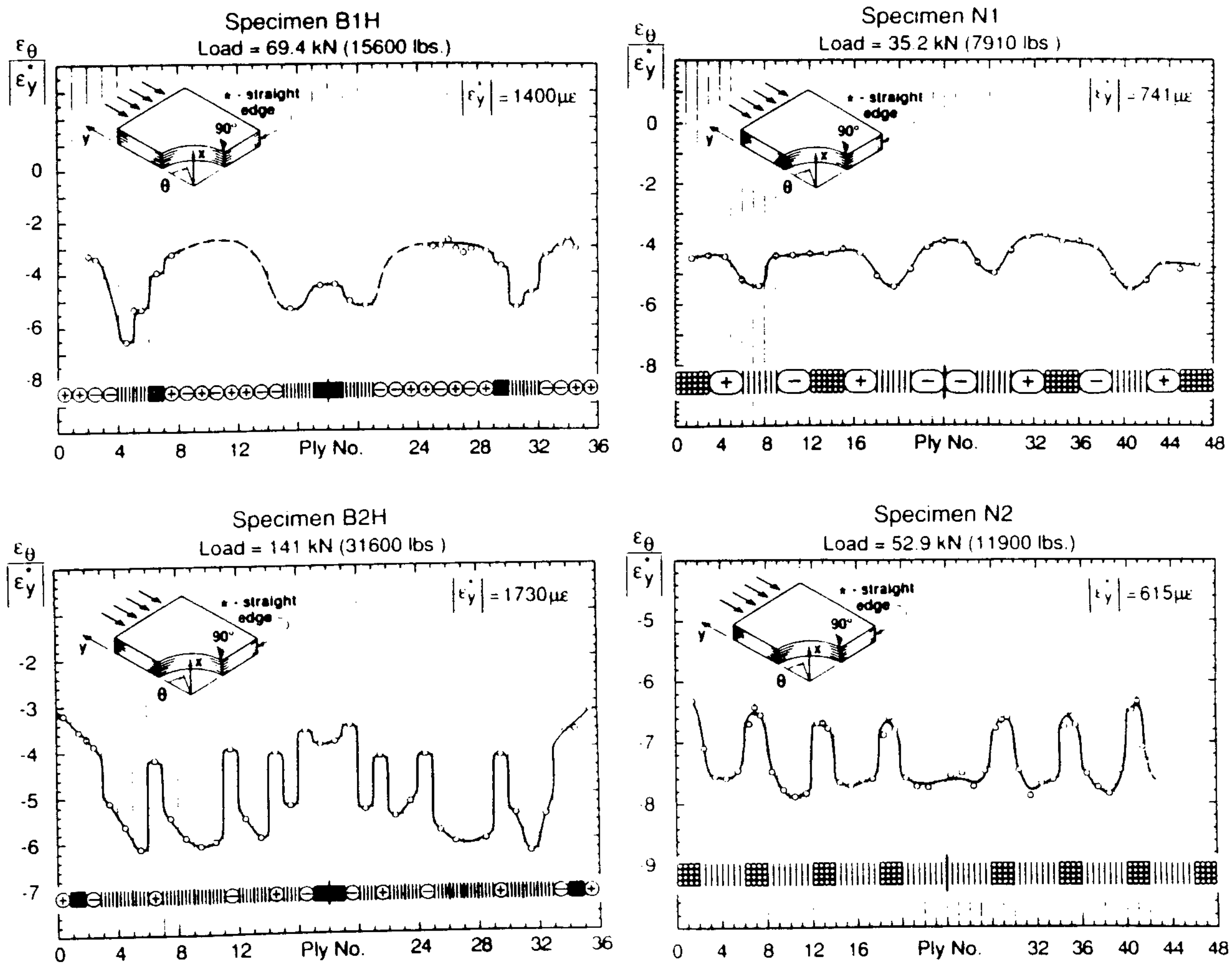
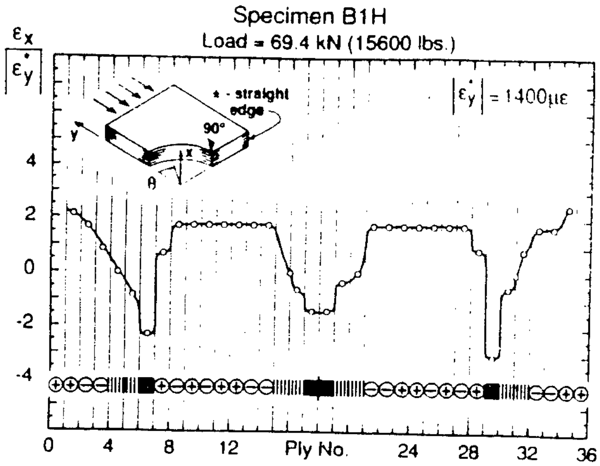


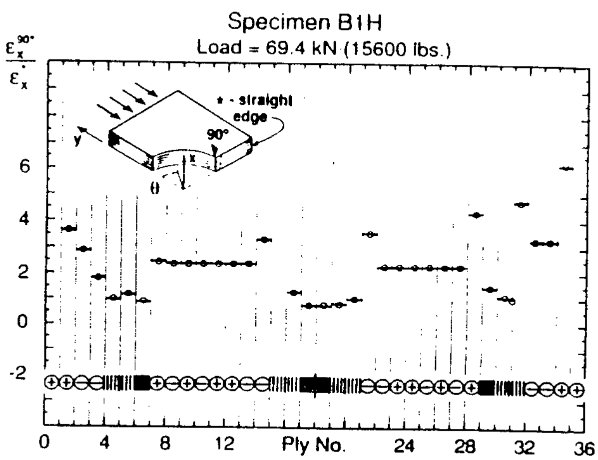
Fig. 5

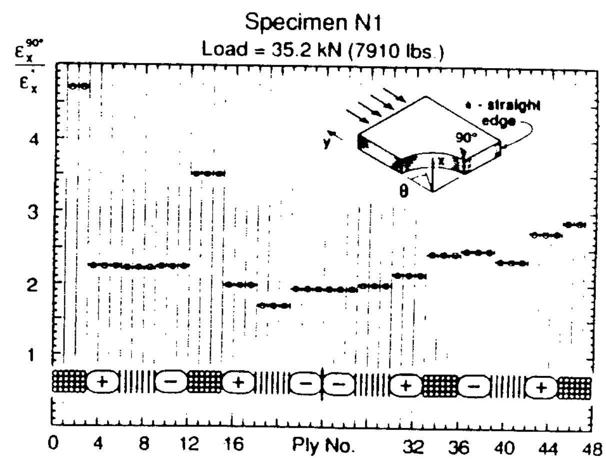


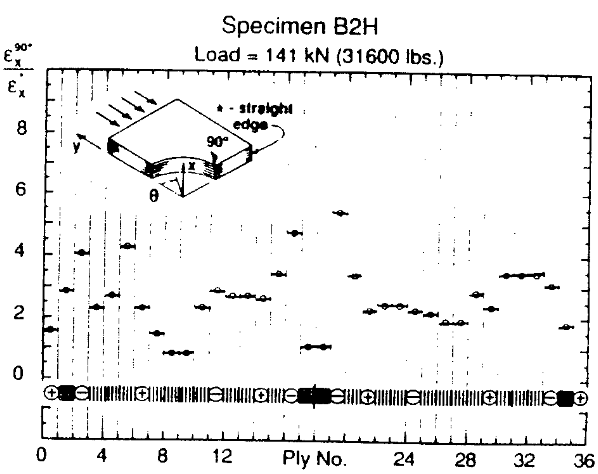
Transverse Strain in Hole at θ = 90°

Ratio for each ply:

$$\frac{\varepsilon_x \text{ at hole boundary}}{\varepsilon_x \text{ at straight edge}}$$







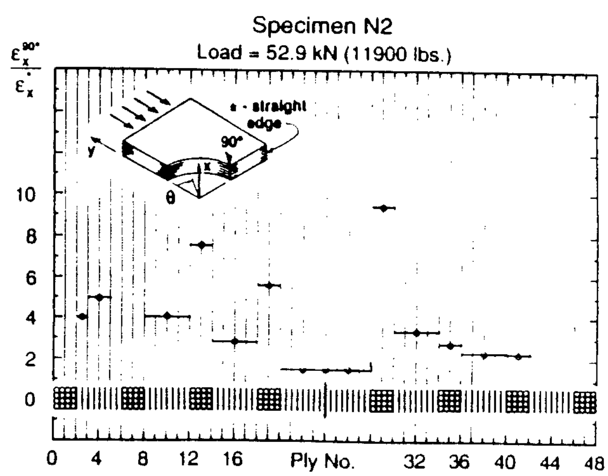
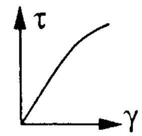


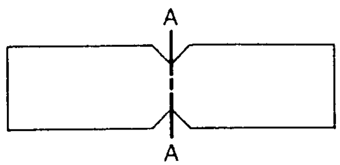
Fig. 6

Shear Test Methods



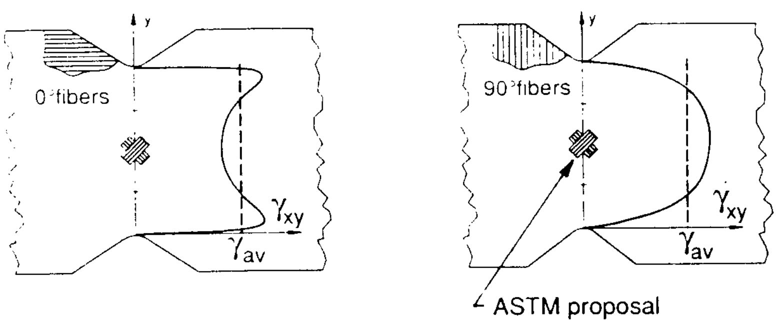
Stress-Strain Properties of Laminates

Problem #1

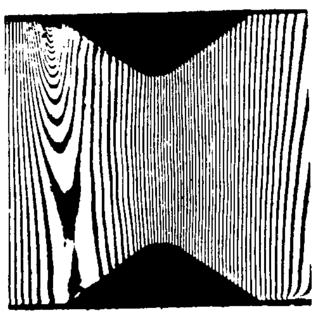


Average shear strain on A-A is required

Actual Distribution (from moire measurements)



Moire



Result

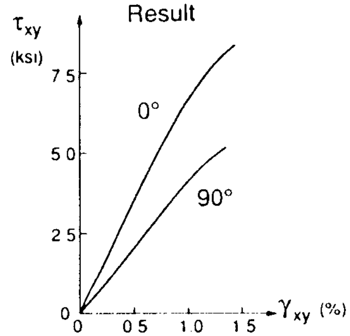


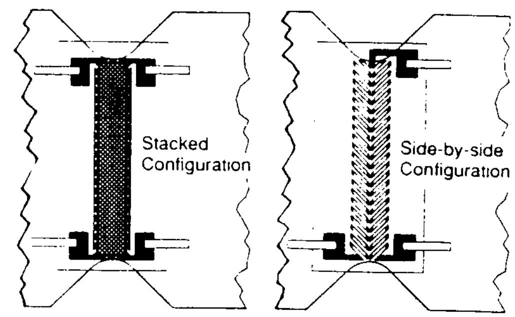
Fig. 8

Shear Test Methods

Solution #1 (Peter Ifju, NCCMR Fellow)

ONR/URI, NSF, VA CIT, Measurements Group Inc.

New Strain Gage



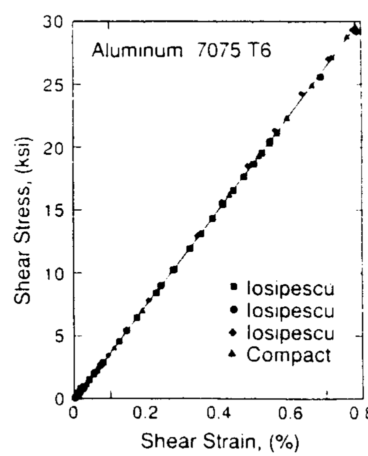
Measures the avearge γ_{xy} across entire test zone

Insensitive to
- Normal strains
- Temperature change

Compensate bending / twisting
- Apply gage both sides

Range
- 0-12% shear strain

Results



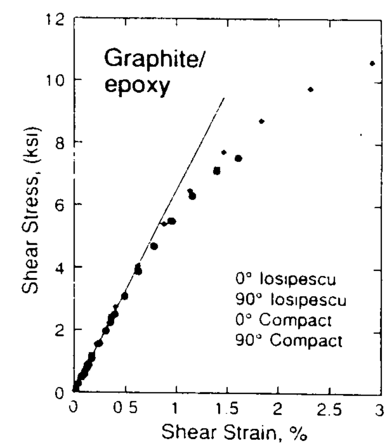
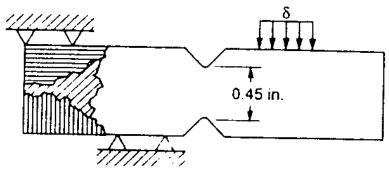


Fig. 9

Shear Test Methods

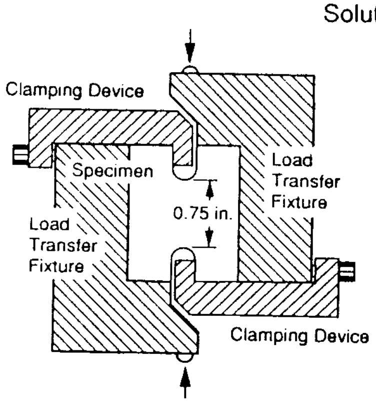
Problem #2

Iosipsecu Specimen with Modified Wyoming Fixture



- Severe front-to-back differences
- Clamping produces normal strains in test zone

Solution (Peter Ifju, NCCMR Fellow)



Compact Specimen

- Less front-to-back difference
- No clamping influence in test zone
- larger volume of mat'l. in test zone
- Simpler fixturing, loading arrangements

Woven Composite:

importance of larger test zone

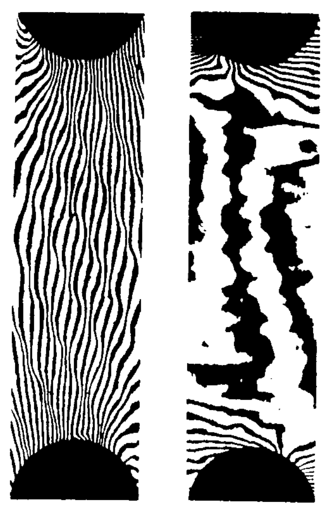
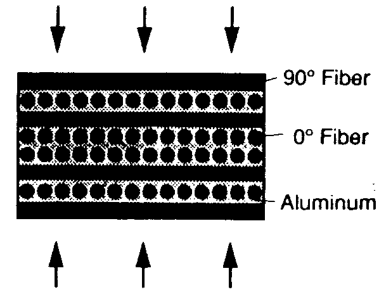


Fig. 10

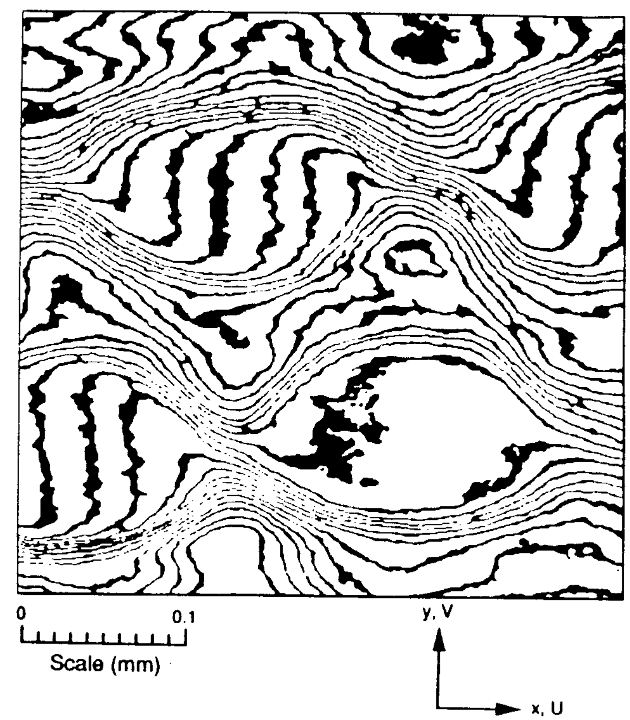
DEMONSTRATION

β = 4

52 nm/fringe contour



Silicon-carbide/Aluminum



V-field with carrier fringes

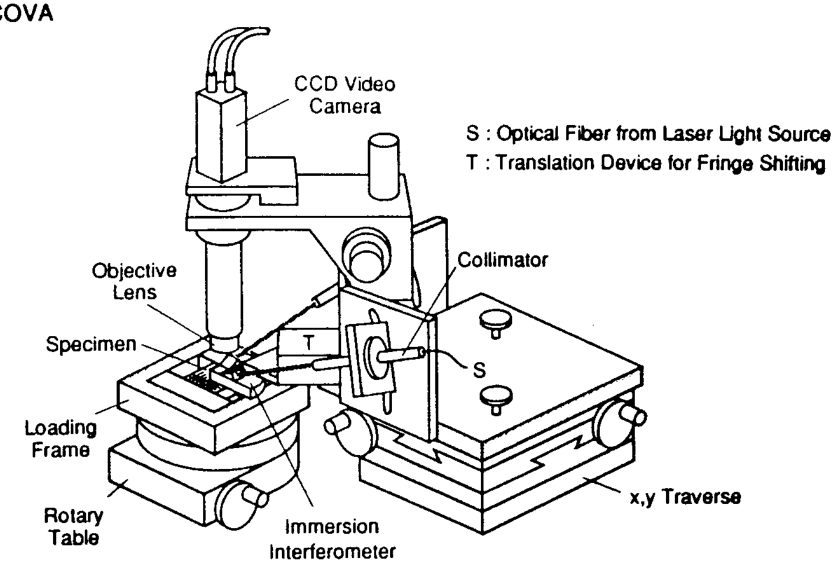
Fig. 13

Microscopic Moire Interferometry

Dr. B. Han

ONR/URI
NSF
VA CIT
ARCOVA

Microscopic Viewing
Enhanced Sensitivity



Data

β Shifted Moire Patterns

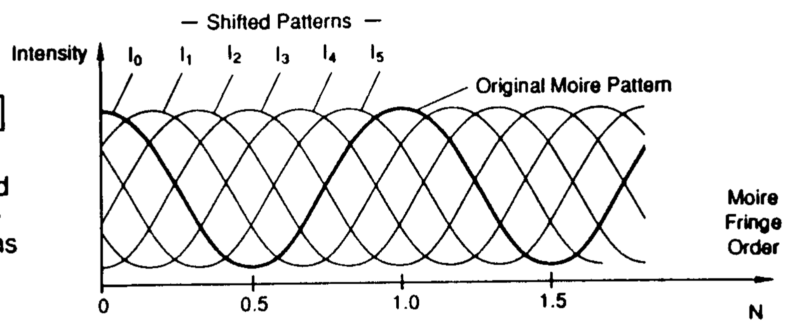


Fig. 11

Priciple of Fringe Multiplication

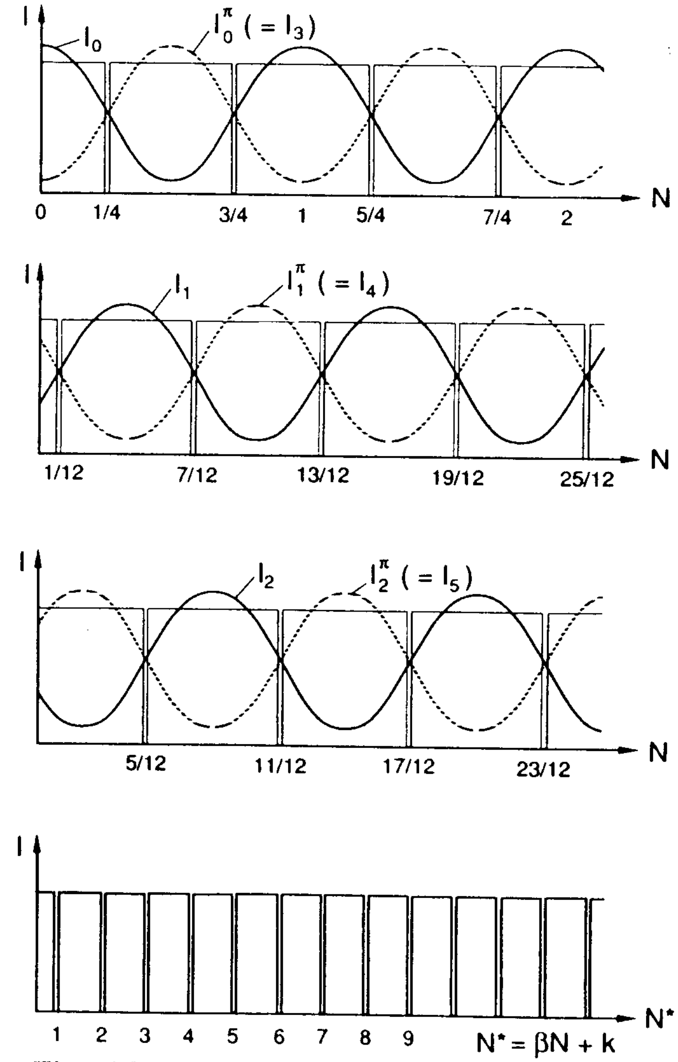
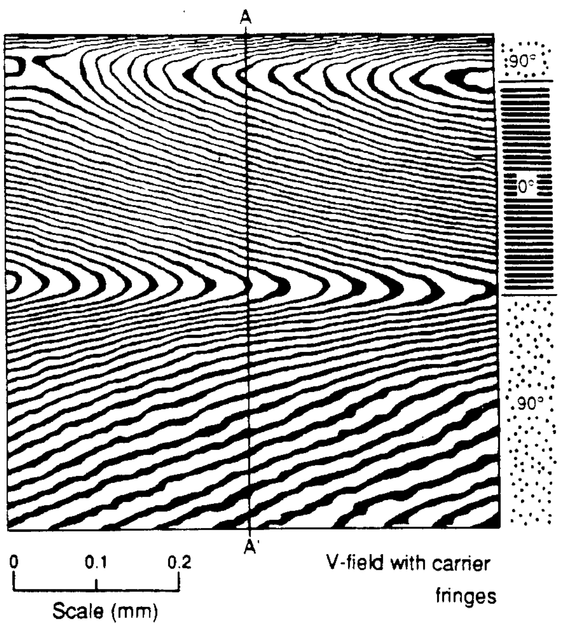


Fig. 12

Demonstration

β = 8

26 nm/fringe contour



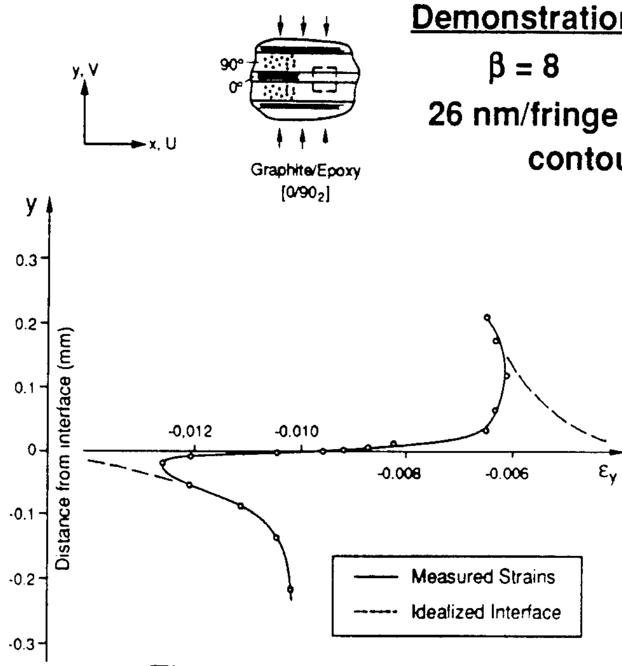


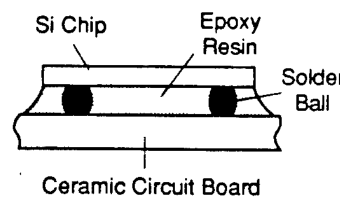
Fig. 14

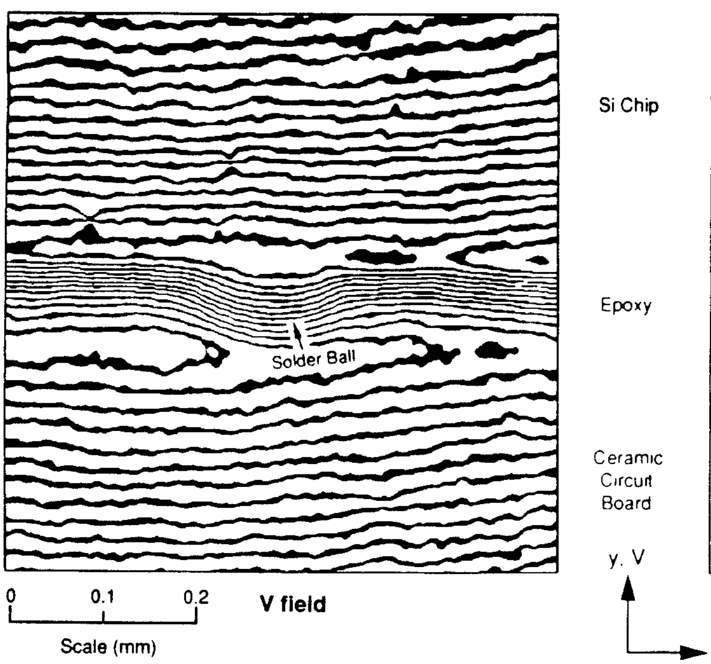
DEMONSTRATION

β = 12

17 nm/fringe contour

Microelectronic Assembly Thermal Strains $\Delta T = 62°C$





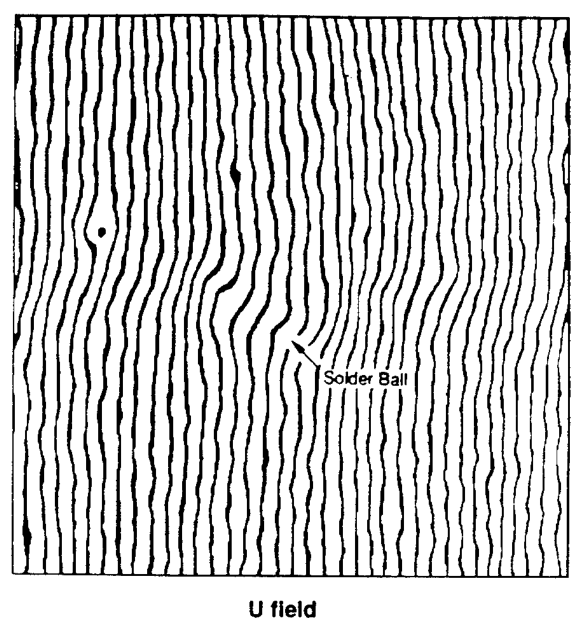


Fig. 15

NONDESTRUCTIVE CHARACTERIZATION OF COMPOSITE LAMINATES

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ABSTRACT

With increasing use of composites in advanced structural systems it has become necessary to have reliable nondestructive evaluation (NDE) methods for monitoring the integrity of such structures. The elastic properties of composite materials may be significantly different in different specimens manufactured under the same general specifications. The properties may also be different for the bulk material form those in the laminate. This variability in the properties requires their careful characterization before they are used in the structure. Conventional destructive techniques for the determination of the elastic stiffness constants can be costly and often inaccurate; this is particularly true for the through-the-thickness properties.

The elastic constants of composites may also vary with age due to environmental and other effects resulting in overstress and eventual failure of the material. Moreover, structural components made out of composite laminates may develop various types of defects (e.g., matrix cracking, delamination, etc.) some of which may also cause failure of the component. Careful monitoring of these effects is essential for safeguarding the safety and reliability of the structure. Destructive techniques are clearly inappropriate for such in-service use.

A recently developed ultrasonic technique which has been successful in addressing these issues in the laboratory setting is described in this paper. The technique is based on a two-transducer pitch-catch type arrangement shown in Fig. 1. The specimen is immersed in water and a beam of acoustic waves is launched by one of the transducers. In the continuous wave (CW) mode, the second transducer records the amplitude spectra of the reflected waves as a function of frequency, which can be used to determine the dispersion curves of leaky guided waves generated within the specimen. The dispersion curves are strongly affected by elastic properties as well as the interface and boundary conditions for the specimen. In the pulsed mode, the reflected signal recorded by the second transducer consists of a series of pulses that have traveled through the interior of the specimen; they carry information regarding the material properties of the specimen.

The two types of data obtained in the experiment have been analyzed by means of a theoretical model of wave propagation in the composite laminate. The material of the composite has been modeled as a transversely isotropic and dissipative medium with the axis of elastic symmetry along the fibers and characterized by five complex stiffness constants in the frequency domain. The real parts of the complex stiffness constants are c_{11}, c_{22}, c_{12}, c_{23}, c_{55} and the imaginary parts are proportional to a frequency-dependent damping parameter, p(f) [1]. A suitable form of p containing three constant parameters, f_0, p_0 and a_0 is introduced where f_0 is the frequency below which wave scattering by the fibers can be ignored, p_0 is a measure of attenuation due to viscoelastic effects, and a_0 is the coefficient of the frequency-dependent term due to scattering. A three dimensional elasticity theory has been used to solve the problems of leaky guided wave propagation and reflection of acoustic waves in a laminate containing an arbitrary number of layers with arbitrary orientation and immersed in water [2].

In the case of leaky guided wave problem the theory yields a nonlinear relationship between the phase velocity and the material properties (thickness, density, elastic constants) of the laminate. This equation has been inverted by means of an optimization algorithm to yield the elastic constants of the composite [3]. Typical results for a unidirectional $[0]_8$ and a and a cross ply $[0,90]_{2S}$ laminate are shown in Fig. 2. The elastic constants are consistent with a least square fit between the measured and calculated dispersion curves in the frequency range .1-10 Mhz. The stiffness constants c_{22}, c_{23} and c_{55} could be determined accurately through this inversion scheme.

The same procedure has been used to calculate the stiffness reduction of a cross-ply specimen due to the presence of transverse cracks introduced by static and fatigue loads [4]; the results are shown in Fig. 3.

The amplitude spectrum of the reflected signals has been used to determine the delamination depth in a unidirectional specimen [4]. A comparison between the theoretically predicted and measured frequency spectra of the reflected signals for an undamaged and a damaged specimen are shown in Fig. 4.

In the reflection problem, the incident acoustic waves are obtained as a reference pulse through the experiment and the wave motion at the receiving transducer is calculated from the theory [1]. The pulsed data has been used to determine the damping parameters, f_0, p_0, and a_0 for a number of specimens; two typical case is shown in Fig. 5. The values of f_0 and p_0 were found to be independent of specimen thickness but a_0 increased with thickness.

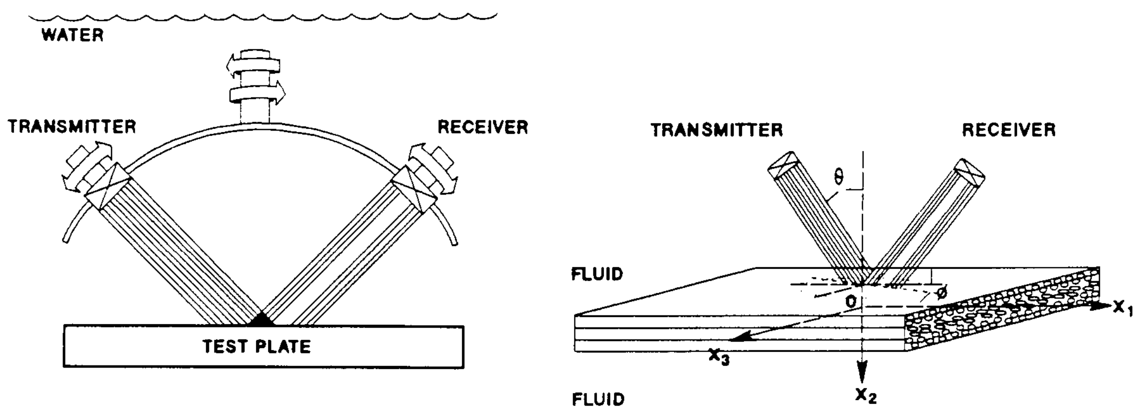


Fig. 1 - Schematic diagram of the ultrasonic experiment.

MATERIAL MODELING

Wave speed: 1.5 - 10 mm/μsec.
Frequency: .1 - 10 MHz.
Wavelength < 150 μm.
Fiber diameter ≈ 7.5 μm.
Overall elastic properties: transversely isotropic.

CONSTITUTIVE EQUATIONS

$[\sigma] = [C][e]$, 5 independent stiffness constants $c_{11}, c_{12}, c_{22}, c_{23}, c_{55}$.

DISSIPATIVE PROPERTIES

Causes: viscoelasticity, wave scattering (by fibers and inhomogeneities).

Assume complex-valued elastic moduli

$$C_{11} = c_{11}/(1 + ip\sqrt{c_{55}/c_{11}}), \quad C_{22} = c_{22}/(1 + ip\sqrt{c_{55}/c_{22}})$$

$$C_{12} = (c_{12} + c_{55})/[1 + ip\sqrt{c_{55}/(c_{12}+c_{55})}] - C_{55}$$

$$C_{44} = c_{44}/(1 + ip\sqrt{c_{55}/c_{44}}), \; C_{55} = c_{55}/(1 + ip)$$

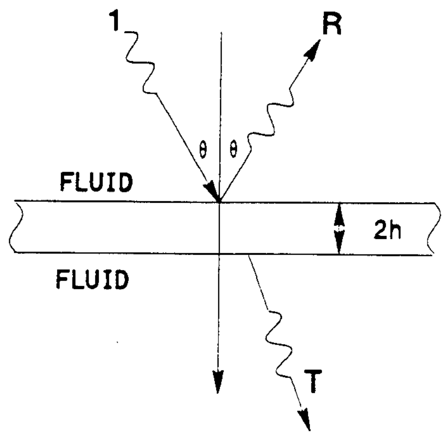
$$p = p_0[1 + a_0(\frac{f}{f_0} - 1)^2 H(f - f_0)]$$

THEORY: Reflected field, dispersion.

Uniform plate, multilayered laminate.
Frequency domain formulation. Use FFT to obtain time history.
Stress-displacement vector in frequency domain

$$\{u_1,\ u_2,\ u_3,\ \sigma_{13},\ \sigma_{23},\ \sigma_{33}\} = \{S(x_3)\}e^{i(\xi_1 x_1 + \xi_2 x_2)}$$

$\{S(x_3)\}$ satisfies system of first order ODE



General solution:

$$\{S(x_3)\} = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix} \begin{bmatrix} E^{+}(x_3) & 0 \\ 0 & E^{-}(x_3) \end{bmatrix} \begin{Bmatrix} C^{+} \\ C^{-} \end{Bmatrix}$$

$[Q_{ij}]$ are "known" 3 × 3 matrices
$[E^{\pm}]$ propagator prpagator along $\pm x_3$
$\{C^{\pm}\}$ unknown constant vectors.

Boundary conditions

$$\{S(0)\} = [U_0 \quad V_0 \quad i\eta_0(1-R) \quad 0 \quad 0 \quad -\rho_0\omega^2(1+R)]$$

$$\{S(2h)\} = [U_1 \quad V_1 \quad i\eta_0 T \quad 0 \quad 0 \quad -\rho_0\omega^2 T]$$

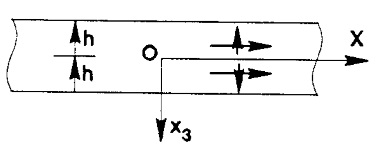
U_0, V_0, U_1, V_1 are unknown slip at fluid-solid interface
ρ_0 = density of fluid
ω = frequency
η_0 = wavenumber of acoustic waves in x_3- direction
R = reflection factor
T = transmission factor

Reflection coefficients: Solve system of linear equation

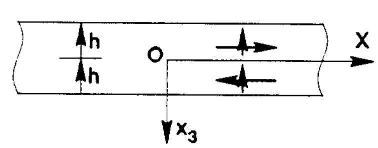
$$[A]\{C\} = \{F\}$$

Dispersion equation: Det $[A] = 0$

symmetric



antisymmetric



DETERMINATION OF THE STIFFNESS CONSTANTS

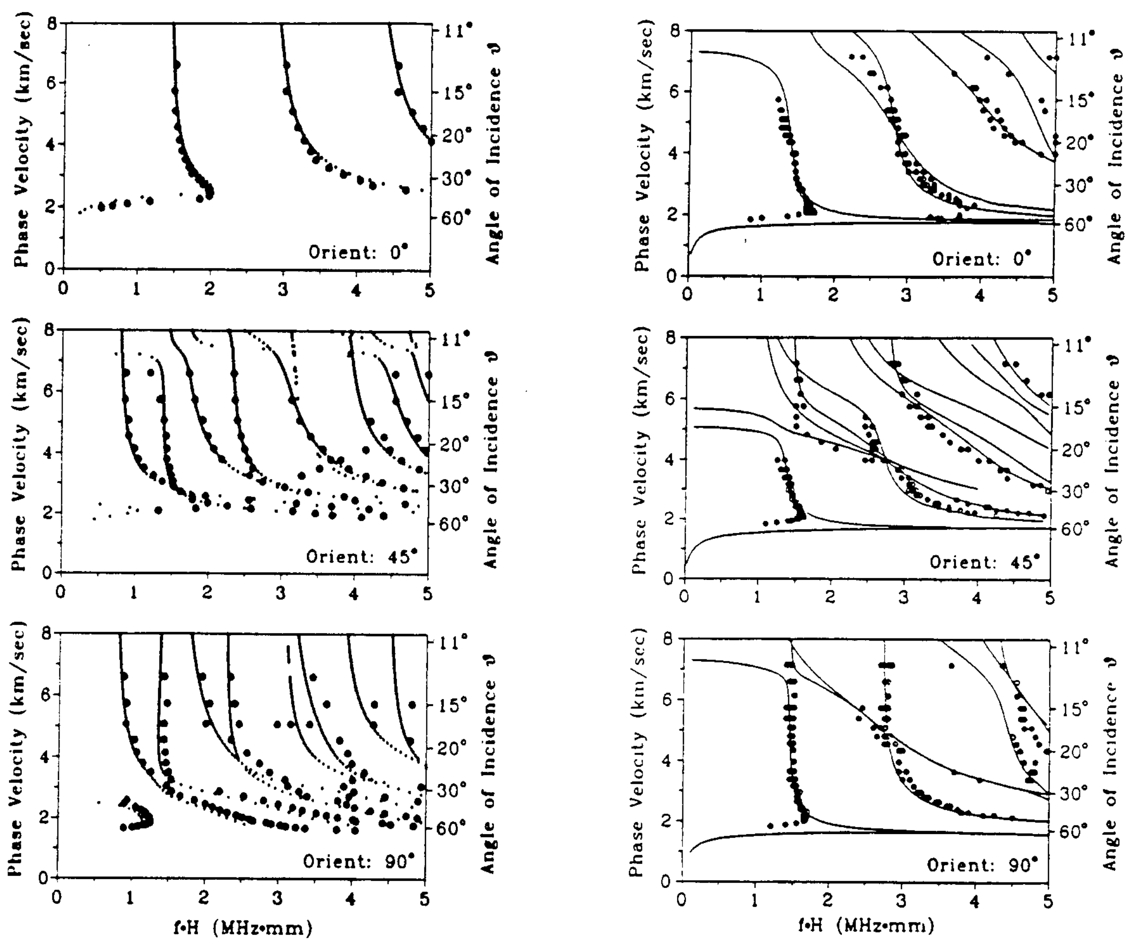


Fig. 2. Measured (⊙) and calculated (···) leaky guided wave dispersion curves for a unidirectional $[0]_8$ (left panel) and a cross - ply $[0, 90]_{2s}$ (right panel) graphite epoxy laminate of nominal thickness 1 mm each. The data for the unidirectional laminate for phase velocity greater than 3 km/sec were inverted to yield the stiffness constants given in Table. 1. These stiffness constants were then used to calculate the theoretical dispersion curves for both laminates.

Table 1. The stiffness constants determined through inversion of dispersion data for the unidirectional laminate.

Mass density (g/cm^3)	c_{11}	c_{12}	c_{22}	c_{23}	c_{55} (GPa)
1.578	160.73	6.44	13.92	6.92	7.07

INVERSION OF LLW DATA FOR DAMAGED $[0/90]_{2S}$ GRAPHITE/EPOXY

Assumptions:

Material properties in the uncracked 0° ply remains unchanged.
Material of 90° plies remains transversely isotropic after the formation of transverse cracks in it.
Only effect of transverse cracks is to change the stiffness.

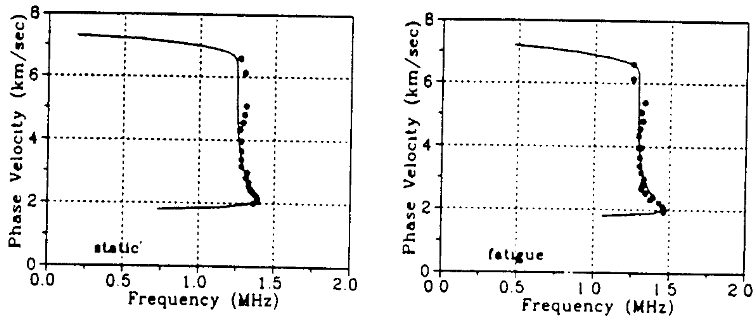


Fig. 3. Low frequency dispersion data and calculated dispersion curves for leaky guided waves in undamaged and fatigued samples of graphite/epoxy cross-ply laminates. Cracks were caused by static loading in one sample and by fatigue loading of 60,000 cycles at 30% of ultimate load in the other.

Table 2. Stiffness reduction due to transverse matrix cracks in 90° plies for one of the fatigued specimens.

Specimen	Thickness(mm)	c_{11}	c_{12}	c_{22}	c_{23}	c_{55}(GPa)
Defect-free	1.9	160.73	6.319	14.487	7.745	6.191
Fatigued	1.8	160.73	6.319	12.175	6.312	6.191

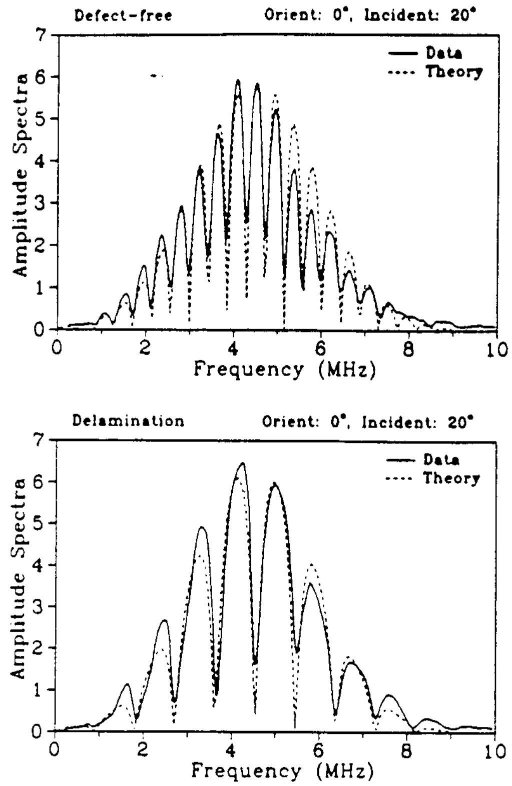
The engineering constants

Specimen	E_{11}	E_{22}	G_{12}	G_{23}	ν_{12}	ν_{23}
Defect-free	157.13	10.292	6.191	3.371	0.2842	0.5265
Fatigued	156.41	8.844	6.191	2.932	0.3418	0.5084

Observations:
For specimens cracked either by static or fatigue loads, stiffness always decreases.
Crack has a larger effect on c_{23} than on c_{22}.
For samples cracked by different fatigue cycle shows different change in stiffness.

DELAMINATION

$[0]_{24}$



$h^o = 3.81$ mm

$h^d = 1.78$ mm

$$h_i^d = \frac{h^o f_i^o}{f_i^d}, \qquad i = 1, \cdots, m$$

$$h^d = \frac{h^o}{m} \sum_{i=1}^{m} \frac{f_i^o}{f_i^d}$$

i^{th}	f_i^o	f_i^d	f_i^o / f_i^d
3	1.27	2.71	0.469
4	1.72	3.67	0.468
.	.	.	.
.	.	.	.
.	.	.	.

Fig. 4. Reflected spectra for 0.15" thick unidirectional specimen at 20° angle of incidence. One specimen is free of defect, another contains interface-delamination between the 11^{th}-12^{th} laminae.

THE DAMPING PARAMETERS

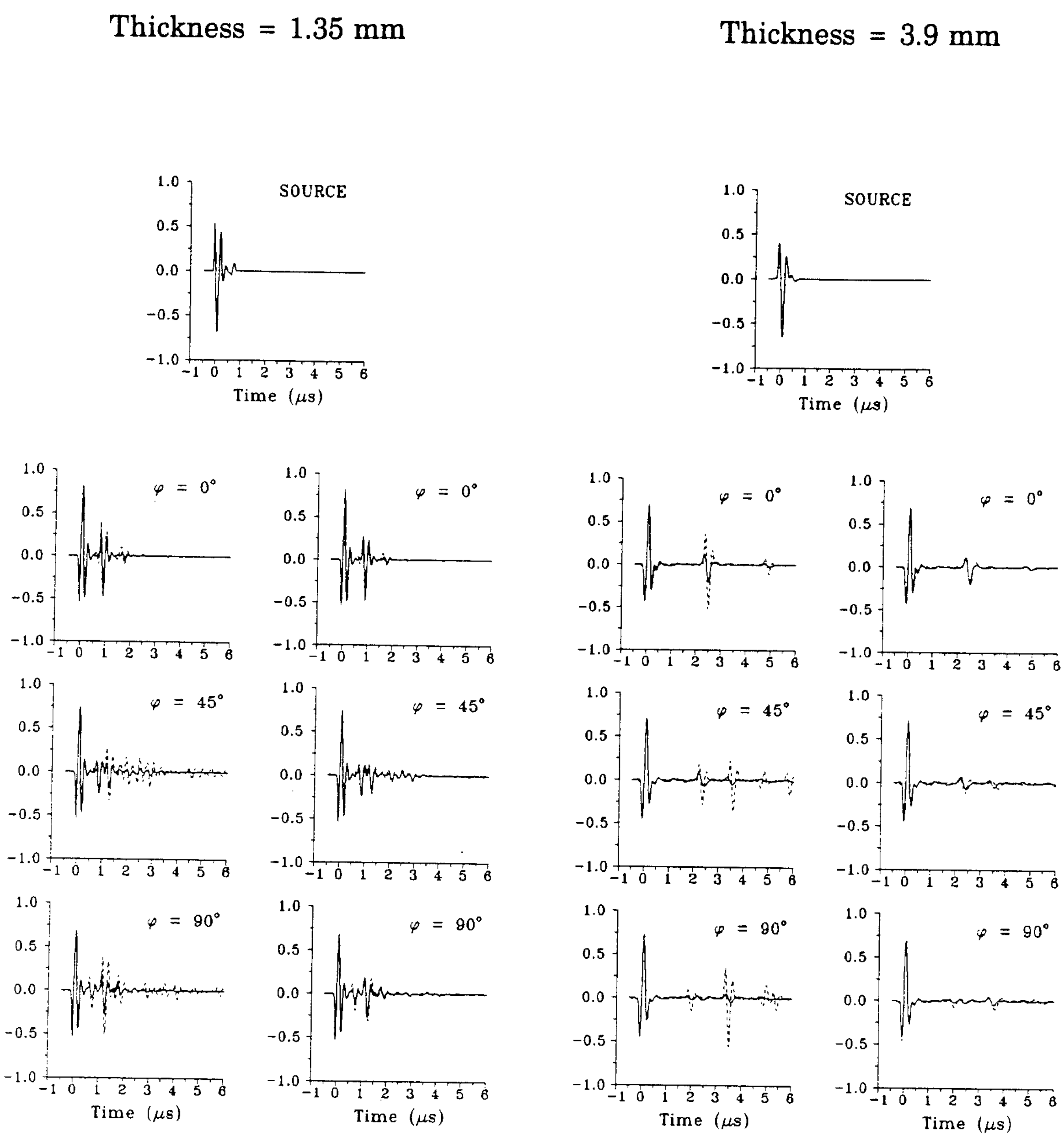


Fig. 5. Comparison between measured (solid curves) and calculated (dashed curves) reflected signals from two unidirectional graphite/epoxy plates of different thicknesses. Calculated results in the left panel in each figure assume perfect elasticity while those in the right panel include dissipation, with parameters f_0 = .3, p_0 = .005, a_0 = .1 for the thinner specimen and a_0 = .3 for the thicker specimen.

CONCLUDING REMARKS

The ultrasonic technique appears to yield accurate estimates of the through-the-thickness elastic stiffness constants and the damping parameters in the propose model of graphite/epoxy composite. The technique can be used in conjunction with a C-scan to detect and size delaminations in composite laminates. It is hoped that further research will lead to the development of a system that can be used effectively in field environments.

It should be noted that the dispersion curves in the frequency range used in the experiment are relatively insensitive to the constants c_{11} and c_{12} and their precise values can not be determined by this method. Moreover, the inversion process is inherently nonlinear and may lead to widely different sets of stiffness constants unless they are subjected suitable restrictions based on other considerations.

ACKNOWLEDGEMENT

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Structural Response of Composite Cylinders to External Hydrostatic Pressure

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David Taylor Research Center

Dr. Reaz Chaudhuri
University of Utah

Prior investigations into the hydrostatic strength of thick-section graphite-epoxy cylinders resulted in failures which were significantly lower (50 - 70% of design pressure) than anticipated. Some of the uncertainty in the failure modes and strength can be attributed to the lack of information on the interaction between the fibers and matrix material. It has been determined from several prior studies that fiber microbuckling is a potential failure mechanism under compressive loading, and that matrix support of the fiber is needed to attain significant compressive strength. The relative roles of fiber and matrix under the biaxial compressive loads associated with hydrostatic loading are very complex and not yet fully understood.

The effects of fiber waviness on compressive strength of composite cylinders has been studied at the David Taylor Research Center (DTRC) while Drs. M. Hyer and R. Chaudhuri were in residence under the sponsorship of the Navy-ASEE Summer Faculty Research Program. Their numerical studies showed that initial fiber misalignment, ultimate fiber strain, and the two transverse shear moduli were key parameters affecting the compressive strength. Questions remain regarding what specifically should be done to improve compressive strength. It is theorized that one way to improve compressive strength is through the use of a hybrid fiber design. Commingling glass fibers with graphite fibers should provide stability for the graphite fibers and result in an increase in the compressive strength.

The goal of the current project is to determine the failure mechanisms and compressive strength of commingled glass/graphite reinforced composite cylinders. A combined analytical and experimental approach is being employed. This project will use findings from a separate study by Dr. Reaz Chaudhuri of the University of Utah on the stability of a glass fiber or group (tow) of glass fibers in the neighborhood of a wavy graphite fiber or group (tow) of graphite fibers undergoing kinking type deformation. Under this project, parametric analyses are being performed to evaluate the effects of fiber orientation, fiber distribution, and fiber lay-up on the predicted compressive strength. Using these results and those from the study by Dr. Reaz, an optimized cylinder design will be developed and fabricated. Several rings and cylinder test sections will be cut from the cylinder. All test specimens will be thoroughly inspected, instrumented, tested and re-inspected in order to determine failure modes and compressive/hydrostatic strength. The ring tests will be performed using a test fixture recently developed by the Hercules Aerospace Company. The cylindrical specimens will be fitted with end closures and tested in a pressure tank at DTRC under external hydrostatic pressure. All experimental results will be compared with analytical predictions.

FY-91 was the first year of this project. The parametric analyses and design optimization study has identified an improved fiber orientation to suppress predicted global buckling modes. As compared to the baseline configuration $[(90_3/0)_{15}]_S$, an increase of 122% in shear modulus, G_{12}, and an increase of 20% in axial modulus, E_2, is expected by placing selected off-axis fibers at the mid thickness in the fiber orientation of $[(90_3/0)_{10}/(90_2/54/-54/0)_8/(90_3/0)_{10}/90_2]_T$. This results in an improvement of 20% in predicted global buckling pressure. Reduction in material compressive strength due to fiber waviness caused by fiber cross overs in the off-axis plies is expected to be minimized since the off-axis plies are located at mid-thickness.

A micro and macro-mechanics formulation has been initiated by Dr. Reaz Chaudhuri to characterize the stability of glass and graphite commingled fibers undergoing kinking deformation. A Green's Function approach is taken in this formulation. Constitutive relation models will be developed for analysis of compression loaded composites with defects such as fiber waviness or misalignment.

Concepts for commingling glass with graphite fibers have been formulated based on practical methods of producing commingled fibers. The desirable ratio of glass to graphite fibers is currently being investigated using a micro-mechanics kink band propagation theory.

During FY-92 and FY-93 a macro level large deformation analysis will be performed on thick-section hybrid composite rings/cylinders to investigate failure mechanisms. Effective moduli of hybrid composites will be derived and finite element analyses will be performed to predict stresses and buckling strength. A hybrid composite cylinder will be fabricated for compression strength tests. The strengths and failure modes observed in the ring and cylinder tests will be used to verify or modify the micro and macro-mechanics model formulations.

PREDICTION OF FIBER-MATRIX INTERPHASE PROPERTIES AND THEIR INFLUENCE ON THE STRENGTH AND FRACTURE TOUGHNESS OF COMPOSITE MATERIAL

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ABSTRACT

An elastic shear lag analysis, which includes an interphase region, has been developed and correlated with the tensioned fiber test data of Rockwell [1] to determine the thickness and shear modulus of the interphase. The results show: (1) good correlation between analytical results and test results (2) for uncoated and hydrogenated fibers, $G_i/G_m \approx .5$, while for sized fibers $G_i/G_m \approx 2.0$, and (3) interphase thickness $\leq 1.0\ \mu m$.

To study how the interphase influences the transverse tensile strength of the composite material, a simple one-dimensional model, which includes fiber, matrix and an interphase region, has also been developed. From this study, it was found that interphase thickness and modulus have significant influence on the transverse tensile strength of unidirectional fiber reinforced composites. A soft interphase is shown to reduce the stress concentration factor, hence increasing the transverse tensile strength of the composite. In order to increase transverse tensile strength of a composite, the interphase modulus should be decreased and/or the thickness of the interphase should be increased. The location for maximum stress concentration factor varies with interphase modulus and thickness, hence the mode and location of failures may be changed by changing these parameters.

Results are also included on how the interphase influences the Mode I fracture toughness [2]. To toughen the composite, a smaller interphase thickness and G_m/G_i ratio is desired. To achieve a higher transverse tensile strength, the opposite is true.

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2. H. C. Tsai, A. M. Arocho and L. W. Gause, "Prediction of Fiber-Matrix Interphase Properties and Their Influence on Interface Stress, Displacement and Fracture Toughness of the Composite Material," Material Science and Engineering, A126, pp. 295-304, 1990.

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PREDICTION OF FIBER-MATRIX PROPERTIES AND THEIR INFLUENCE ON THE STRENGTH AND FRACTURE TOUGHNESS OF COMPOSITE MATERIALS

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AGENDA

- OBJECTIVE
- DETERMINATION OF INTERPHASE PROPERTIES
- INFLUENCE OF INTERPHASE PROPERTIES ON:
  - TRANSVERSE TENSILE STRENGTH
  - MODE I FRACTURE TOUGHNESS
- CONCLUSIONS

OBJECTIVE

- REVIEW THE WORK DONE BY NADC ON THE FOLLOWING AREAS:
  - DETERMINATION OF INTERPHASE PROPERTIES
  - THE INFLUENCE OF INTERPHASE PROPERTIES ON THE STRENGTH AND FRACTURE TOUGHNESS OF COMPOSITE MATERIALS

DETERMINATION OF INTERPHASE PROPERTIES

- **EXPERIMENTAL DATA**
  - TENSIONED-FIBER TEST
  - NANO-INDENTATION TEST
- **SHEAR LAG THEORY**

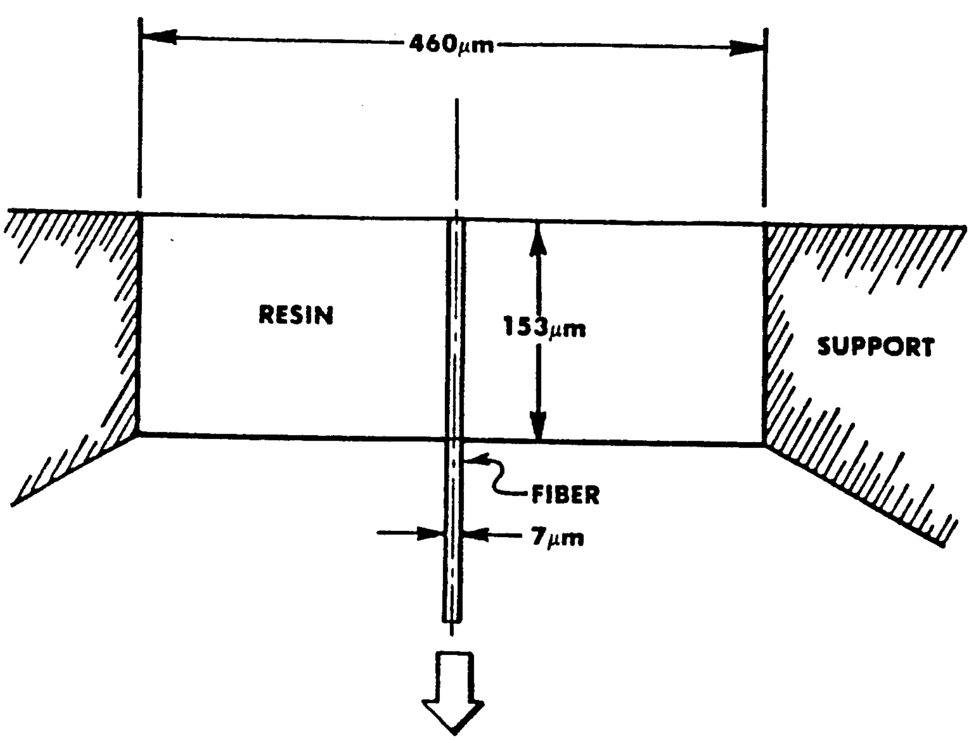
APPROACH

* Obtain approximate relationship between $\frac{G_m}{G_i}$ and t_i using shear lag analysis and test data, $F_0(G_m/G_i, t_i)=0$

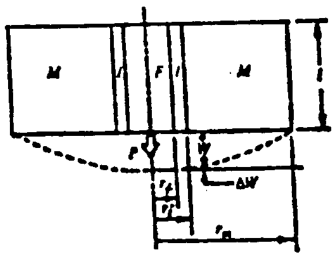
* Use F.E.A. to iterate approximate $\frac{G_m}{G_i}$ and t_i relationship and obtain accurate relationship, $F_f(G_m/G_i, t_i)=0$

* Use $F_f(G_m/G_i, t_i)=0$ as a constraint in multi-phase Composite Cylinders Assemblage analysis (MPCCA) to extract interphase properties.

TENSIONED-FIBER TEST



SHEAR LAG ANALYSIS



$\underline{r_f \le r \le r_i}$

$$\Delta W = \bar{\sigma}\, csch(\alpha l)\left(\frac{1}{E_f \alpha} - \frac{r_f^2 \alpha}{2G_m}\ln\frac{r_m}{r_i}\right)\frac{\ln(r/r_f)}{\ln(r_i/r_f)}$$

$\underline{r_i \le r \le r_m}$

$$\Delta W = \bar{\sigma}\, csch(\alpha l)\left(\frac{1}{E_f \alpha} - \frac{r_f^2 \alpha}{2G_m}\ln\frac{r_m}{r}\right)$$

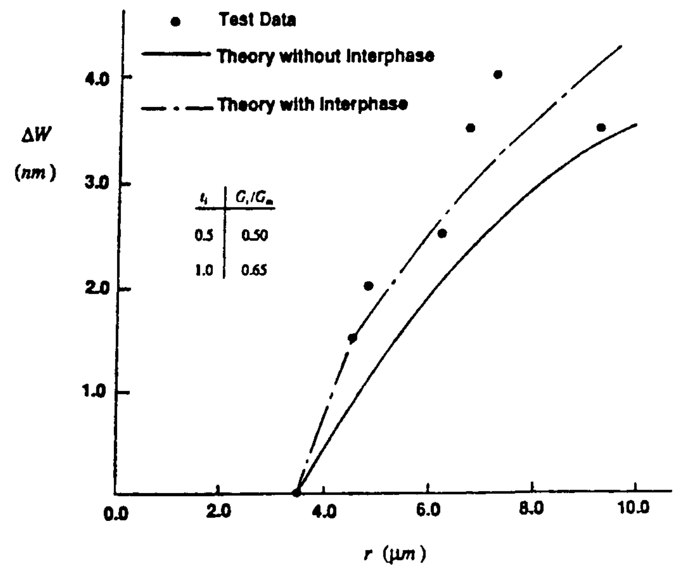
where

$$\alpha = \frac{1}{r_f}\left(\frac{2G_m}{E_f}\right)^{\frac{1}{2}}\left(\left(\frac{G_m}{G_i} - 1\right)\ln\left(\frac{r_i}{r_f}\right) + \ln\left(\frac{r_m}{r_f}\right)\right)^{-\frac{1}{2}}$$

$$\bar{\sigma} = \frac{P}{\pi r_f^2}$$

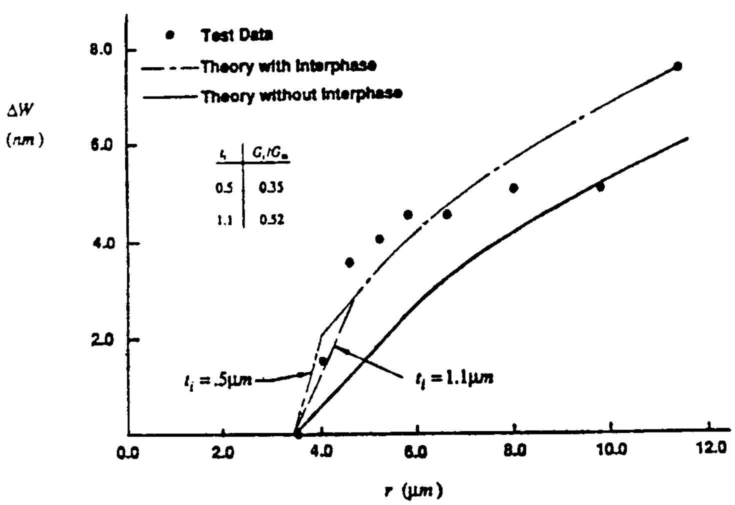
SHEAR LAG ANALYSIS OF UNCOATED FIBER

0.094% FIBER STRAIN



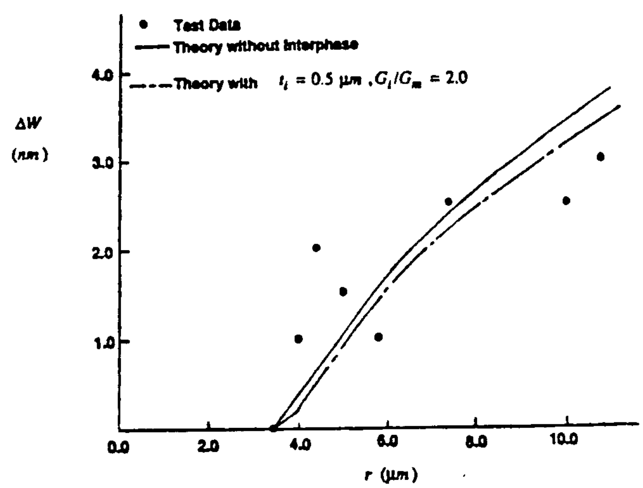
SHEAR LAG ANALYSIS OF THE HYDROGENATED FIBER

0.13% FIBER STRAIN



SHEAR LAG ANALYSIS OF THE SIZED FIBER

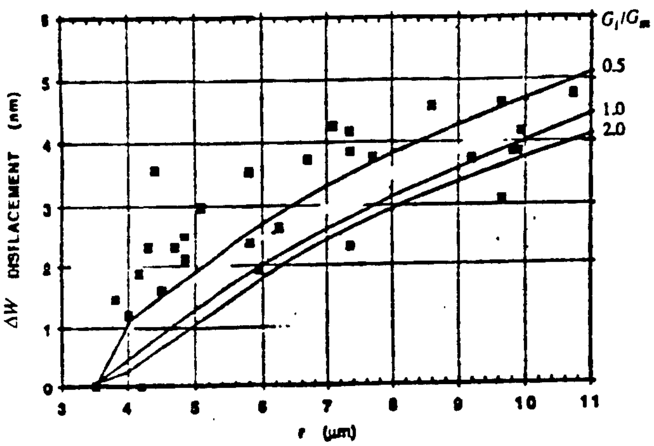
0.084% FIBER STRAIN



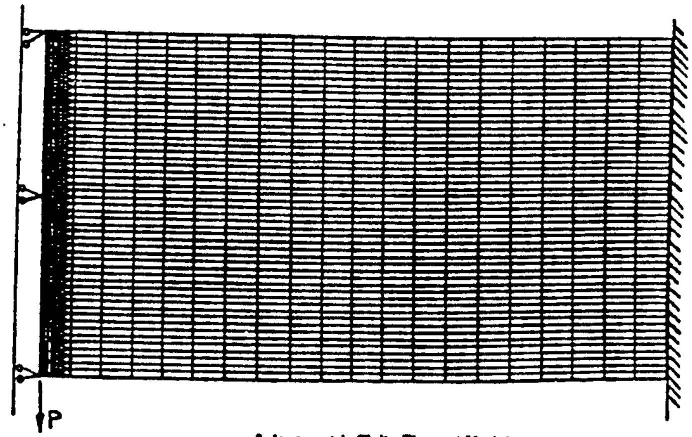
SHEAR LAG ANALYSIS OF ALL THE FIBER TYPES

LOW LOAD COMPARISON

DATA SCALED TO 0.1%

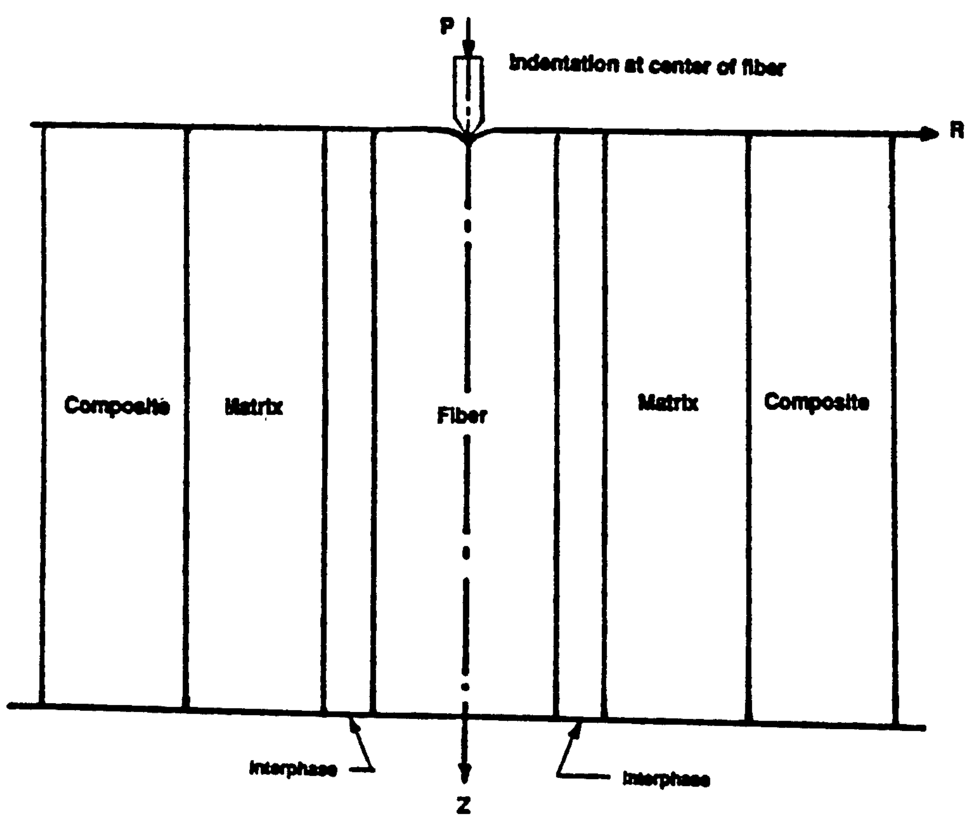


FINITE ELEMENT ANALYSIS

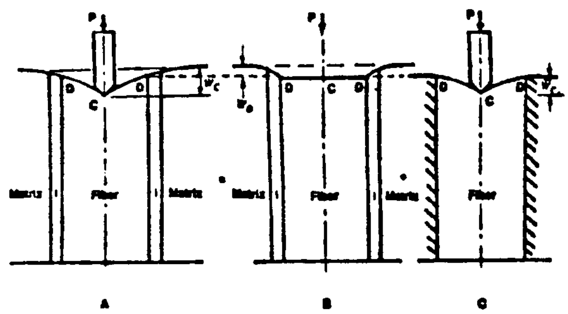


Axisymmetric Finite Element Model

NANO-INDENTATION TEST



METHOD OF ANALYSIS



$$W_C = W_D + \bar{W}_C$$

$$W_C^i = W_D^i + \bar{W}_C^i \quad \text{for } V_f^i$$

$$W_C^{i+1} = W_D^{i+1} + \bar{W}_C^{i+1} \quad \text{for } V_f^{i+1}$$

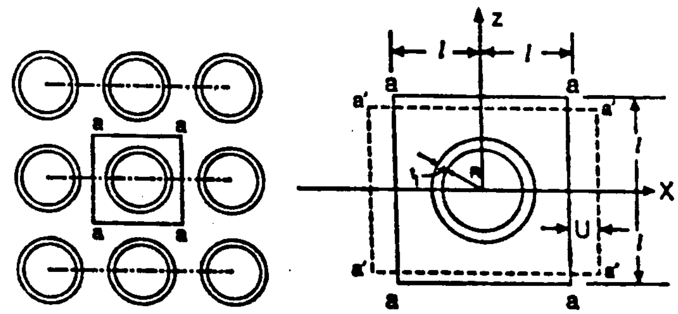
$$W_C^{i+1} - W_C^i = (W_D^{i+1} - W_D^i) + (\bar{W}_C^{i+1} + \bar{W}_C^i)$$

But $$\bar{W}_C^{i+1} = \bar{W}_C^i$$

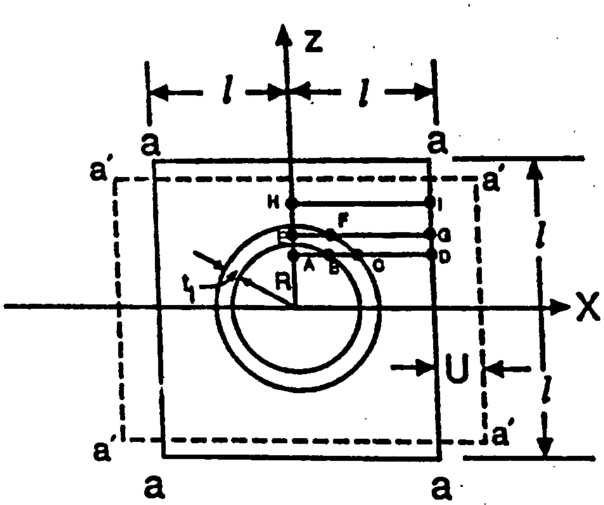
$$W_C^{i+1} - W_C^i = W_D^{i+1} - W_D^i$$

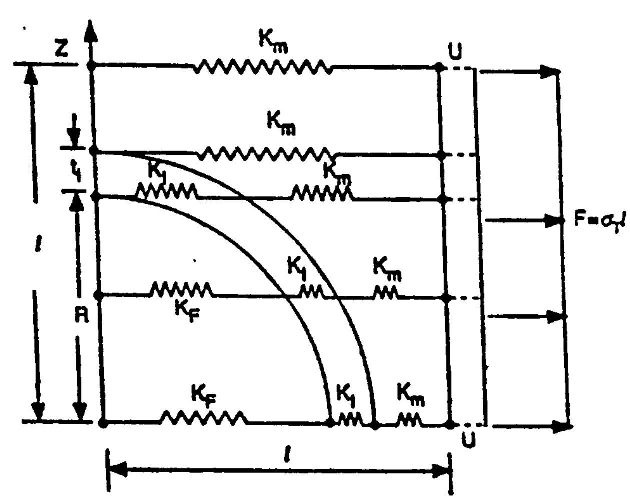
$$\Delta_i = W_D^{i+1} - W_D^i$$

INFLUENCE OF INTERPHASE MODULUS AND THICKNESS ON THE TRANSVERSE TENSILE STRENGTH OF COMPOSITE MATERIALS

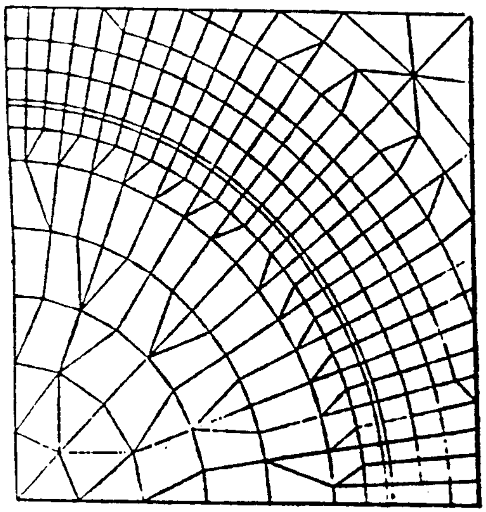


BASIC CONCEPT FOR ONE-DIMENSIONAL MODEL

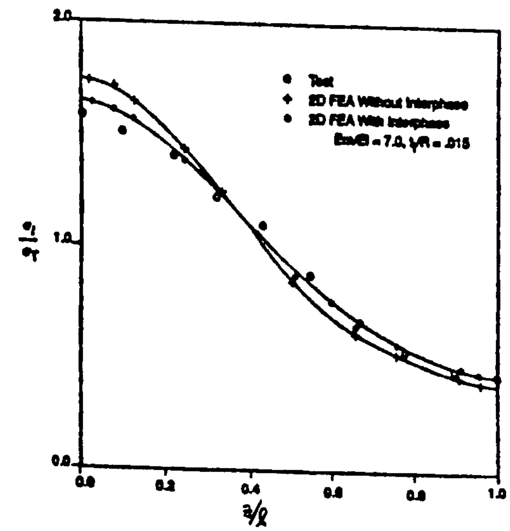




TWO-DIMENSIONAL FINITE ELEMENT MODEL



TRANSVERSE TENSILE STRESS DISTRIBUTION 2-D F.E.A. VS. TEST

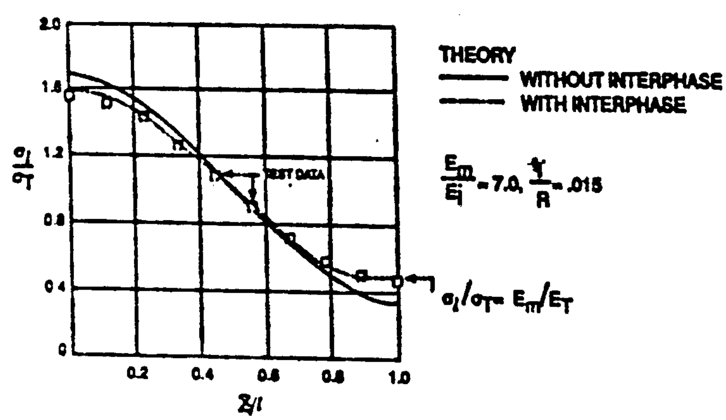


TRANSVERSE TENSILE STRESS DISTRIBUTION 1-D THEORY VS. TEST

A_l/E_p

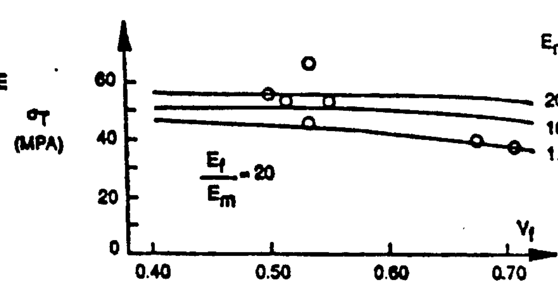
$E_f = 10.0 \times 10^6$ psi , $\nu_f = 0.31$ · $V_f = 0.502$

$E_m = 0.47 \times 10^6$ psi , $\nu_m = 0.36$



CORRELATION OF 1-D THEORY WITH TEST DATA Gl/Ep COMPOSITES

(σ_{mi} = 74.2 MPA, t_i/R = .0286)



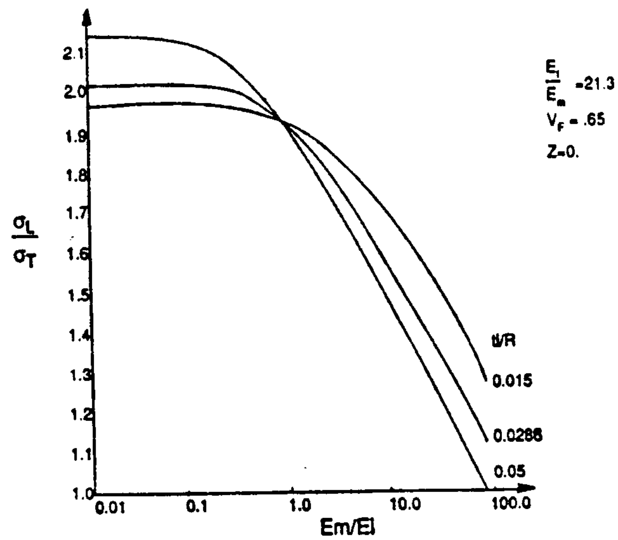
COMPARISON OF 1-D AND 2-D ANALYSIS RESULTS

($E_f/E_m = 21.3$, $V_F = 0.65$, $t/R = .015$)

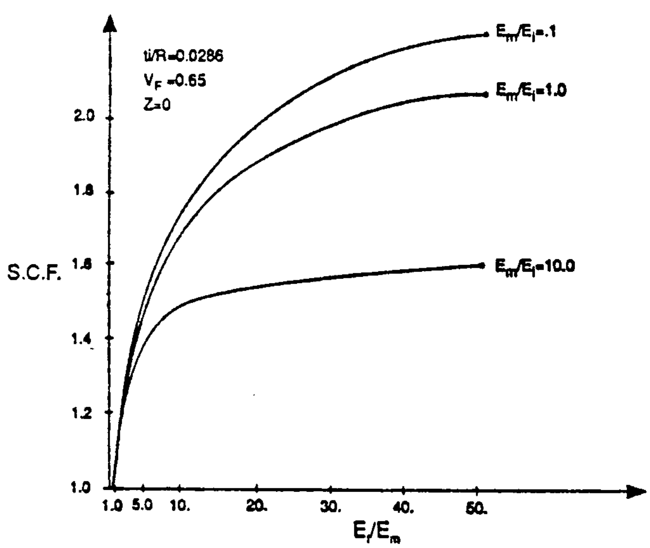
S.C.F.

Em/Ei / METHOD	1.0	10.0	15.0	20.0	30.0	40.0	50.0
1-D	1.905	1.651	1.582	1.531	1.460	1.410	1.371
2-D	2.019	1.716	1.643	1.592	1.518	1.459	1.412
1-D/2-D	.944	.962	.963	.962	.961	.966	.971

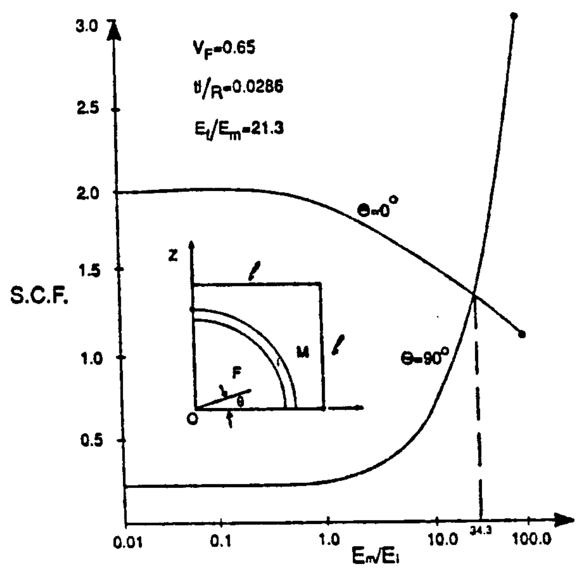
EFFECT OF INTERPHASE MODULUS AND THICKNESS ON THE MAXIMUM TRANSVERSE TENSILE STRESS



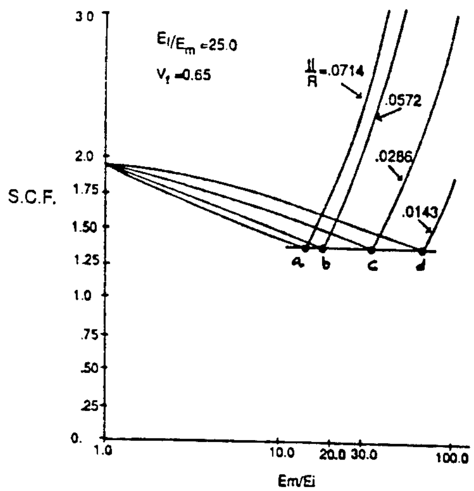
EFFECT OF Ef/Em AND Em/Ei ON THE MAXIMUM STRESS CONCENTRATION FACTORS



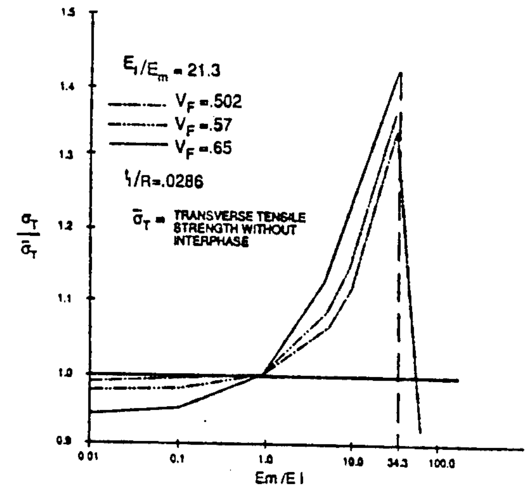
THE SHIFT OF THE CRITICAL LOCATION



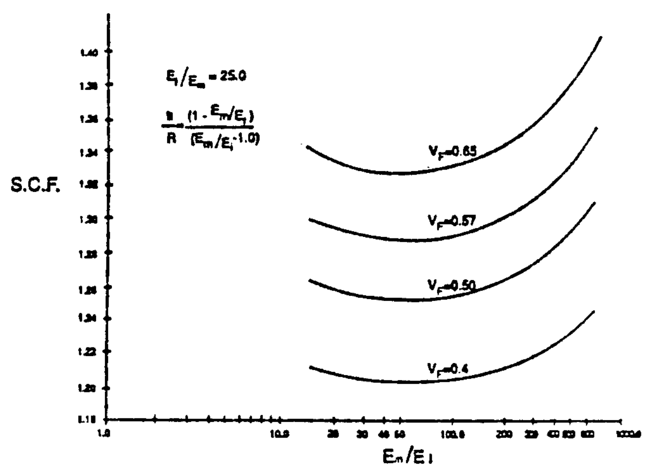
CRITICAL STRESS CONCENTRATION FACTORS AS FUNCTIONS OF INTERPHASE MODULI AND THICKNESS



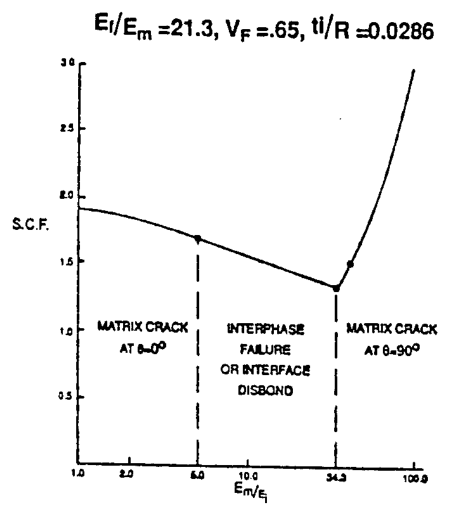
EFFECT OF INTERPHASE MODULI ON THE TRANSVERSE TENSILE STRENGTH OF THE COMPOSITE MATERIAL



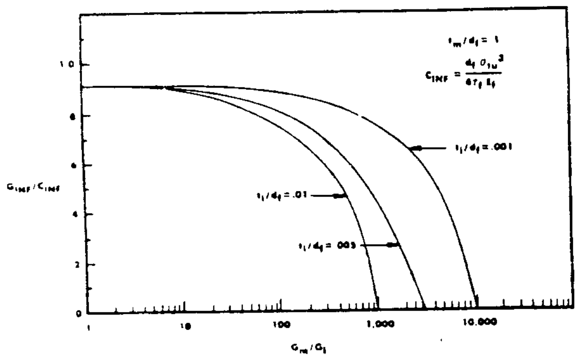
DESIGN CURVES FOR OPTIMAL INTERPHASE MODULUS AND THICKNESS



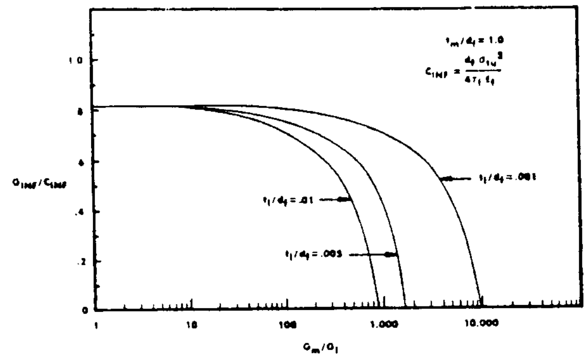
DESIGN CURVE FOR TRANSVERSE TENSILE FAILURE OF THE COMPOSITE MATERIAL.



EFFECT OF THE INTERPHASE ON THE OPENING MODE FRACTURE ENERGY OF A UNIDIRECTIONAL COMPOSITE FOR $t_m/d_f = 0.1$.



EFFECT OF THE INTERPHASE ON THE OPENING MODE FRACTURE ENERGY OF A UNIDIRECTIONAL COMPOSITE FOR $t_m/d_f = 1.0$.



CONCLUSIONS

<u>PREDICTION OF INTERPHASE PROPERTIES</u>

- SHEAR LAG MODEL HAS GOOD CORRELATION WITH ROCKWELL'S TEST DATA AND FEM ANALYSIS

- INTERPHASE THICKNESS ≤ 1.0 μM

- INTERPHASE MODULUS

  $G_i/G_m \approx .5$ FOR UNCOATED AND HYDROGENATED FIBER
  $G_i/G_m \approx 2$ FOR SIZED FIBER

- LOW STRAIN LEVEL OF TENSION-FIBER TEST MAKE DRAWING INTERPHASE PROPERTY CONCLUSIONS DIFFICULT. NEED MORE DATA NEAR INTERPHASE, $r < r_f + 1\ \mu m$

<u>EFFECT OF INTERPHASE PROPERTIES ON THE STRENGTH AND FRACTURE TOUGHNESS OF THE COMPOSITE MATERIAL</u>

- THE INTERPHASE HAS SIGNIFICANT EFFECT ON TRANSVERSE TENSILE STRENGTH, TRANSVERSE FAILURE MODE AND FRACTURE TOUGHNESS OF THE COMPOSITE MATERIAL

- TO TOUGHEN THE COMPOSITE A SMALLER INTERPHASE THICKNESS AND Gm/Gi RATIO IS DESIRED. TO ACHIEVE A HIGHER TRANSVERSE TENSILE STRENGTH, THE OPPOSITE IS TRUE.

Ten Year Ground Exposure of Composite Materials Used on Bell Model 206 L Helicopter Flight Service Evaluation

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ABSTRACT

Over the past 15 years NASA has sponsored programs to build a data base and establish confidence in the long-term durability of advanced composite materials in aircraft structures. Primary and secondary composite components have been installed on commercial aircraft to obtain worldwide experience. Concurrent with the flight service programs, materials used to fabricate the components have been exposed in ground racks and have been tested at prescribed intervals to determine the effects of outdoor environments.

Residual strength results are presented on four composite material systems that have been exposed up to ten years at five locations on the North American continent. The exposure areas are near where the Bell Model 206L helicopters, that are in a NASA/U.S. Army sponsored flight service program, are flying in daily commercial service. The composite material systems are: 1.) Kevlar-49 fabric/F-185 epoxy; 2.) Kevlar-49 fabric/LRF-277 epoxy; 3.) Kevlar-49 fabric/CE-306 epoxy; and 4.) T-300 graphite/E-788 epoxy. Six replicates of each material were removed after 1, 3, 5 , 7, and 10 years of exposure and tested. The average baseline strength was determined from testing six as fabricated specimens. Over 1700 specimens have been tested. All specimens that were tested for strength were painted with a polyurethane paint. Each set of specimens removed also included an unpainted panel for observing the weathering effects on the composite materials.

Residual compression strength of the Kevlar-49/LRF-277 material varied between 88 and 90 percent of the baseline average over the ten-year outdoor exposure period. Residual compression strength of the other materials exceeded 92 percent of the baseline average for the ten-year exposure period. Residual short beam shear strength for the Kevlar-49/LRF-277 material varied between 89 and 92 percent of the baseline average, while the other materials exceeded 92 percent of the baseline average. Residual tensile strength of all materials did not show a significant reduction. Visual observations of the unpainted specimens indicated loss of resin and fibers in the exposed ply with increasing exposure time. Moisture absorption data through seven years of exposure are presented. The Kelvar-49/F-185 absorbs more moisture when painted. Paint has little effect on moisture absorption of the other materials.

TEN YEAR GROUND EXPOSURE OF COMPOSITE MATERIALS USED ON BELL MODEL 206L HELICOPTER FLIGHT SERVICE EVALUATION

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Mechanics of Composites Review
November 12-13, 1991

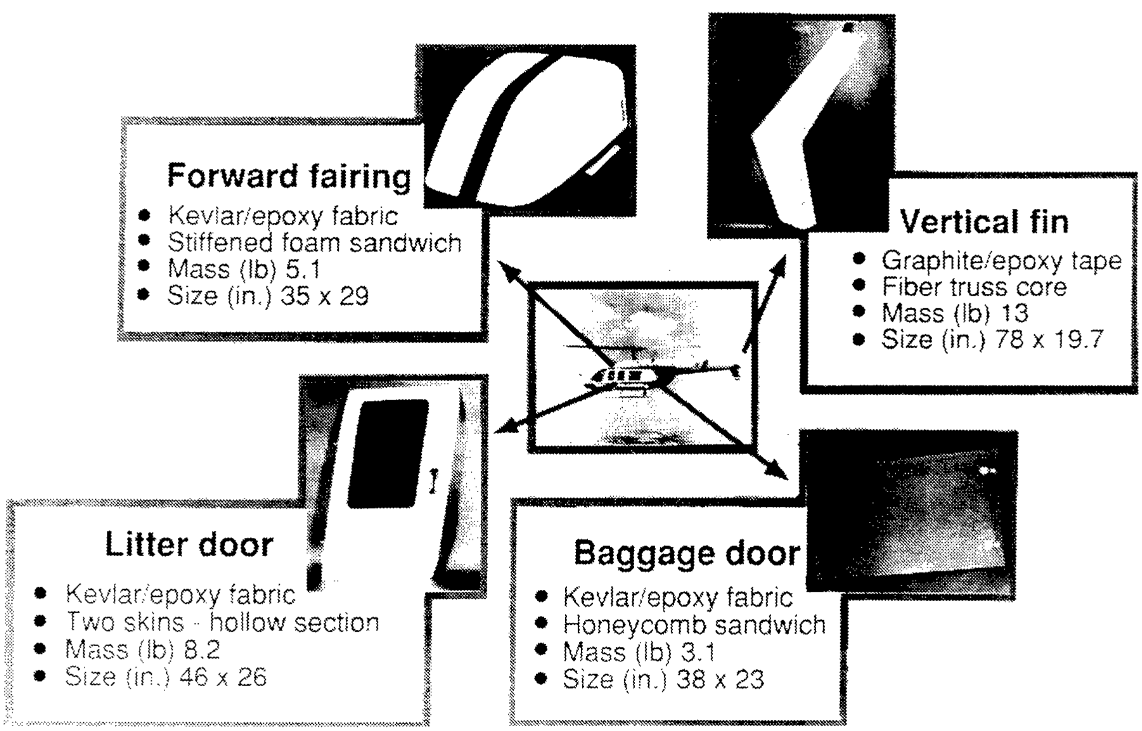
OUTLINE

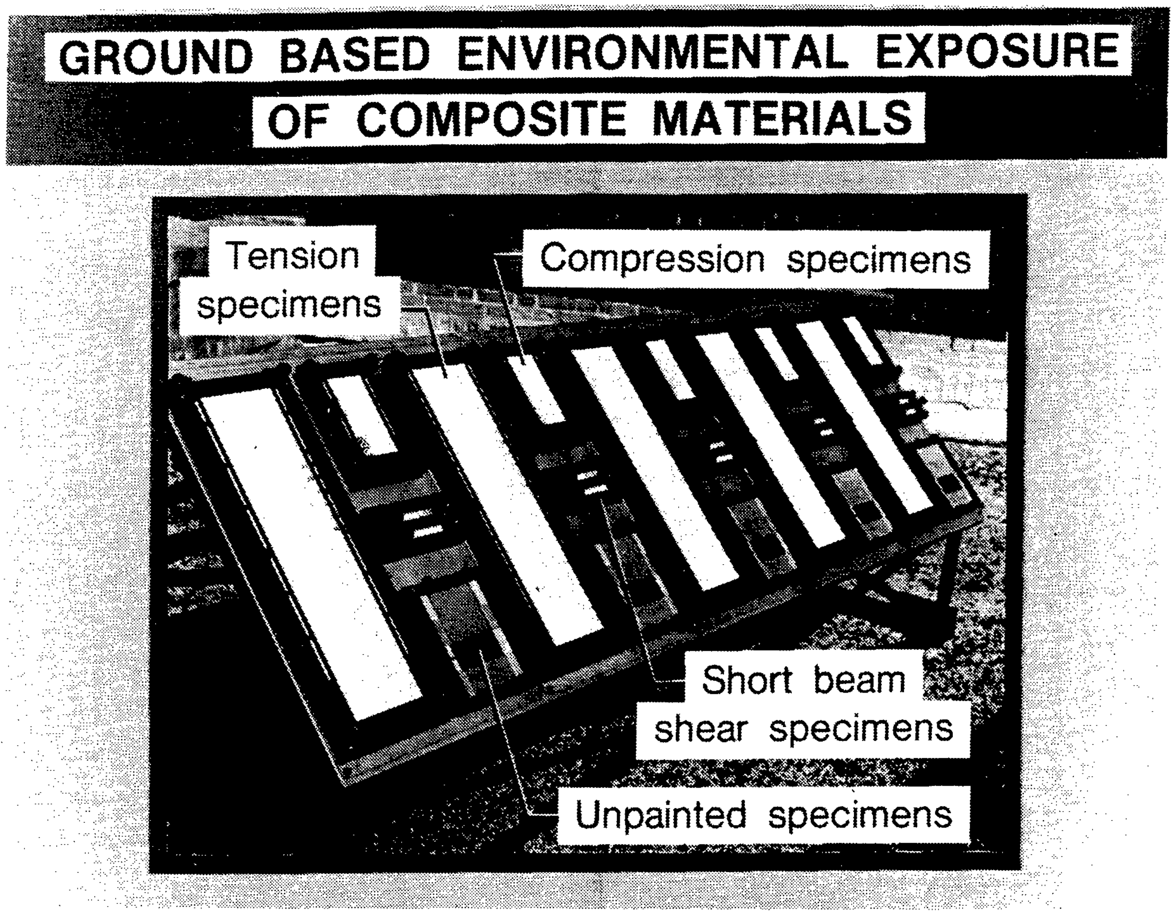
- Flight Service Program
- Exposure Sites
- Specimens
- Strength Results
- Moisture Absorption Results

OBJECTIVES

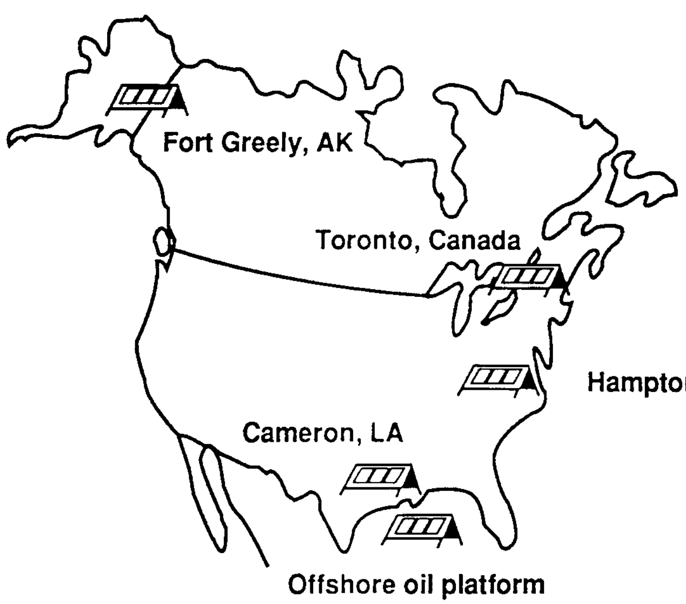
- Access the Effects of Ground-based Environments on Material Systems used in the Bell 206L Flight Service program
- Supplement Component Data with less Expensive Coupon Data
- Correlate Ground Exposure Data with Flight Exposure Data
- Access the Requirement for Future Flight Service Programs

BELL 206L HELICOPTER COMPOSITE COMPONENTS





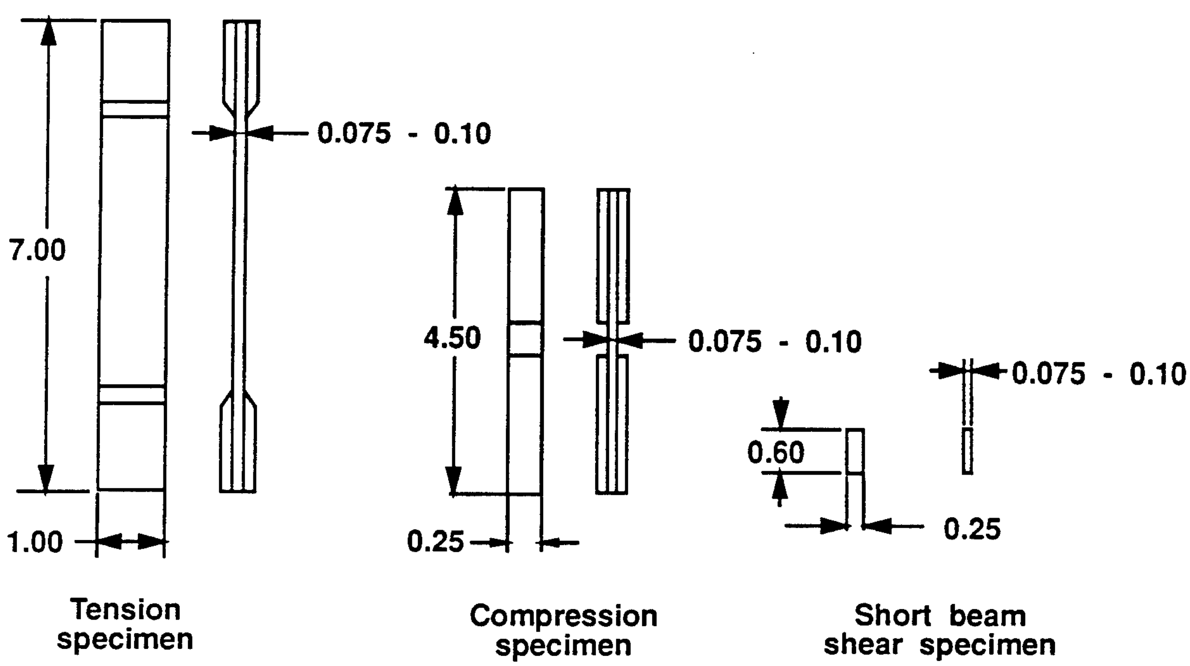
LOCATIONS OF GROUND BASED ENVIRONMENTAL EXPOSURE OF COMPOSITE MATERIALS USED IN BELL 206L COMPONENTS



MATERIAL SYSTEMS AND SPECIMEN LAY-UP

- Kevlar-49 Fabric (Style 281) /F-185 Epoxy - $[0/45/0]_s$
- Kevlar-49 Fabric (Style 120) /LRF-277 Epoxy - [0]
- Kevlar-49 Fabric (Style 281) /CE-306 Epoxy - [0]
- T-300 Tape/E-788 Epoxy - $[0/45/-45/0]_{2s}$

SPECIMEN GEOMETRY

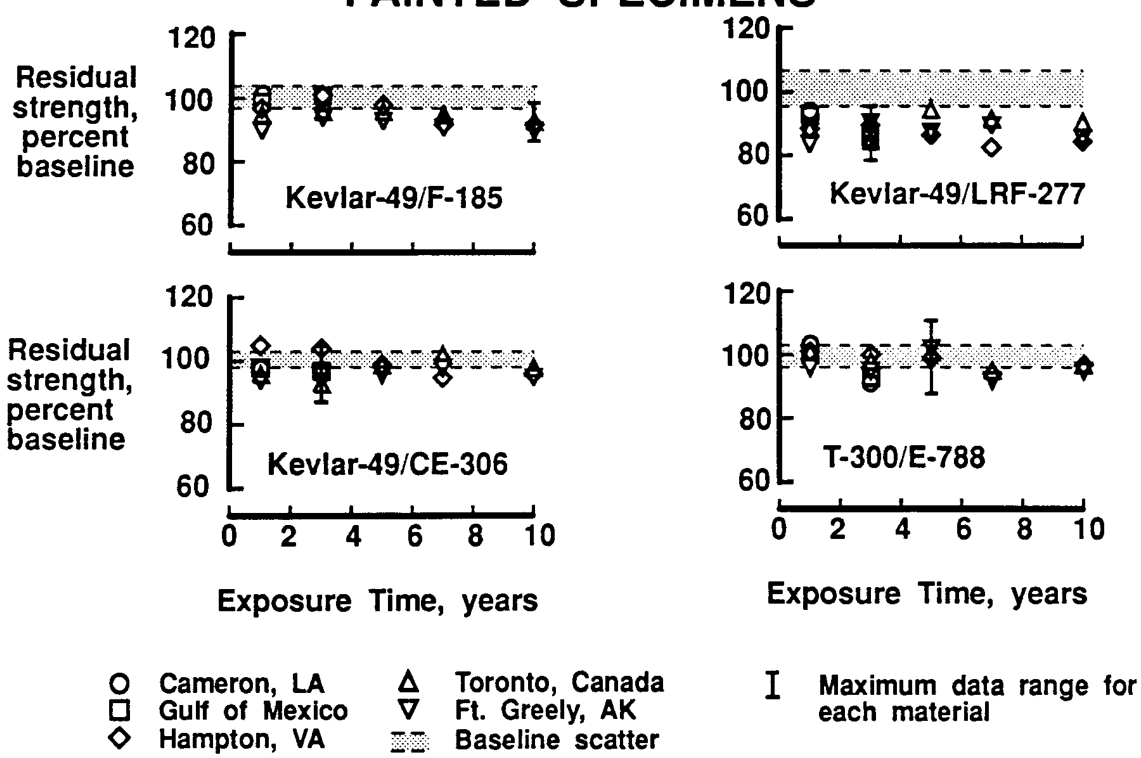


BASELINE STRENGTHS OF AS-FABRICATED SPECIMENS

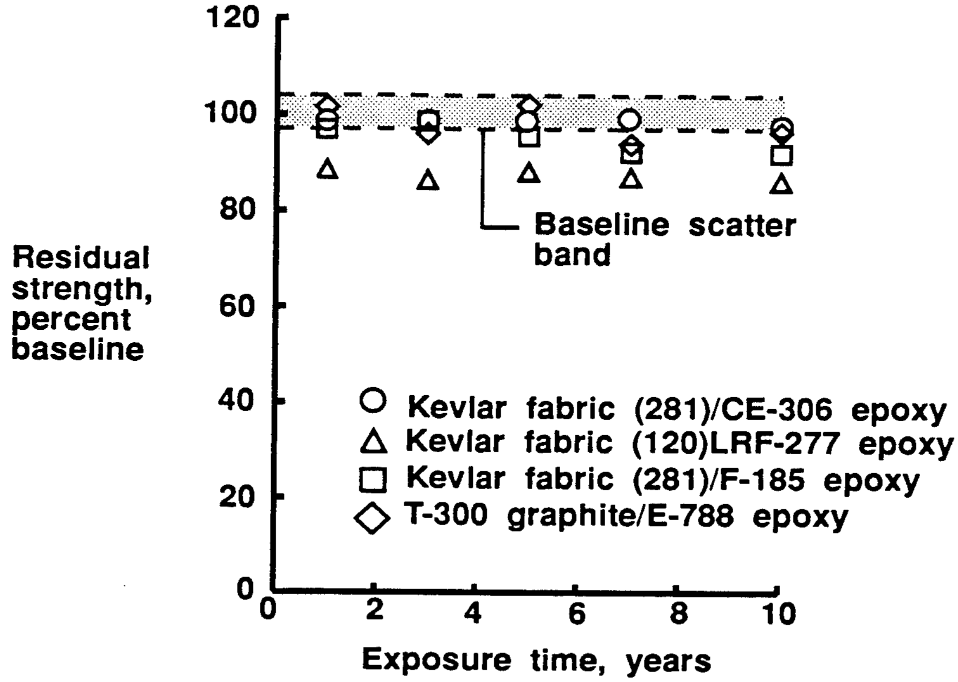
Material Systems	Strength (psi)					
	Short Beam Shear		Compression		Tension	
	Mean [a]	S. D. [b]	Mean	S. D.	Mean	S. D.
Kevlar-49/ F-185	6018	197	20176	489	57363	2448
Kevlar-49/ LRF-277	3873	119	22363	909	83658	2198
Kevlar-49/ CE-306	5277	258	18265	337	61090	2917
T-300/ E-788	11222	285	126343	4025	126478	4209

a Mean of 6 Specimens
b S.D. - Standard Deviation

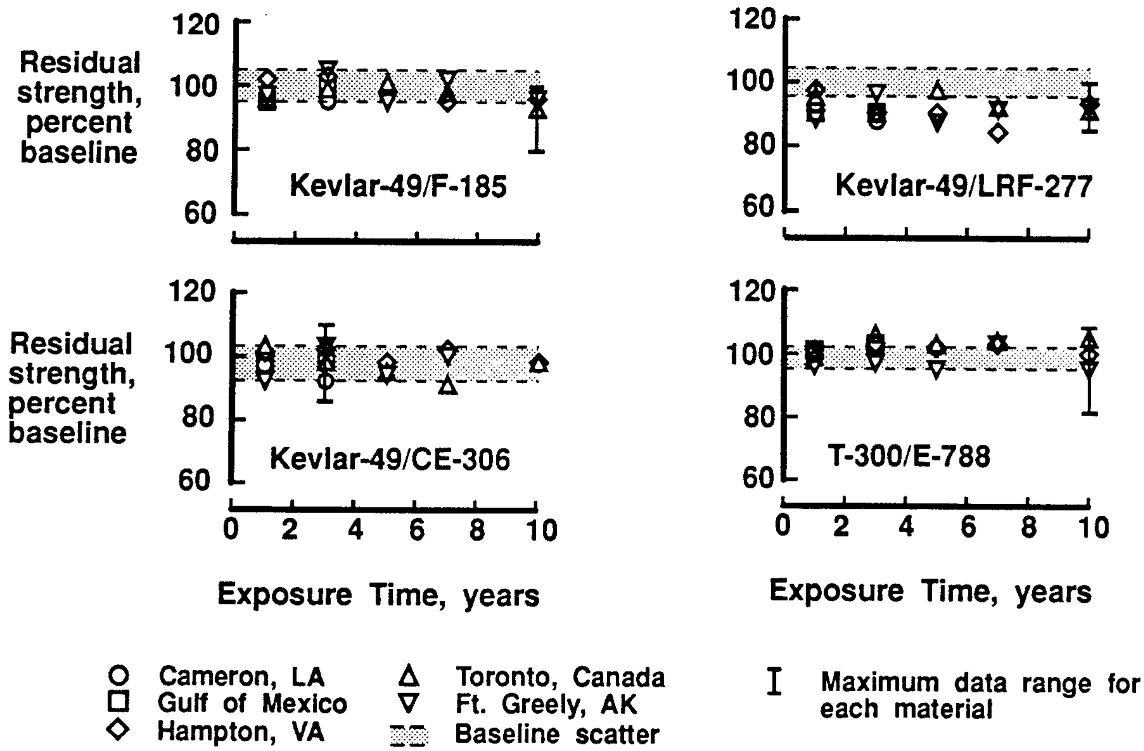
EFFECT OF EXPOSURE LOCATION ON THE RESIDUAL COMPRESSION STRENGTH OF PAINTED SPECIMENS



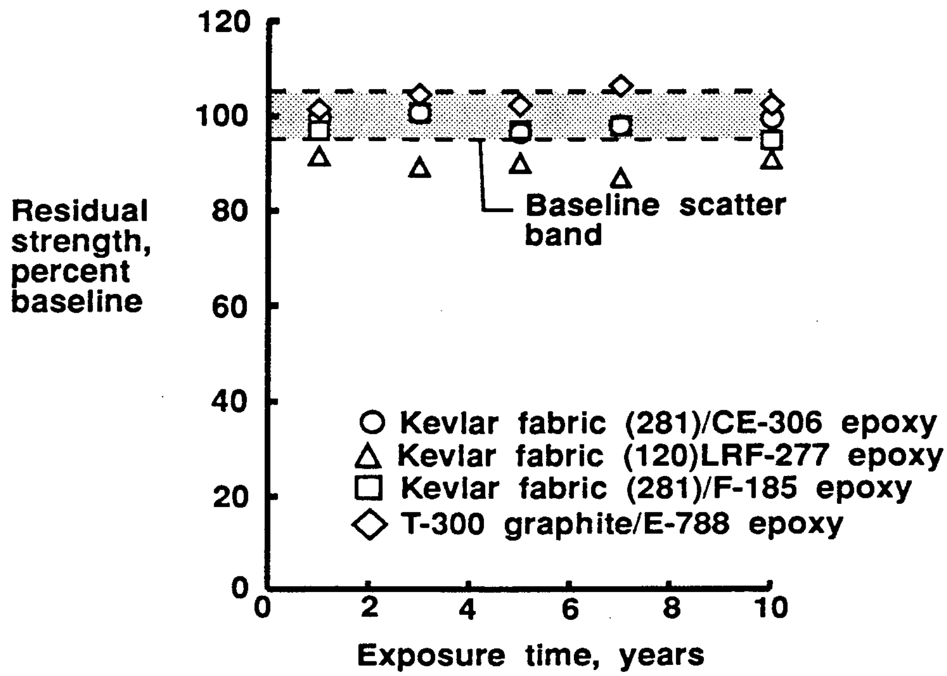
RESIDUAL COMPRESSION STRENGTH OF PAINTED COMPOSITE SPECIMENS AFTER OUTDOOR EXPOSURE



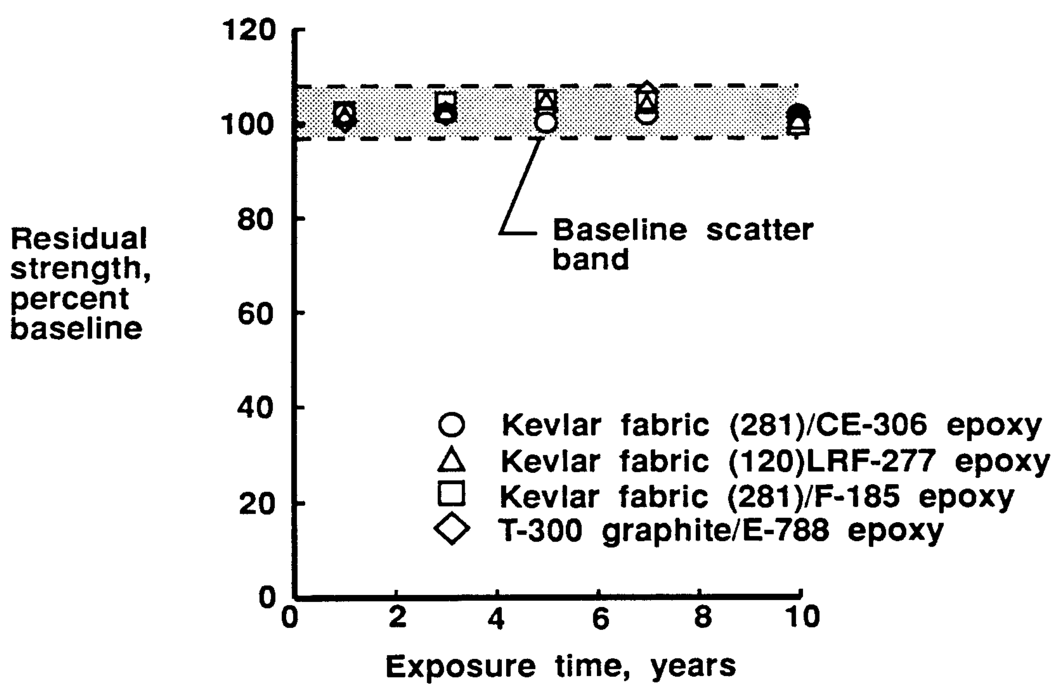
EFFECT OF EXPOSURE LOCATION ON THE RESIDUAL SHORT BEAM SHEAR STRENGTH OF PAINTED SPECIMENS



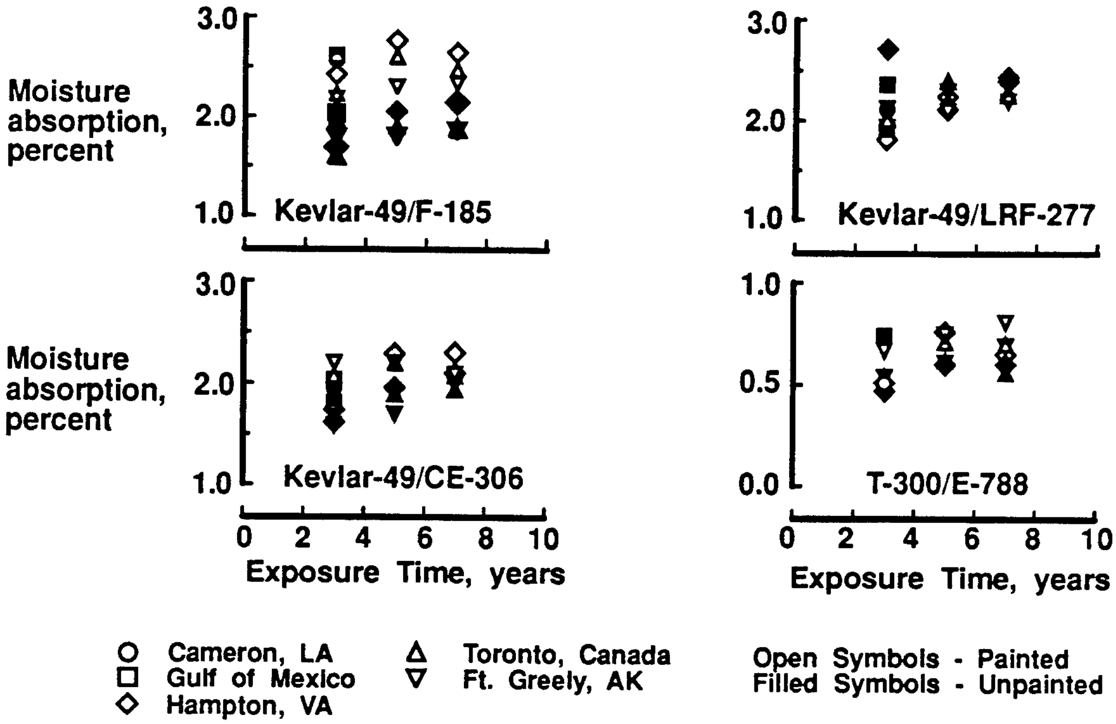
RESIDUAL SHORT BEAM SHEAR STRENGTH OF PAINTED COMPOSITE SPECIMENS AFTER OUTDOOR EXPOSURE



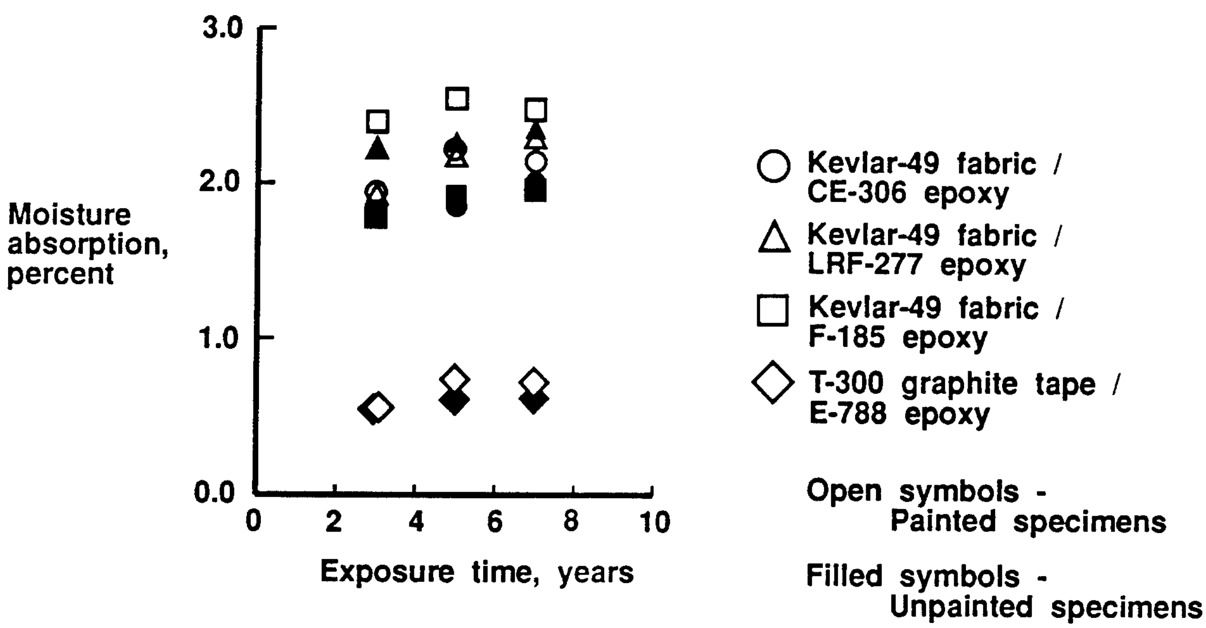
RESIDUAL TENSION STRENGTH OF PAINTED COMPOSITE SPECIMENS AFTER OUTDOOR EXPOSURE



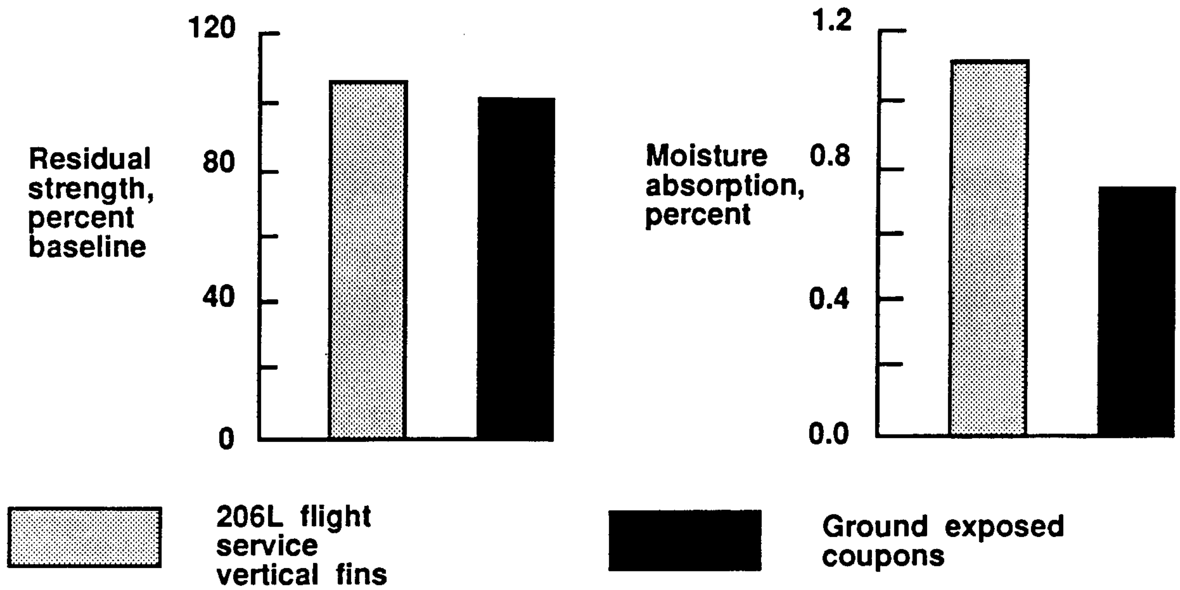
EFFECT OF EXPOSURE LOCATION ON THE MOISTURE ABSORPTION OF COMPOSITE SPECIMENS



AVERAGE MOISTURE ABSORPTION OF COMPOSITE MATERIAL SPECIMENS



STRENGTH RETENTION AND MOISTURE ABSORPTION OF T300/E-788 AFTER 5 YEARS OF GROUND AND FLIGHT EXPOSURE



CONCLUDING REMARKS

- After ten years of ground exposure
  - Compression and short beam shear strength
    - Residual strength for Kevlar-49/LRF-277 is 88 to 92 percent of baseline
    - Residual strength of other materials exceeds 92 percent of baseline
  - Tensile strength of all materials do not show a significant reduction
- After seven years of ground exposure
  - Kevlar-49/F-185 absorbs more moisture when painted
  - Paint has little effect on moisture absorption of other materials

PROGRESSIVE FRACTURE OF COMPOSITE THIN SHELLS UNDER INTERNAL PRESSURE

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National Aeronautics and Space Administration
Lewis Research Center, Cleveland, Ohio 44135

The ultimate load capacity of a composite cylindrical shell under internal pressure is investigated via computational simulation. The effects of initial fiber damage on composite durability are evaluated. The CODSTRAN (COmposite Durability STRuctural ANalysis) computer code (1–5) is used for computational simulation of composite structural degradation. CODSTRAN is able to simulate damage initiation, damage growth and fracture in composites under various loading and environmental conditions. The simulation of progressive fracture by CODSTRAN has been verified to be in reasonable agreement with experimental data from tensile tests (6).

In general, overall structural damage may include individual ply damage and also through-the-thickness fracture of the composite laminate. CODSTRAN is able to simulate varied and complex composite damage mechanisms via evaluation of the individual ply failure modes and associated degradation of laminate properties. In general, the type of damage growth and the sequence of damage progression depend on the composite structure, loading, material properties, and hygrothermal conditions. A scalar damage variable, derived from the total volume of the composite material affected by the various damage mechanisms is also computed as an indicator of the level of overall damage induced by loading. This damage variable is useful for assessing the overall degradation of the given structure under the prescribed loading condition. The rate of overall damage growth with work done during composite degradation is used to evaluate the propensity of structural fracture with increasing loading. Computation of the overall damage variable has no interactive feedback on the

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†Aerospace Engineer, Structures Division.
‡Senior Aerospace Scientist, Structures Division.

detailed simulation of composite degradation. The procedure by which the overall damage variable is computed is given in reference (4).

A composite system made of Thornel-300 graphite fibers in an epoxy matrix (T300/Epoxy) is used to illustrate a CODSTRAN durability analysis. The laminate consists of fourteen 0.127 mm (0.005 in.) plies resulting in a composite shell thickness of 1.778 mm (0.07 in.). The laminate configuration is $[90_2/\pm15/90_2/\pm15/90_2/\mp15/90_2]$. The 90° plies are in the hoop direction and the ±15° plies are oriented with respect to the axial direction of the shell. The cylindrical shell has a diameter of 1.016 m (40 in.) and a length of 2.032 m (80 in.). The finite element model contains 612 nodes and 576 quadrilateral elements. At one point along the circumference, at half-length of the cylinder, initial fiber fractures in two hoop plies are prescribed. The composite shell is subjected to an internal pressure that is gradually increased until the shell is fractured. To simulate the stresses in a closed-end cylindrical pressure vessel, a uniformly distributed axial tension is applied to the cylinder such that axial stresses in the shell wall are half those developed in the hoop direction. Results demonstrate the significance of local damage on the structural durability of pressurized composite cylindrical shells.

REFERENCES

1. C. C. Chamis and G. T. Smith, "Composite Durability Structural Analysis," NASA TM-79070, 1978.

2. L. Minnetyan, C. C. Chamis, and P. L. N. Murthy, "Structural Behavior of Composites with Progressive Fracture," NASA TM-102370, January 1990, 18 pp.

3. L. Minnetyan, P. L. N. Murthy, and C. C. Chamis, "Progression of Damage and Fracture in Composites under Dynamic Loading," NASA TM-103118, April 1990, 16 pp.

4. L. Minnetyan, P. L. N. Murthy, and C. C. Chamis, "Composite Structure Global Fracture Toughness via Computational Simulation," *Computers & Structures*, Vol. 37, No. 2, pp.175-180, 1990

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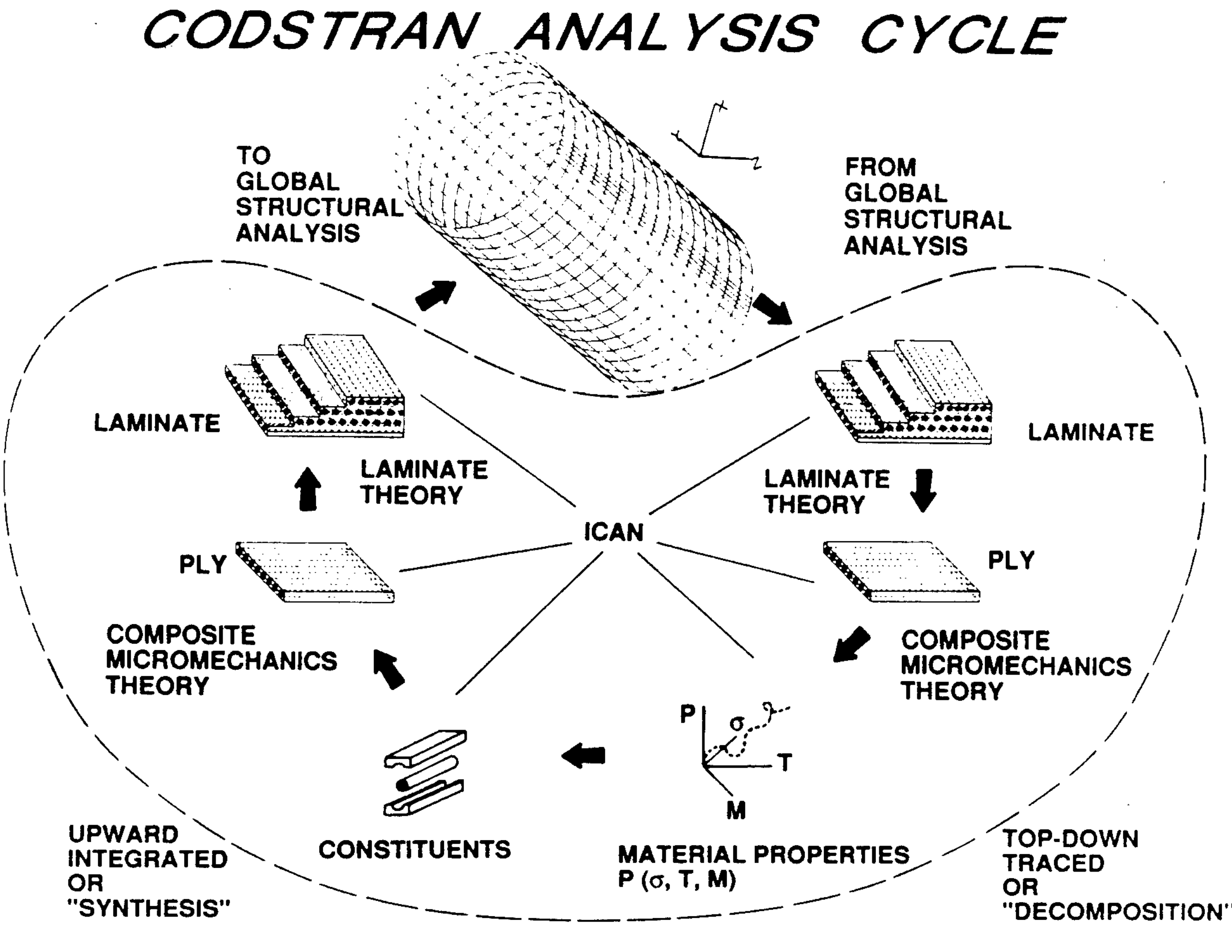
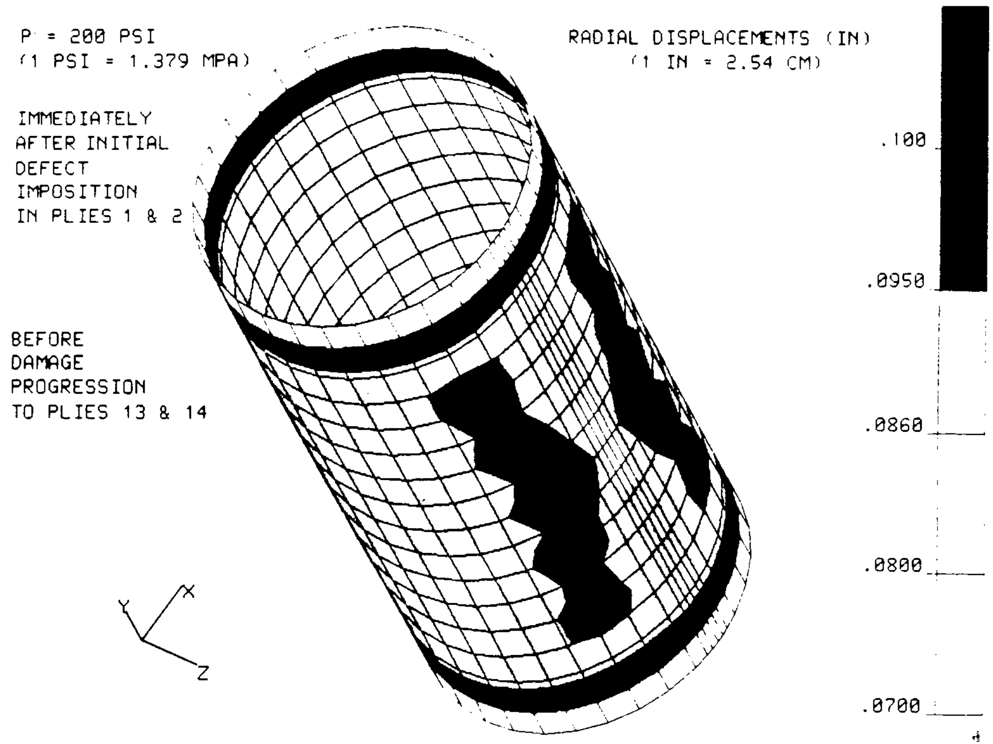
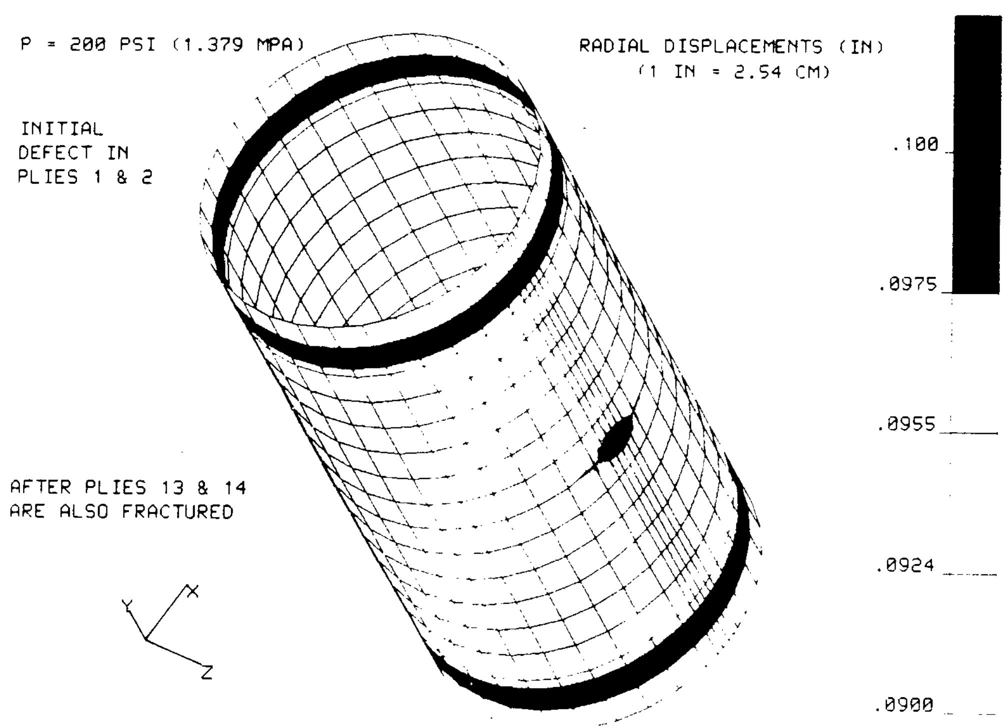
7. P. L. N. Murthy and C. C. Chamis, *Integrated Composite Analyzer (ICAN): Users and Programmers Manual*, NASA Technical Paper 2515, March 1986.

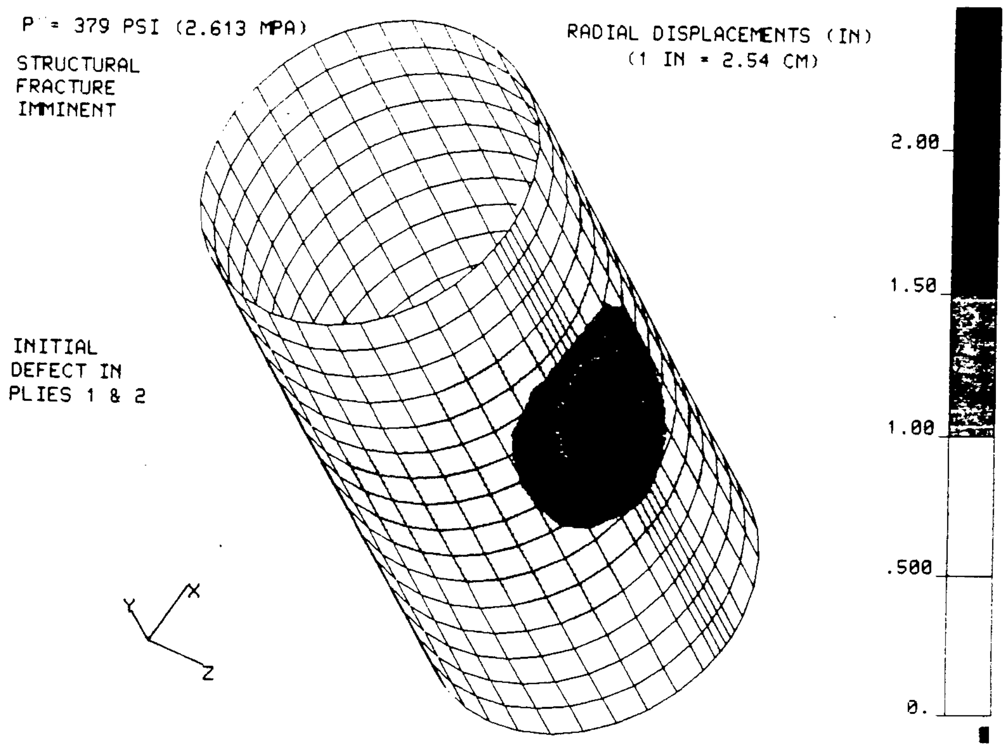


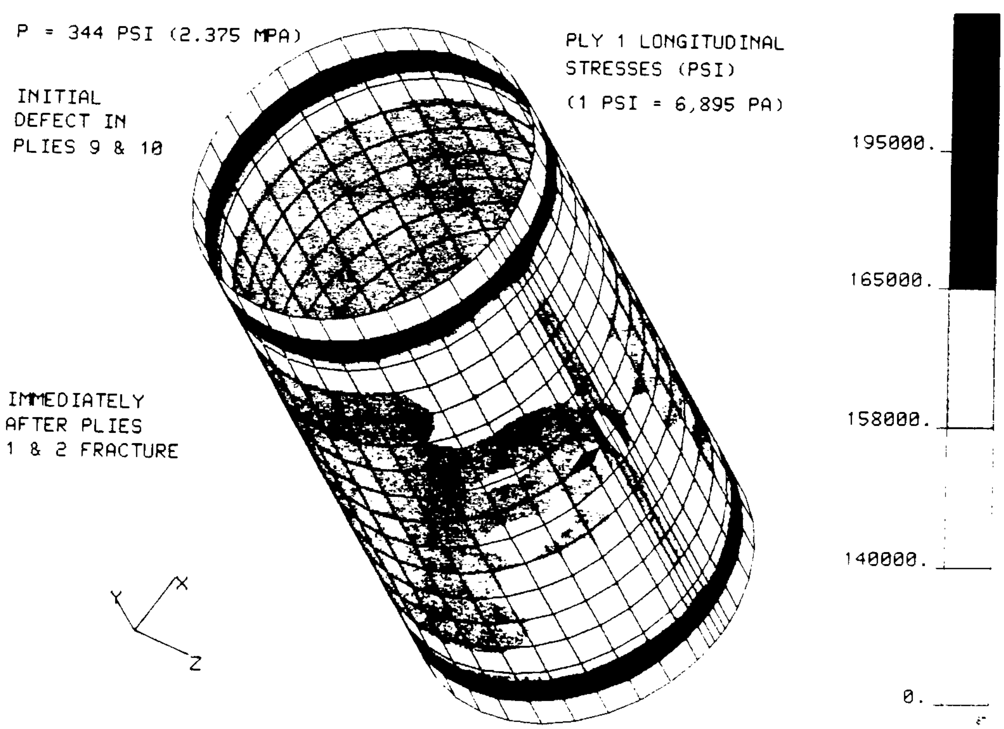
Composite Shell/ Internal Pressure

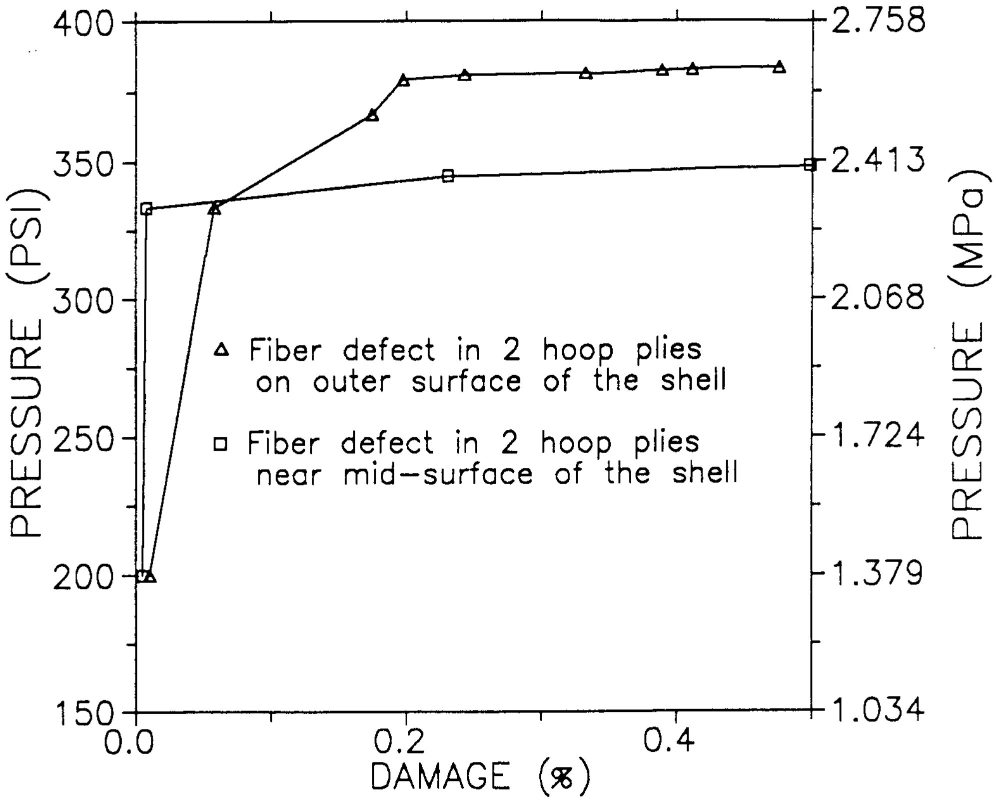
- Surface ply fiber fractures
- Mid-thickness ply fiber fractures
- Damage growth/ fracture progression
- Structural fracture resistance
- Ultimate load capacity
- Hygrothermal effects

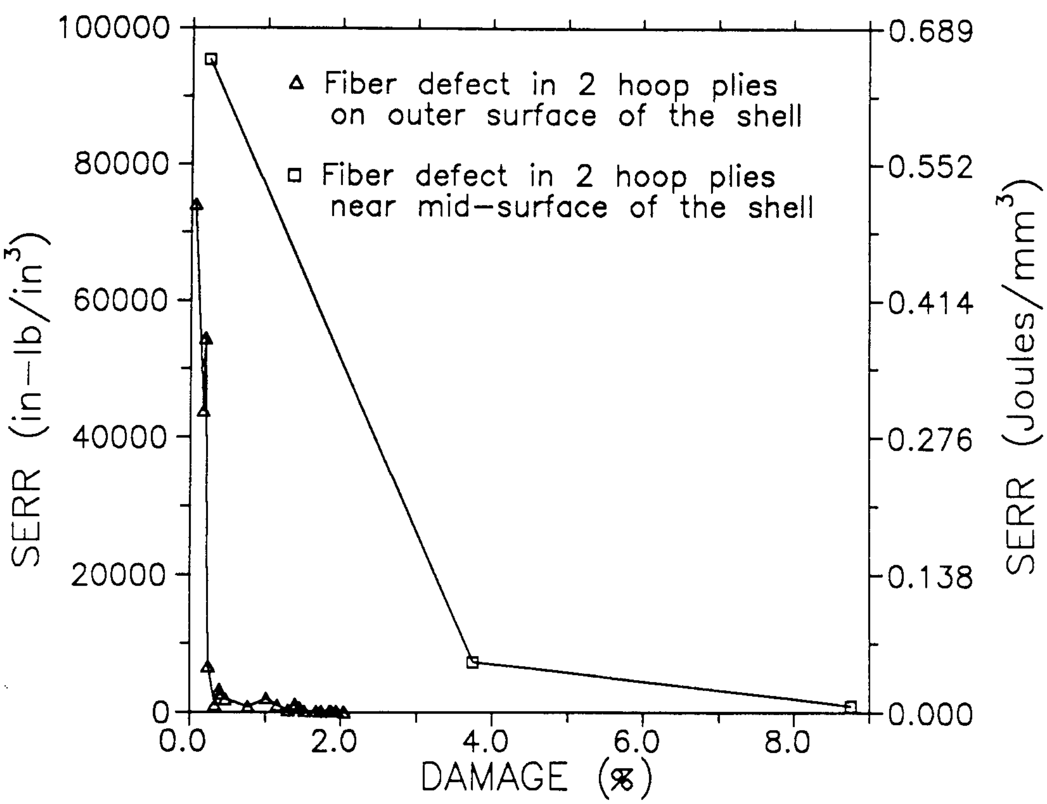

P = 200 PSI
(1 PSI = 1.379 MPA)
IMMEDIATELY
AFTER INITIAL
DEFECT
IMPOSITION
IN PLIES 1 & 2
BEFORE
DAMAGE
PROGRESSION
TO PLIES 13 & 14
RADIAL DISPLACEMENTS (IN)
(1 IN = 2.54 CM)
.100
.0950
.0860
.0800
.0700
Y
X
Z


P = 200 PSI (1.379 MPA)
INITIAL
DEFECT IN
PLIES 1 & 2
AFTER PLIES 13 & 14
ARE ALSO FRACTURED
RADIAL DISPLACEMENTS (IN)
(1 IN = 2.54 CM)
.100
.0975
.0955
.0924
.0900
Y
X
Z


P = 379 PSI (2.613 MPA)
STRUCTURAL
FRACTURE
IMMINENT
INITIAL
DEFECT IN
PLIES 1 & 2
RADIAL DISPLACEMENTS (IN)
(1 IN = 2.54 CM)
2.00
1.50
1.00
.500
0.
Y
X
Z


P = 344 PSI (2.375 MPA)
INITIAL
DEFECT IN
PLIES 9 & 10
IMMEDIATELY
AFTER PLIES
1 & 2 FRACTURE
PLY 1 LONGITUDINAL
STRESSES (PSI)
(1 PSI = 6,895 PA)
195000.
165000.
158000.
140000.
0.
Y
X
Z

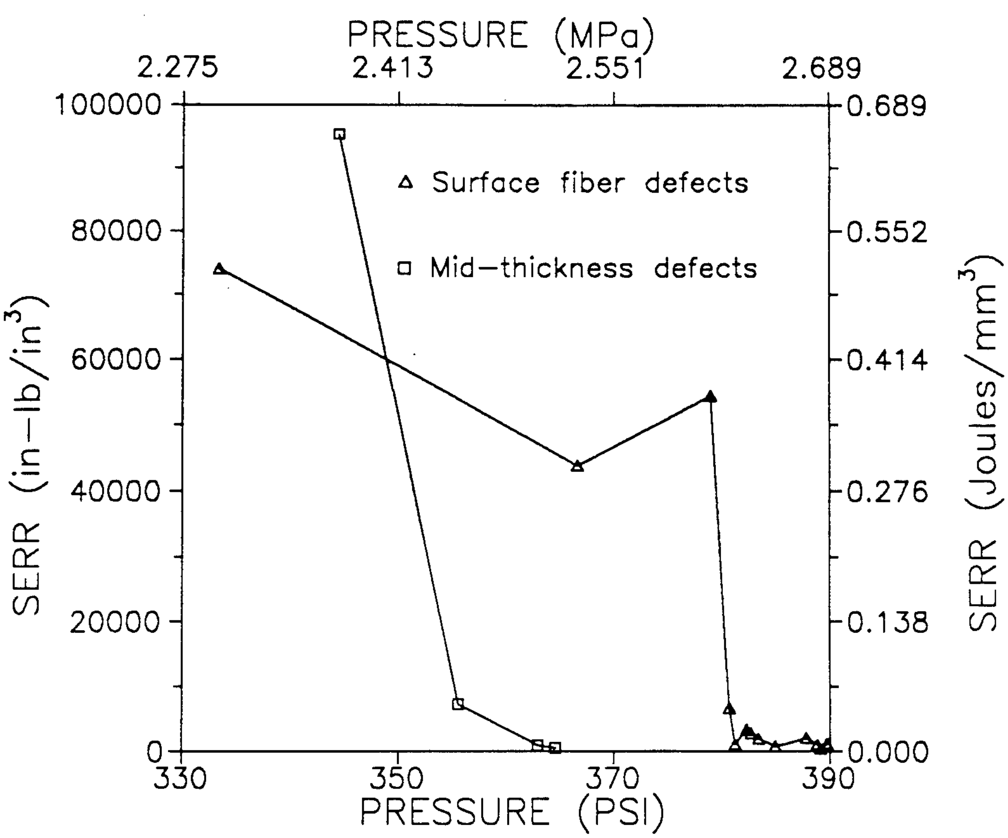

PRESSURE (PSI)
PRESSURE (MPa)
DAMAGE (%)
400
350
300
250
200
150
2.758
2.413
2.068
1.724
1.379
1.034
0.0
0.2
0.4
Fiber defect in 2 hoop plies on outer surface of the shell
Fiber defect in 2 hoop plies near mid-surface of the shell


SERR (in-lb/in³)
SERR (Joules/mm³)
DAMAGE (%)
100000
80000
60000
40000
20000
0
0.689
0.552
0.414
0.276
0.138
0.000
0.0
2.0
4.0
6.0
8.0
Fiber defect in 2 hoop plies on outer surface of the shell
Fiber defect in 2 hoop plies near mid-surface of the shell

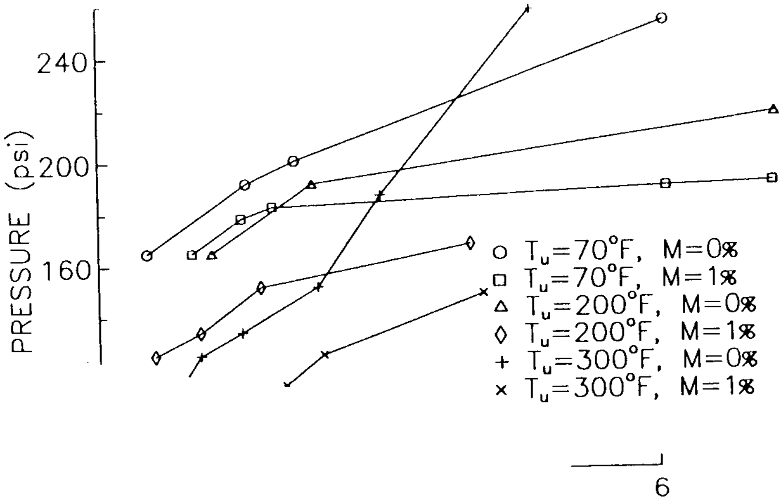
Composite Shell T300/Epoxy$[90_2/\pm15/90_2/\pm15/90_2/\mp15/90_2]$

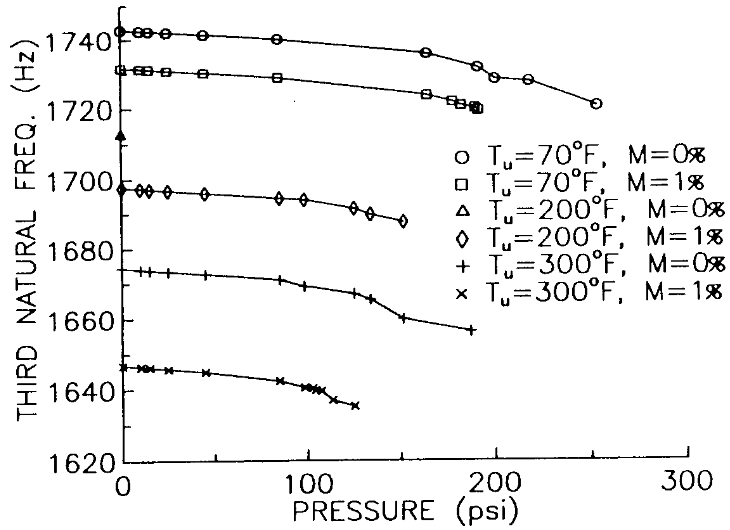
	Percent of Undamaged Ultimate Pressure		
	Without Initial Damage	Initial Damage in Surface Ply Fibers	Initial Damage in Mid-thickness Ply Fibers
First Damage Growth	84	45	75
Ultimate Structural Fracture	100	85	77

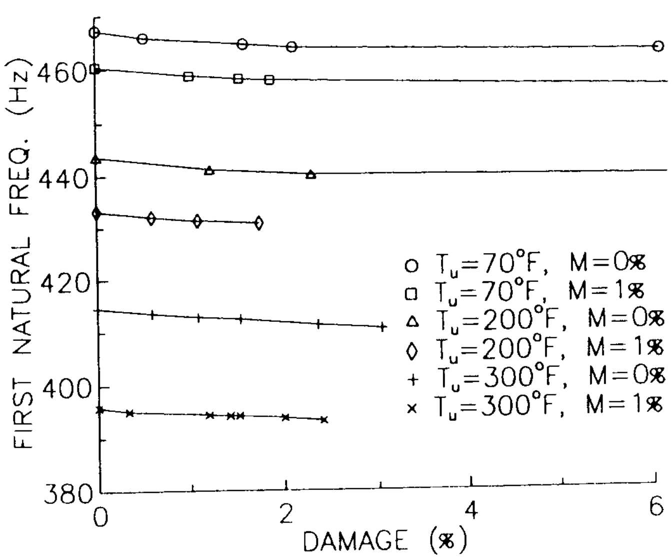
Undamaged Ultimate Pressure = 445 psi

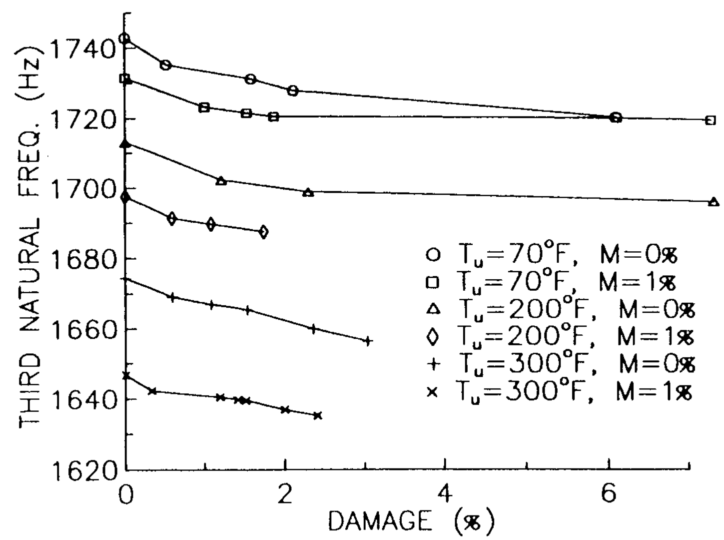


T-300/Epoxy (90,±15)s Shell – Hygrothermal Effects









Other loading cases that may be investigated:

- compression
- bending
- torsion
- external pressure/stability
- impact/blast pressure
- fatigue, and combinations of these loads.
- pressurized tank drop
- hygrothermal environment
- variable thickness composites, hybrid composites
- thick composite shells
- multi-component structures
- post-buckling behavior

Paper Proposed for Presentation at
16th Mechanics of Composites Review
Dayton, Ohio, November 12-13, 1991

COMPUTATIONAL MECHANICS FOR HOT COMPOSITE STRUCTURES

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Cleveland, Ohio

ABSTRACT

High temperature metal matrix composites (HT-MMCs) are emerging as materials with potentially high payoffs in aerospace structural applications. Realization of these payoffs depends on the parallel and synergistic development of: (1) a technology base for fabricating HT-MMC structural components, (2) experimental techniques for measuring their thermal and mechanical characteristics, and (3) computational methodologies for predicting their nonlinear behavior in complex service environments. In fact, it might be argued that the development of computational methodologies should precede the others because the structural integrity and durability of HT-MMCs can be computationally simulated, and the potential payoff for a specific application can be assessed, at least qualitatively. In this way, it is possible to minimize the costly and time consuming experimental effort that would otherwise be required in the absence of a representative simulation capability.

Recent research at NASA Lewis is directed towards the development of a computational capability to predict the nonlinear behavior of HT-MMCs. This capability is in the form of stand-alone computer codes which are used to computationally simulate HT-MMC behavior in all its inherent hierarchical scales. The simulation starts with constituents and the fabrication process and proceeds to determine the effects induced by the severe service loading environments. Five computer codes have been developed or are under development in order to provide computational capability for the hierarchical simulation of hot composite laminate/tailoring. These computer codes are: (1) CEMCAN (CEramic Matrix Composite ANalyzer), (2) METCAN (MEtal Matrix Composite ANalyzer), (3) MMLT (Metal Matrix Laminate Tailoring), (4) HITCAN (High Temperature Composite ANalyzer), and (5) STAHYC (Structural Tailoring of HYpersonic Composites). The primary objectives for these codes are: (1) laminate specific synthesis, (2) component specific structural analysis, and (3) component specific structural tailoring.

The attached viewgraphs provide schematics of the capability of each computer code and typical results obtained therefrom. Available literature on some of these codes is found in the appended list of relevant reports. Additional information is available from the authors.

Planned near future efforts include: (1) complete documentation, (2) hold a workshop at Lewis for early code dissemination to government contractors and grantees, and (3) continue comparisons with experimental data as they become available. Longer term planned efforts include: (1) addition of enhanced capabilities as needed, (2) increase in computational efficiency, and (3) improve robustness and use-friendliness.

RELEVANT REPORTS

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2. Hopkins, D. A. and Chamis, C. C.: A Unique Set of Micromechanics Equations for High Temperature Metal Matrix Composites. NASA TM-87154, 1985.

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7. Singhal, S. N., Lackney, J. J., Chamis, C. C. and Murthy, P. L. N.: Demonstration of Capabilities of High Temperature Composite Analyzer Code HITCAN. NASA TM-102560, 1990.

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9. Chamis, C. C., Murthy, P. L. N., and Singhal, S. N.: Computational Simulation of Hot Composite Structures. NASA TM 103681, 1991.

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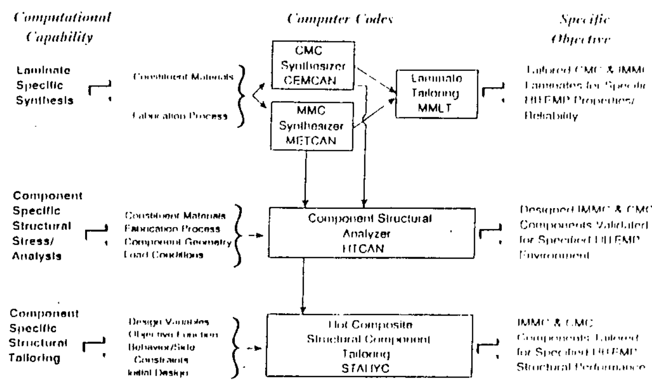
11. Murthy, P. L. N. and Chamis, C. C.: Towards the Development of Micromechanics Equations for Ceramic Matrix Composites via Fiber Substructuring (in print).

COMPUTATIONAL MECHANICS FOR HOT COMPOSITE STRUCTURES

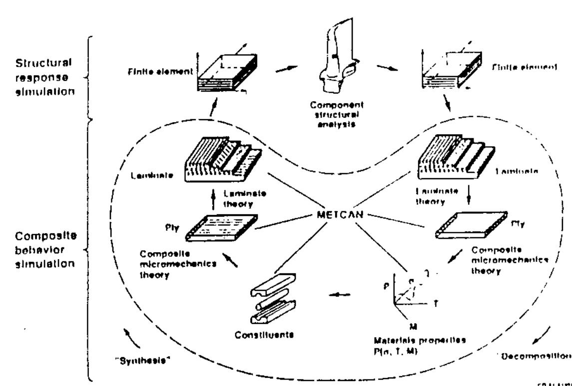
by
C. C. Chamis and P. L. N. Murthy
NASA Lewis Research Center
Cleveland, OHIO

Sixteen Annual Mechanics of Composites Review
November 12-13, 1991, Dayton, OHIO

HIERARCHICAL COMPUTATIONAL SIMULATION/TAILORING OF HOT COMPOSITE LAMINATES/STRUCTURES

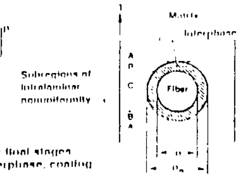


METCAN (Metal Matrix Composite Analyzer) for the Computational Simulation of High Temperature Metal Matrix Composites Behavior



Assumed Multi-factor Interaction Model (MFIM) to Represent the Various Factors Which Influence In Situ Constituent Materials Behavior

$$\frac{P}{P_O} = \left[\frac{T_F - T}{T_F - T_O}\right]^n \left[\frac{S_F - \sigma}{S_F - \sigma_O}\right]^m \left[\frac{S_F - \dot{\sigma}}{S_F - \dot{\sigma}_O}\right]^l \left[\frac{T_F - \dot{T}}{T_F - \dot{T}_O}\right]^k \left[\frac{R_F - R}{R_F - R_O}\right]^p \cdots \left[\frac{N_{MF} - N_M}{N_{MF} - N_{MO}}\right]^q \left[\frac{N_{TF} - N_T}{N_{TF} - N_{TO}}\right]^r \left[\frac{t_F - t}{t_F - t_O}\right]^s \cdots$$



Rationale:

- Gradual effects during most range, rapidly degrading near final stages
- Representative of the in situ behavior for fiber, matrix, interphase, coating
- Introduction of primitive variables (PV)
- Consistent in situ representation of all constituent properties in terms of PV
- Room-temperature values for reference properties
- Continuous interphase growth
- Simultaneous interaction of all primitive variables
- Adaptability to new materials
- Amenable to verification inclusive of all properties
- Readily adaptable to incremental computational simulation

Notations:

P – property; T – temperature; S – strength; R – metallurgical reaction; N – number of cycles; t – time; over dot – rate; subscripts: O – reference; F – final; M – mechanical; T – thermal

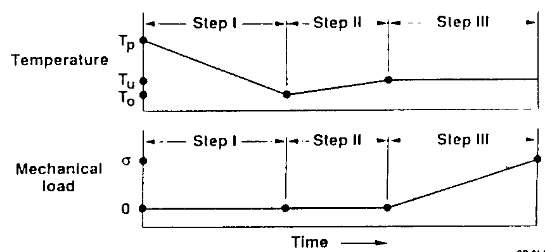
CD-91-51555

METCAN Computational Simulation Sequence

Step I Processing - Cool down from processing temperature (T_p) to room temperature (T_o)

Step II Heat up to use temperature (T_u) from room temperature

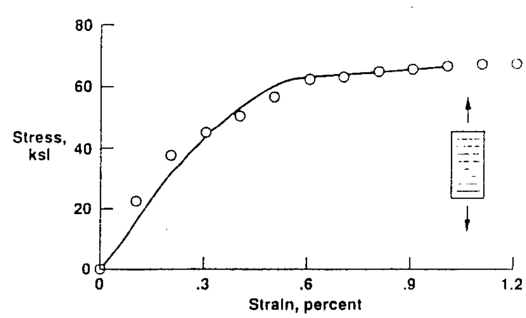
Step III Apply mechanical load to obtain stress-strain data



CD-91-51562

METCAN Accurately Simulates Transverse Stress Strain Curve of SiC/Ti-6-4

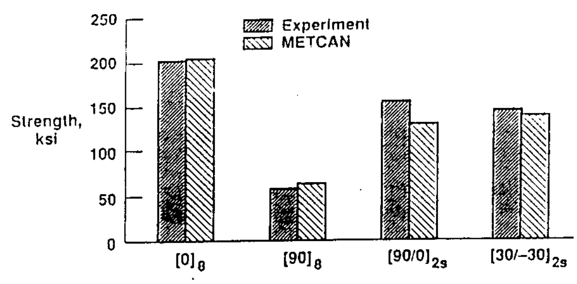
T = 73 °F, FVR = .34



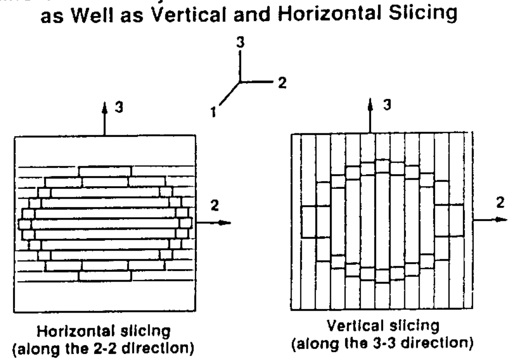
CD-91-51563

METCAN Predictions of Room–Temperature Strengths for SiC/Ti–15–3

Fiber Volume Ratio, 0.34



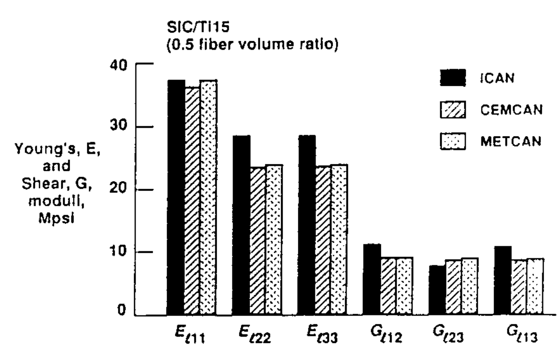
CEMCAN Currently Can Handle Different Fiber Shapes as Well as Vertical and Horizontal Slicing



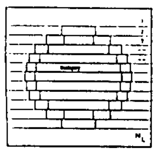
(Note: 11 is along the fiber direction)

Comparison of ICAN, CEMCAN, and METCAN

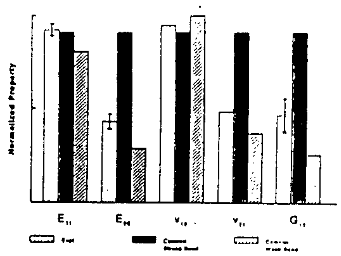
Young's and Shear Moduli



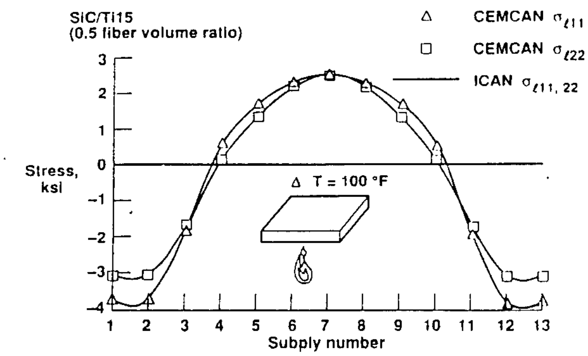
FIBER SUBSTRUCTURING CAPTURES INTERFACIAL CONDITIONS IN CMC's



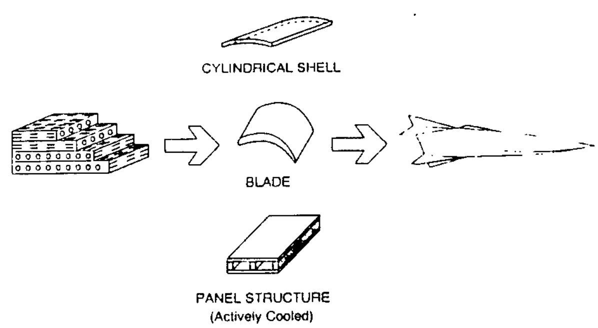
Unit cell with fiber, matrix, and interphase divided into N_L slices (subplies)



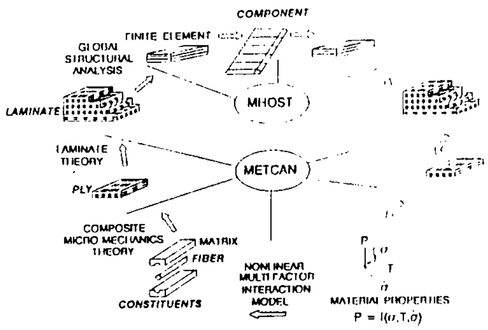
CEMCAN Predicts Variations in Stresses Due to 100 °F Uniform Heating



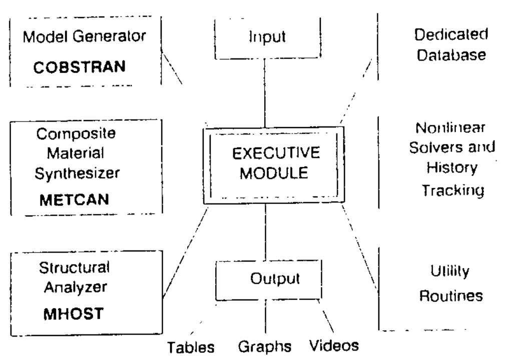
Actively Cooled Hot-Structures



HITCAN: An Integrated Approach for Hot Composite Structures

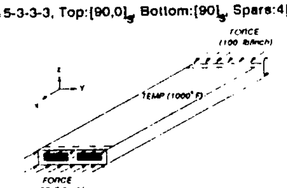


HITCAN MODULAR STRUCTURE



Demonstration: Actively Cooled Hot-Composite Panel

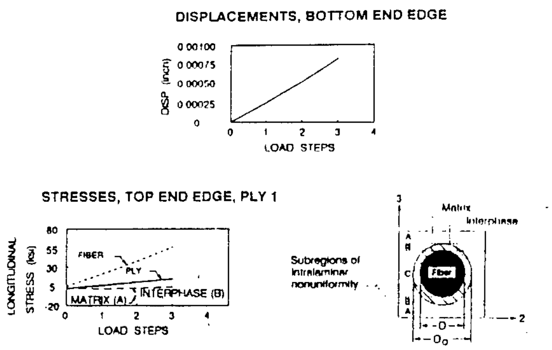
Simply Supported-Free Actively-Cooled Structure under axial & uniform Temp. Load for (SiC/Ti-15-3-3-3, Top:[90,0]$_s$, Bottom:[90]$_s$, Spars:4[0]$_s$); 0.4 FVR



CRITICAL BUCKLING FORCE

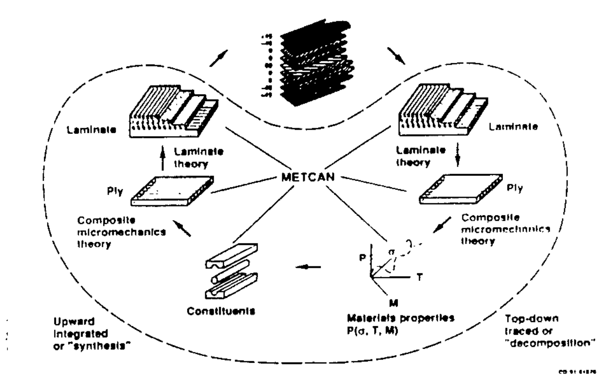
- UNDER MECHANICAL LOADING ONLY = 2950 lb/inch
- WITH FIBER DEGRADATION, UNDER MECHANICAL LOADING ONLY = 2850 lb/inch
- UNDER THERMO-MECHANICAL LOADING = 2720 lb/inch

Demonstration: Actively Cooled Hot-Composite Panel

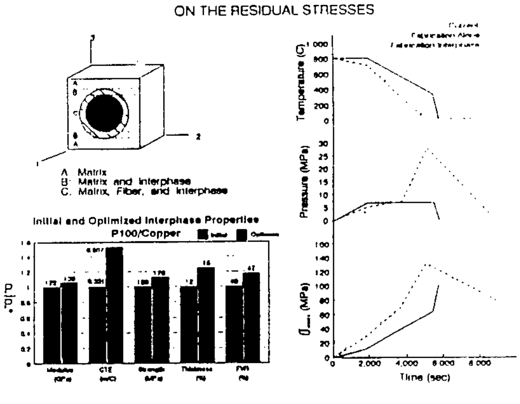


Metal Matrix Laminate Tailoring (MMLT)

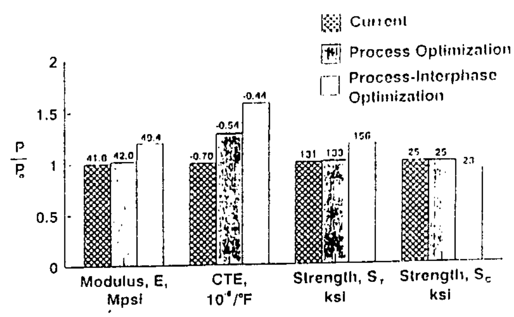
Couple METCAN with Optimizer



EFFECTS OF CONCURRENT INTERPHASE-FABRICATION OPTIMIZATION ON THE RESIDUAL STRESSES



CURRENT AND OPTIMUM LONGITUDINAL COMPOSITE PROPERTIES P100/COPPER



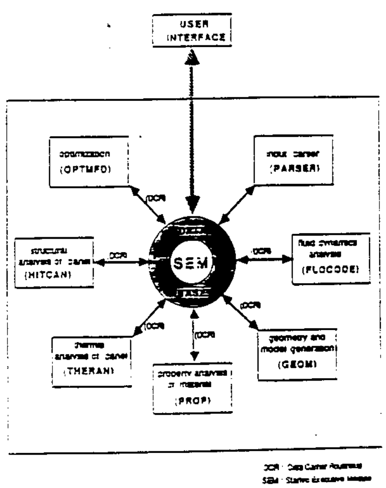


Figure 1. Conceptual View of STAHYC System

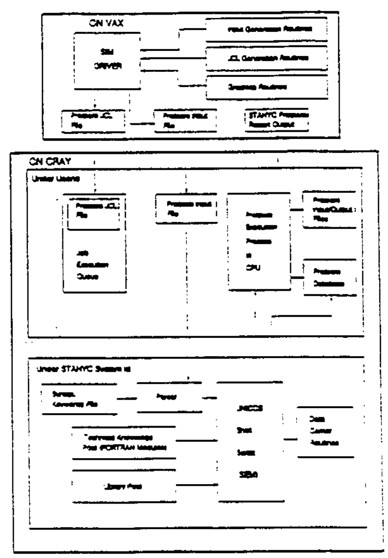


Figure 2: STAHYC System Components Block Diagram

STRUCTURAL TAILORING OF HYPERSONIC COMPOSITE PANEL

<<< SUMMARY OF DESIGN PROBLEM >>>

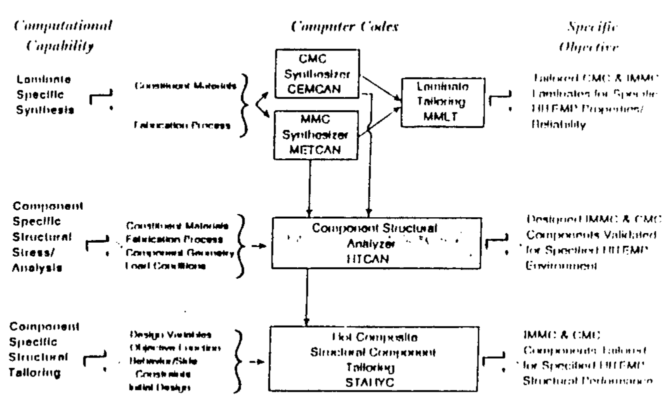
pa.el length .... :	6.700"
panel width .... :	3.000"
number of layers .... :	3
number of ducts .... :	6
ducts are placed in layer .... :	2
width of duct .... :	0.500"
height of duct .... :	0.100"
spacing of ducts .... :	0.250"
center distance of duct (right) .. :	0.500"
center distance of duct (left) .. :	0.250"
no. of nodes in structural model . :	28
no. of nodes in thermal model .... :	632
number of design variable .... :	6
number of constraints .... :	625
objective function considered .... :	MASS (LB)

layer # (from top)	volume frac	fiber angle	fiber density	matrix density	thickness	fiber type	matrix type
1	0.400	0.000	0.110	0.172	0.050	SICA	ALUM
2	0.667	0.000	0.003	0.172	0.100	CHTD	ALUM1
3	0.400	0.000	0.110	0.172	0.050	SICA	ALUM

var. #	variable name	lower bound	initial value	final value	upper bound
1	vol. frac. of layer 1	0.300	0.400	0.476	0.650
2	vol. frac. of layer 3	0.300	0.400	0.476	0.650
3	fiber ang. of layer 1	-90.000	0.000	0.000	90.000
4	fiber ang. of layer 3	-90.000	0.000	0.000	90.000

INITIAL OBJECTIVE FUNCTION VALUE = 0.291
FINAL OBJECTIVE FUNCTION VALUE = 0.285
NUMBER OF FUNCTION EVALUATIONS = 40

HIERARCHICAL COMPUTATIONAL SIMULATION/TAILORING OF HOT COMPOSITE LAMINATES/STRUCTURES



Probabilistic Composite Integrated Analysis

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NASA Lewis Research Center
Cleveland, Ohio

G. T. Mase
GMI Engineering & Management Institute
Flint, Michigan

Probabilistic composite mechanics and probabilistic composite structural analysis are formal methods which are used to quantify the scatter that is observed in composite material properties and structural response. The observed scatter in composite material properties is the range of measured values in modulus, strength, thermal expansion coefficient, etc., while that in structural response is the range of measured values for displacement, frequency, buckling load, etc. The formal methods relate the scatter in the observed values to the corresponding scatter in the physical parameters which make up the composite and/or the composite structure. For example, these parameters include constituent material properties, fabrication process variables, structural component geometry, and any other variables which contribute to the composite behavior and/or structural response.

The development of these types of formal methods has been the subject of considerable research at NASA Lewis Research Center. This research has led to computational simulation methods for relating the scatter (uncertainties) in the composite properties of composite structural response to the corresponding uncertainties in the respective parameters (primitive variables) which are used to describe the composite in all its inherent scales: micro, macro, laminate and structural. The objective of this paper is to summarize salient features of these computational simulation methods and to present typical results to illustrate their applications.

Formal procedures are described which are used to computationally simulate the probabilistic behavior of composite structures. The computational simulation starts with the uncertainties associated with all aspects of a composite structure (constituents, fabrication, assembling, etc.) and encompasses all aspects of composite behavior (micromechanics, macromechanics, combined stress failure and laminate theory. These are embedded in a computer code identified as PICAN for Probabilistic Integrated Composite Analyzer. A brief description of the fundamental concepts, probabilistic composite micromechanics and probabilistic laminate theory are summarized below followed with some typical results and future plans. Results and schematics are attached in copies of the view graphs. Pertinent references are included for additional details.

Fundamental considerations: The fundamental concepts/assumptions in the probabilistic composite mechanics described herein are: (1) the scatter in all the primitive variables, which describe the composite, can be represented by well known probabilistic distributions, (2) the values for the primitive variables can be randomly selected from the known distributions for a specific composite, (3) these values can be used in composite mechanics to predict composite behavior, (4) the whole process can be repeated many times to obtain sufficient information to develop the distribution of the ply property, composite property, or structural response. These concepts are analogous to making and testing a composite. The probabilistic distributions represent available material that the composite can be made from. The composite mechanics represent the physical experiment and the processes repetition represents several experiments. Subsequent statistical analysis of the data is the same for both approaches. The primitive variables which describe the composite are identified by examining the fabrication process. A schematic depicting the fabrication process for an aircraft wing top cover is shown in figure 2. The respective primitive variables are all those for constituent materials mechanical, thermal and strength properties. The simulation scheme is illustrated in figure 3.

Probabilistic composite micromechanics: The probabilistic simulation is performed by considering the ply as an assembly (equivalent laminate) of 15 subplies, where each subply is made from randomly selected properties. The composite mechanics used in the simulation is that available in the Integrated Composite Analyzer (ICAN) (ref. 1). The structure of ICAN is schematically shown in figure 4. The probabilistic simulation for composite micromechanics is schematically illustrated in figure 5 (ref. 2 and 3). Typical results for unidirectional composite ply properties with respective sensitivities are shown in figures 6-13.

Probabilistic laminate theory: Probabilistic laminate theory consists of using probabilistic ply properties in the laminate theory equations. In the present simulation the probabilistic ply properties are available from the probabilistic micromechanics previously described. The simulation for laminate properties is performed using ICAN (fig. 3) but including uncertainties in the ply orientation angle and in the ply thickness.

Typical probabilistic laminate properties for a quasi-isotropic laminate from graphite-fiber/epoxy composite are shown in figure 14 for laminate modulus, compressive strength and thermal expansion coefficient. PICAN verification results for three different laminates are summarized in figure 15. Only the Poisson's ratio for the quasi-isotropic laminate, last entry in the figure, is slightly outside the predicted bounds. The authors consider these comparisons as an excellent demonstration of the usefulness of probabilistic composite mechanics for stiffness. Comparable results for laminate strengths are shown in figure 16. Here the experimental range is outside the predicted bounds. The major reason for this difference is that the predicted bounds are based on "first-ply-failure." Inclusion of progressive ply failure is currently being investigated.

Future effort planned: The planned effort includes the coupling of PICAN with probabilistic structural analysis to develop a computer code for Integrated Probabilistic Assessment of Composite Structures (IPACS), (refs. 4-6).

REFERENCES

1. Murthy, P. L. N. and Chamis, C. C.: Integrated Composite Analyzer (ICAN) - User's and Programmer's Manual. NASA TP 2515, 1986.
2. Stock, T. A., Bellini, P. X., Murthy, P. L. N., and Chamis, C. C.: A Probabilistic Approach to Composite Micromechanics. NASA TM 101366, 1988.
3. Chamis, C. C. and Stock, T. A.: Probabilistic Simulation of Uncertain ties in Composite Uniaxial Strengths. NASA TM 102483, 1990.
4. Chamis, C. C.:Probabilistic Composite Analysis. NASA CP 3104, Part 2, 1990, pg. 891-900.
5. Thanedar, P. B. and Chamis. C. C.: Composite Laminate Tailoring with Probabilistic Constraints and Loads. NASA TM 102515, 1990.
6. Chamis, C. C.: Probabilistic Structural Analysis Methods for Space Propulsion System Components. NASA TM 88965, 1986.

FIGURE 1

Probabilistic Composite Integrated Analysis

(VIA Computational Simulation)

C. C. Chamis and P. L. N. Murthy

NASA Lewis Research Center

Cleveland, Ohio

G. T. Mase

GMI Engineering & Management Institute

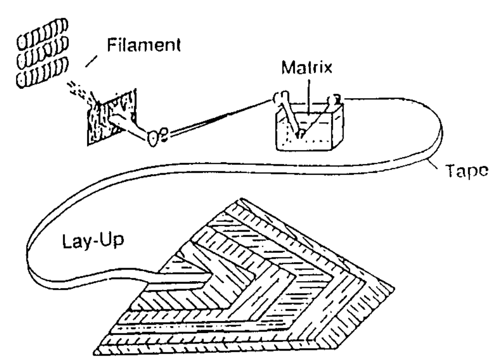
Flint, Michigan

SIXTEENTH ANNUAL MECHANICS OF COMPOSITES REVIEW

NOVEMBER 12-13, 1991, DAYTON, OHIO

FIGURE 2

SOURCES OF SCATTER - FABRICATION PROCESS



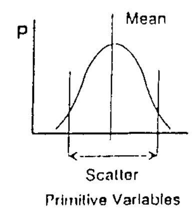
Fabrication Schematic

- o Constituents
- o Fiber Misalignment
- o Fiber Volume Ratio
- o Void Volume Ratio
- o Ply Orientation Angle
- o Ply Thickness

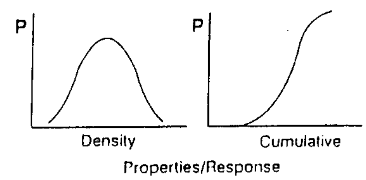
FIGURE 3

PROBABILISTIC SIMULATION

- Assume statistical distributions of scatter in all primitive variables.



- Probabilistically select values from these distributions.
- Enter these values in ICAN to calculate composite properties.
- Repeat process until sufficient values have been obtained to develop statistical distributions for the desired composite properties/structural response.



- Evaluate sensitivities.

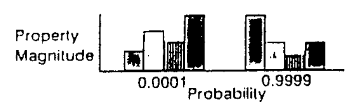


FIGURE 4

COMPOSITE BEHAVIOR SIMULATOR - ICAN

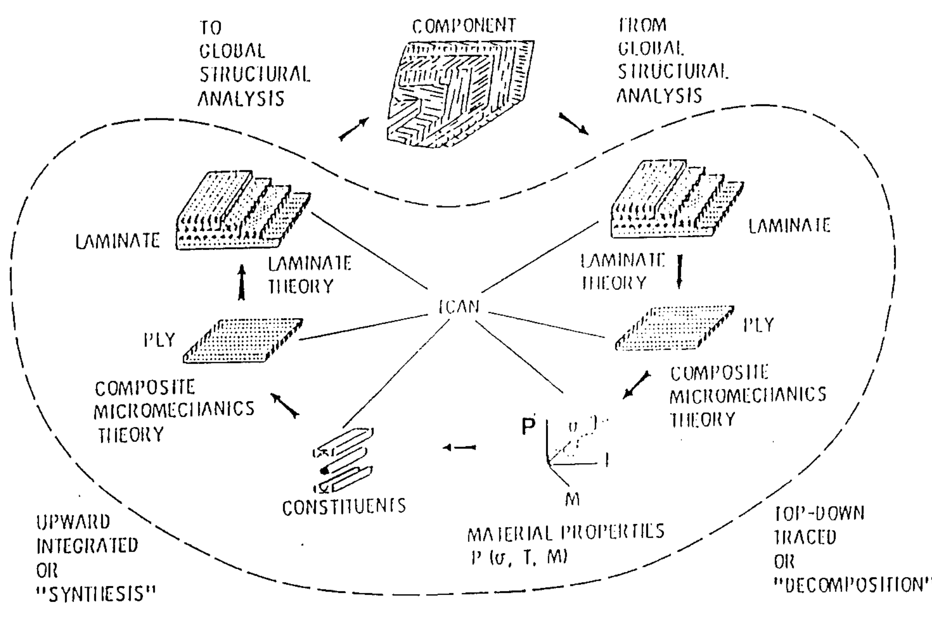
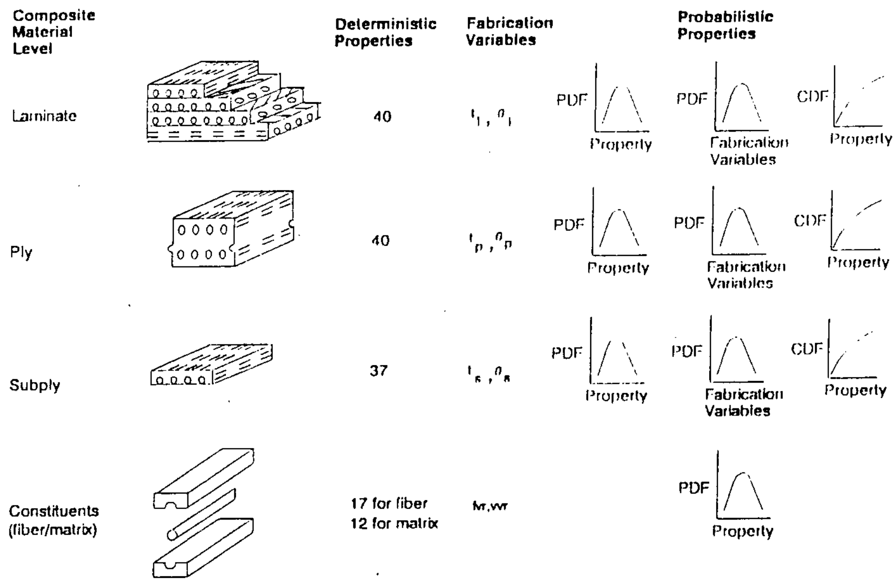


FIGURE 5

Probabilistic Simulation of Composite Mechanics with PCAN



NOTATION: t = thickness, θ = misalignment, fvr = fiber volume ratio,vvr = void volume ratio, PDF = probability density function
CDF = Cumulative Distribution function, Subscripts- l = laminate, p = ply, s = subply

FIGURE 6

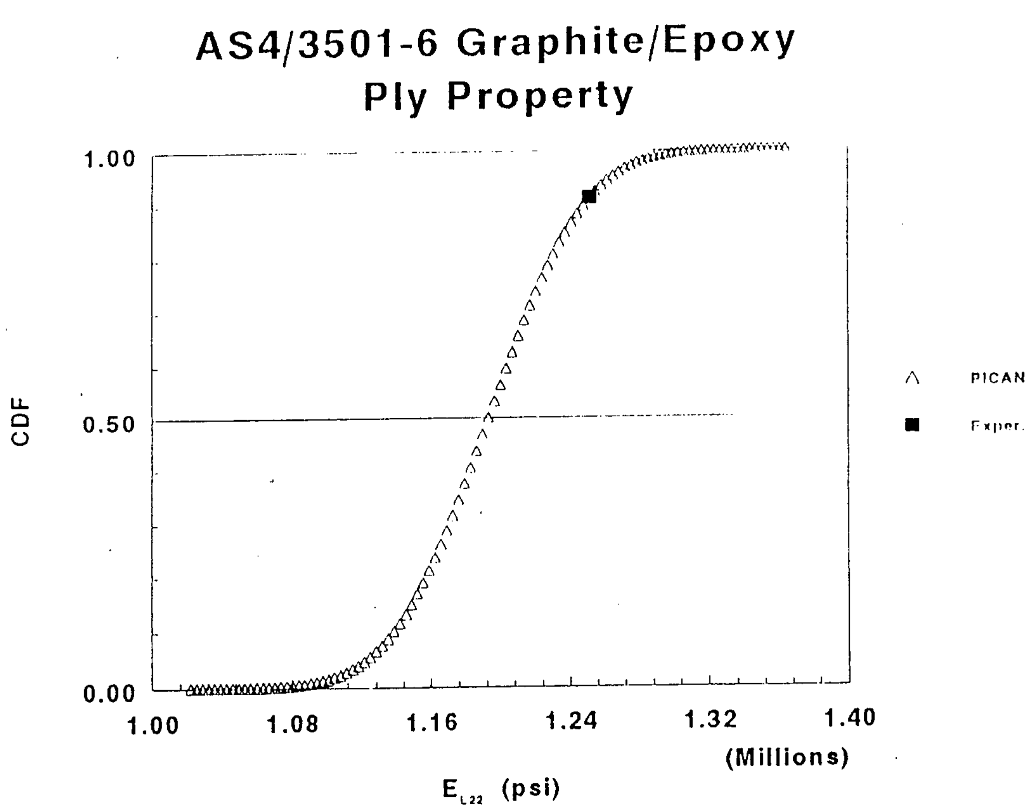


FIGURE 7

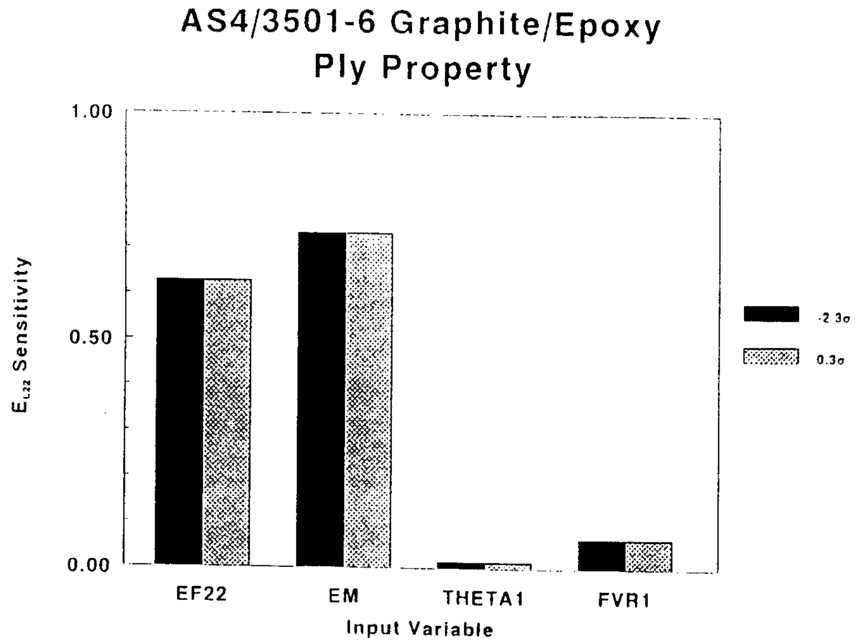


FIGURE 8

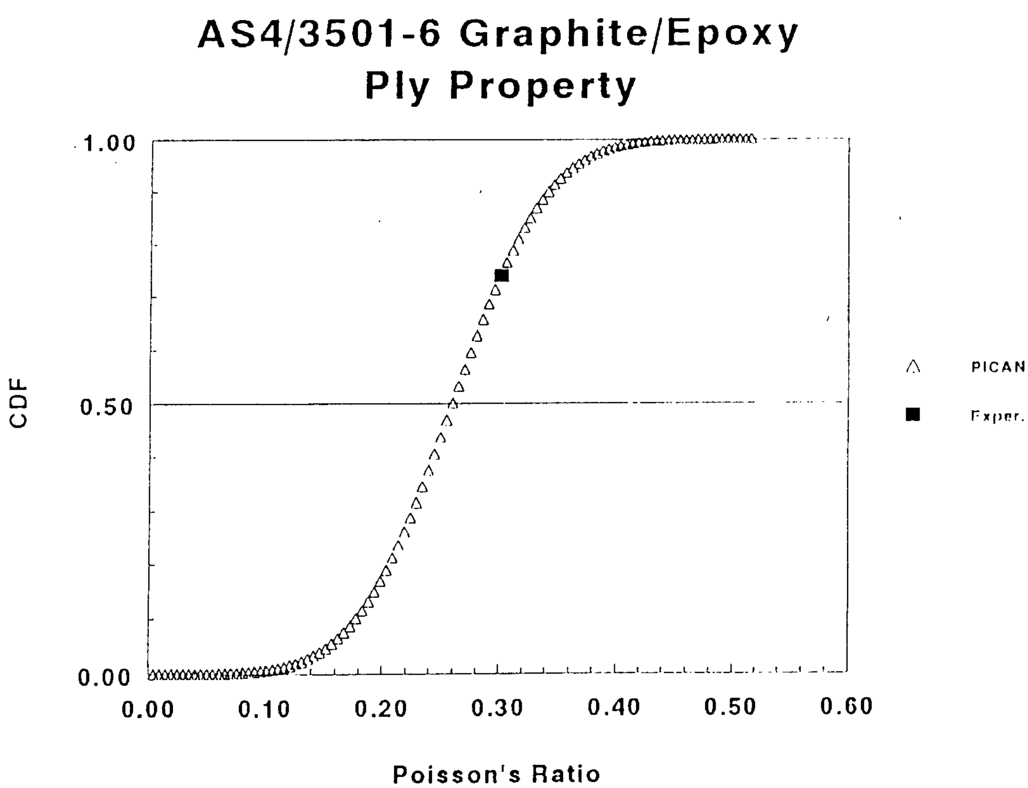


FIGURE 9

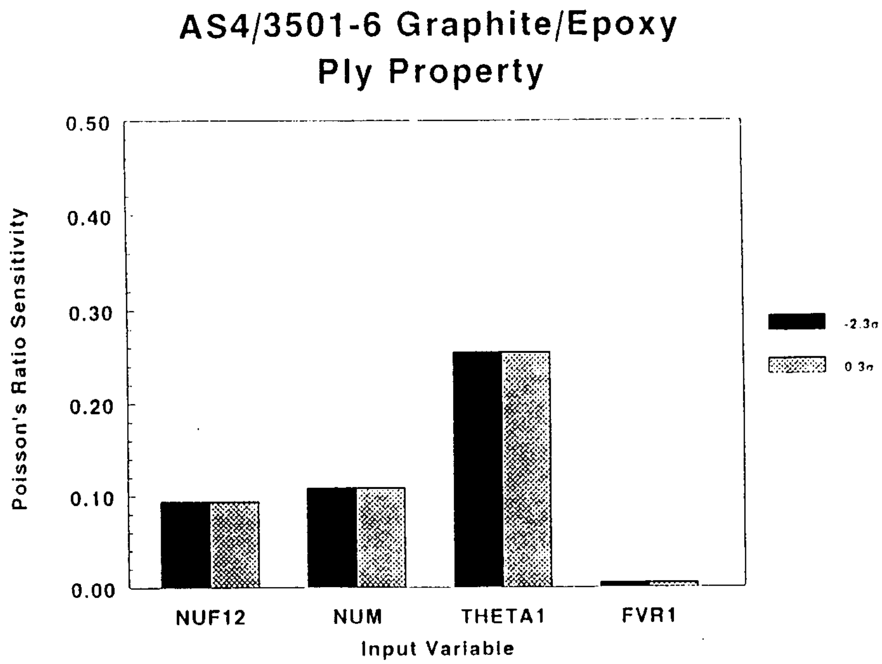


FIGURE 10

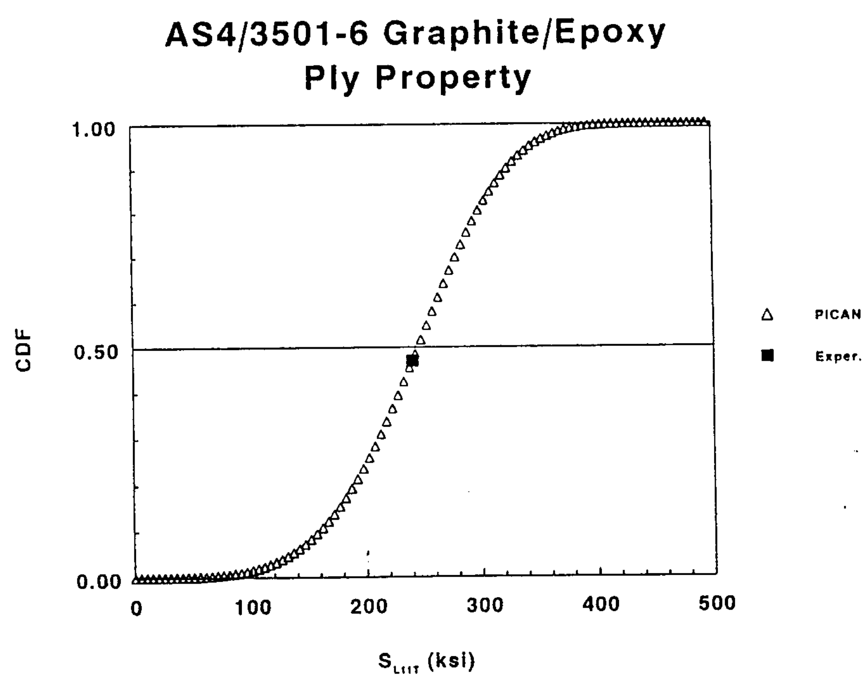


FIGURE 11

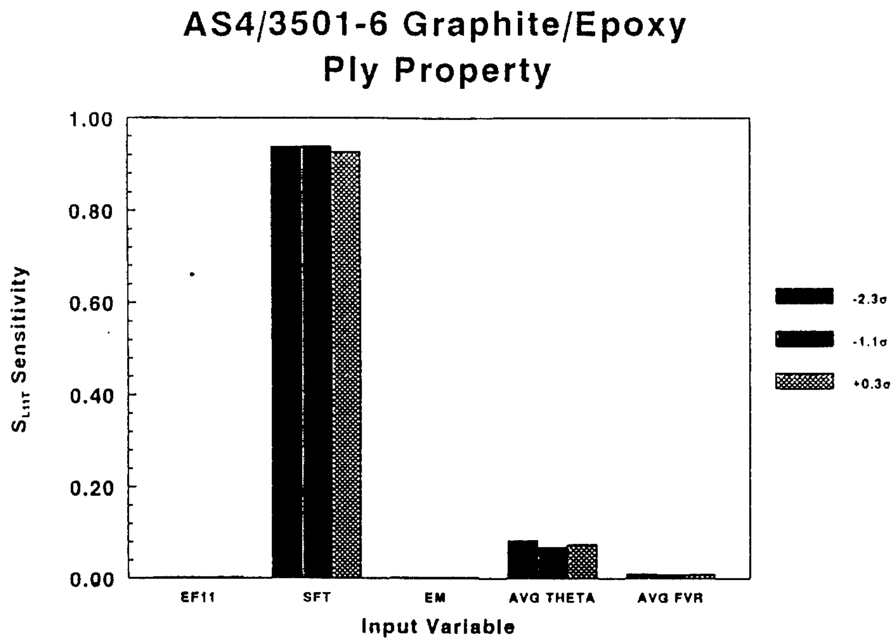


FIGURE 12

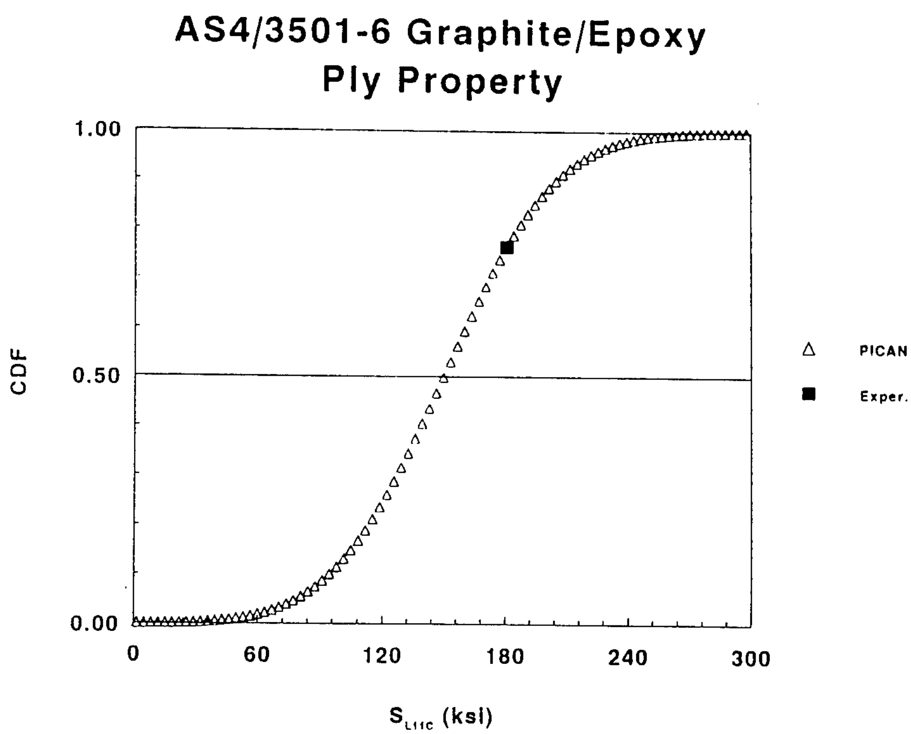


FIGURE 13

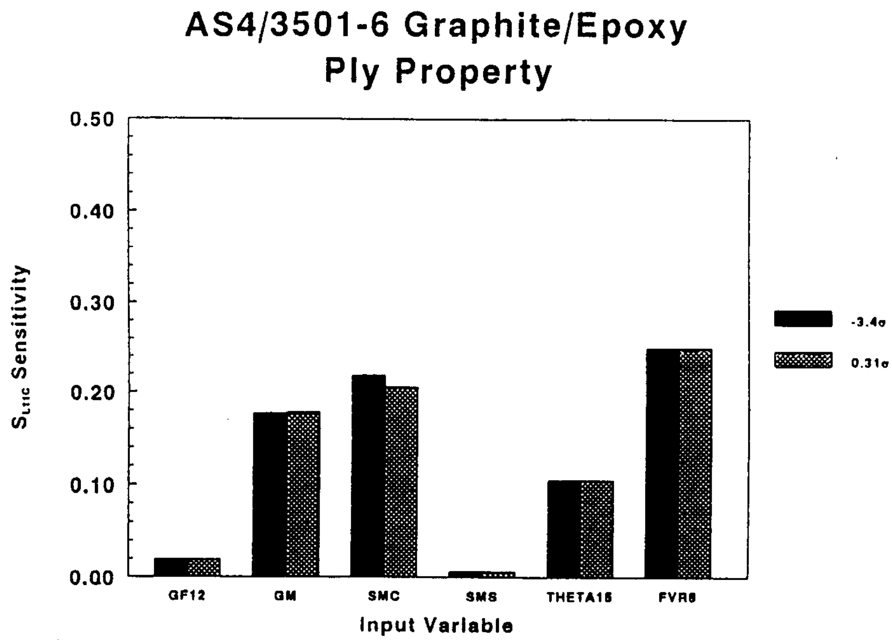


FIGURE 14

PROBABILISTIC LAMINATE PROPERTIES (Gr/E)

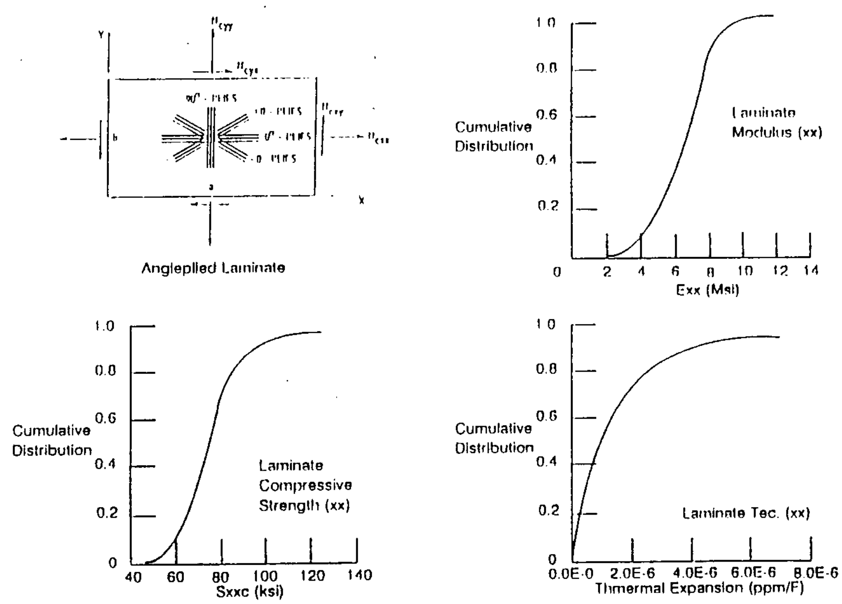


FIGURE 15

PICAN VERIFICATION FOR LAMINATE STIFFNESS

Laminate	lower bound (mean-2σ)	mean	experimental value	upper bound (mean+2σ)
$[0/\pm45_2/0/\pm45]_s$				
Long. modulus (MSI)	5.40	6.19	6.30	6.98
Trans. modulus (MSI)	2.46	3.07	3.08	3.68
Shear modulus (MSI)	3.33	3.84	3.21	4.35
Major Poisson's ratio	0.690	0.806	0.803	0.922
$[0_2/\pm45/0_2/90/0)]_s$				
Long. modulus (MSI)	11.41	13.30	13.00	15.09
Trans. modulus (MSI)	3.69	4.30	4.20	4.96
Shear modulus (MSI)	1.40	1.59	1.50	1.78
Major Poisson's ratio	0.276	0.313	0.325	0.350
$[(0/\pm45/90)_2]_s$				
Long. modulus (MSI)	6.12	7.15	6.68	8.18
Trans. modulus (MSI)	6.12	7.15	6.62	8.18
Shear modulus (MSI)	2.37	2.72	2.34	3.07
Major Poisson's ratio	0.290	0.317	0.350	0.344

FIGURE 16

PICAN VERIFICATION FOR LAMINATE STRENGTH

Laminate	Predicted Lower Bound (mean-2σ)	Measured Lower Bound	Measured Upper Bound	Predicted Upper Bound (mean+2σ)
$[0/\pm45_2/0/\pm45]_s$				
Long. Tension (ksi)	38.0	75.0	82.5	50.7
Long. Comp. (ksi)	35.1	64.7	70.5	37.2
Trans. Tension (ksi)	22.1	30.2	38.5	30.8
Trans. Comp. (ksi)	24.8	42.3	48.0	32.0
Shear (ksi)	42.5	40.1	47.8	49.6
$[0_2/\pm45/0_2/90/0)]_s$				
Long. Tension (ksi)	106.3	113.0	154.4	120.7
Long. Comp. (ksi)	75.1	94.3	108.4	79.5
Trans. Tension (ksi)	29.1	37.7	45.3	38.8
Trans. Comp. (ksi)	25.1	50.9	60.1	27.5
Shear (ksi)	17.9	29.9	34.9	20.5
$[(0/\pm45/90)_2]_s$				
Long. Tension (ksi)	56.7	76.4	91.1	65.7
Long Comp. (ksi)	40.3	63.0	83.8	44.2
Trans. Tension (ksi)	54.9	79.9	95.8	67.5
Trans. Comp. (ksi)	40.1	65.2	85.2	44.4
Shear (ksi)	30.8	33.1	37.4	34.0

A RAYLEIGH-RITZ STRESS ANALYSIS PROCEDURE FOR CUTOUTS IN COMPOSITE STRUCTURES[1]

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Hawthorne, CA 90250

Cutouts of various shapes and sizes occur at numerous locations in aircraft wing and fuselage structures. Large openings are required to provide access through fuselage bulkheads, fuselage and wing skins, and wing spar and rib webs. Smaller openings are used to accommodate mechanical fasteners in joints and splices. The design of cutouts in composite aircraft structures requires accurate stress analysis techniques to ensure structural integrity and maximize structural efficiency.

The analysis of cutouts in orthotropic and anisotropic materials has been the focus of numerous research efforts over the years. Both analytical and numerical methods have been developed for a variety of cutouts under different loading conditions. Many of the analytical methods, especially those based on complex stress function approaches from the theory of elasticity, are restricted to infinite plates. On the other hand, finite element methods are burdened by elaborate pre- and postprocessing requirements, and boundary element and boundary collocation methods are difficult to apply to certain practical problems, such as cutouts in stiffened, reinforced panels. This presentation highlights a new stress analysis technique that overcomes some of these limitations.

The cutout stress analysis methodology discussed in this presentation is based on the Rayleigh-Ritz analysis technique. General assumed displacement fields for circular and elliptical cutouts are used in conjunction with the principle of virtual work to generate solutions for a wide variety of practical stress analysis problems involving finite rectangular composite panels. These include problems with local ply build-ups around the periphery of the cutout and "picture frame" stiffening for cutout reinforcement. In the implementation of the methodology, separate solutions are carried out for biaxial and in-plane shear load cases. Solutions for problems involving generalized in-plane loading are obtained by superposition of these results.

In the following presentation, existing cutout stress analysis techniques are briefly discussed, and the basic concepts of the Rayleigh-Ritz approach are outlined for problems involving biaxial and shear loading. Modifications required in the basic method to accommodate cutout padups and panel stiffening are discussed. A number of benchmark results are presented to demonstrate the accuracy of the Rayleigh-Ritz approach. The presentation concludes with a brief description of a cutout design methodology based on this stress analysis technique.

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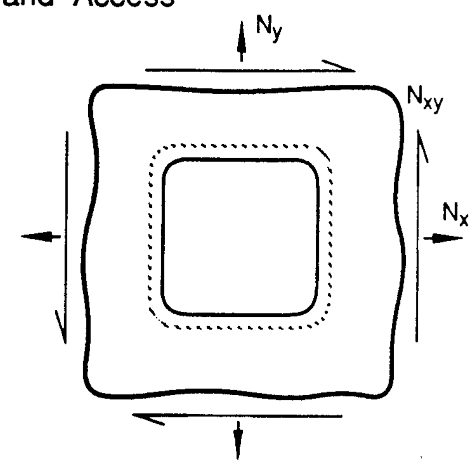
1 This work was performed under NASA/Northrop Contract NAS1-18842, entitled "Innovative Composite Fuselage Structures"

Cutouts in Composite Aircraft Structures

- **STRUCTURAL APPLICATIONS**
  - Bulkheads
  - Frames
  - Substructure

  } System Routing and Access

- **ANALYTICAL CHALLENGES**
  - Irregular Cutout Shapes
  - Generalized Loading Conditions
  - Finite Structure Effects
  - Padups/Reinforcements



V91-3/40

Existing Methodologies

- CLASSICAL ANALYSES (LEKHNITSKII, SAVIN, DE JONG, PRASAD AND SHUART)
  - Available for Many Cutout Geometries (Ellipse, Rectangle, Triangle, Oval)
  - Infinite Plate Solutions
  - Finite Structure, Substructure Effects Difficult to Accomodate
- FINITE AND BOUNDARY ELEMENT ANALYSES (SY5, WEB/CREPAIR)
  - Elaborate Preprocessing and Postprocessing Requirements
  - Inaccuracy in Calculation of Stress Concentration Factor
- BOUNDARY COLLOCATION ANALYSES (SASCJ, KLANG AND OWEN)
  - Based Upon Complex Variable Approach to 2D Anisotropic Elasticity Problems
  - Padups, Reinforcements, Substructure Effects Difficult to Accomodate

V91-3/41

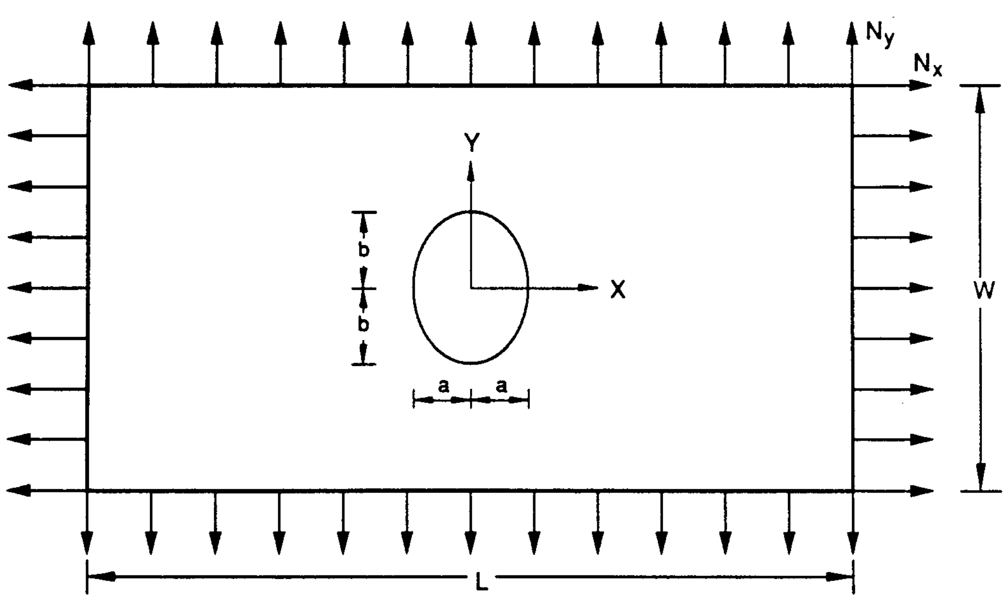
Rayleigh-Ritz Cutout Analysis

- ENERGY BALANCE APPROACH BASED UPON PRINCIPLE OF VIRTUAL WORK
- RAYLEIGH-RITZ SOLUTION USING ASSUMED DISPLACEMENT FIELD
- ADVANTAGES
  - Reduced Processing, Postprocessing Effort
  - Suitable for Finite Structures, Padups, Reinforcements
  - Provides Accurate Calculation of Stress Concentration Factors

V91-3/42

Analysis Geometry

Biaxial Loading



V91-3/43

Analysis Methodology

Biaxial Loading

- PRINCIPLE OF VIRTUAL WORK

$$\int_A \delta\{\epsilon\}^T\{N\}\,dA - \int_S \delta\{u\}^T\{t\}\,ds = 0$$

- RAYLEIGH-RITZ METHOD
  - Assumed Displacement Field

$$u_r = \sum_{j=0}^{N} \sum_{k=1}^{M} q_j^k \; f_k\,(r) \cos 2j\,\theta$$

$$u_\theta = \sum_{j=0}^{N} \sum_{k=1}^{M} q_j^{M+k} \; f_k\,(r) \sin 2j\,\theta$$

$$f_k\,(r) = r^{2(k-M)+1} \qquad \text{for } k = 1, \ldots\ldots, M$$

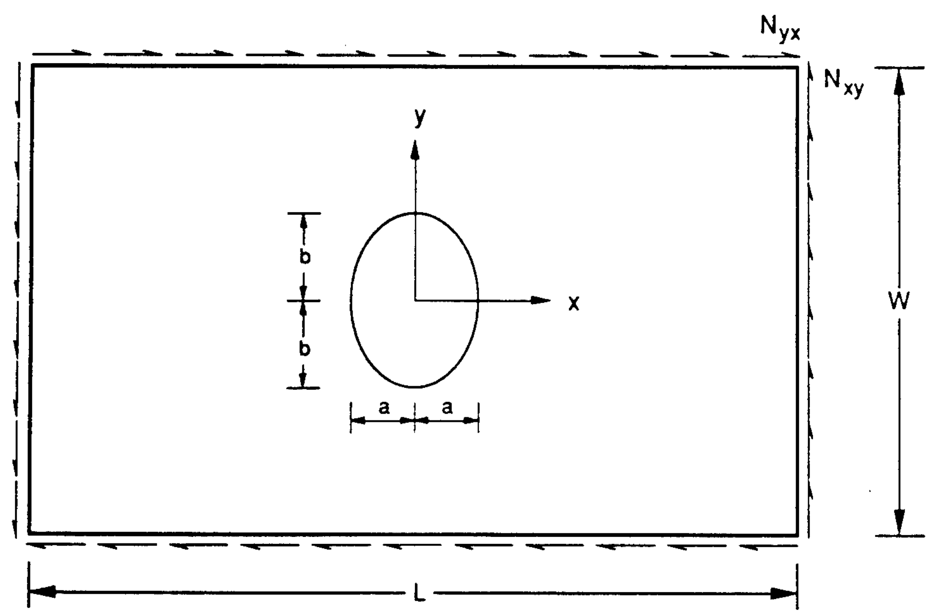
  - Solution of Linear Algebraic Equations

$$[K]\,\{q\} = \{T\}$$

V91-3/44

Analysis Geometry

Shear Loading



V91-3/45

Analysis Methodology

Shear Loading

- PRINCIPLE OF VIRTUAL WORK

$$\int_A \delta \{\epsilon\}^T \{N\}\, dA - \int_S \delta \{u\}^T \{t\}\, ds = 0$$

- RAYLEIGH-RITZ METHOD
  - Assumed Displacement Field

$$u_r = \sum_{j=0}^{N} \sum_{k=1}^{M} q_j^k \; f_k\,(r) \sin 2j\,\theta$$

$$u_\theta = \sum_{j=0}^{N} \sum_{k=1}^{M} q_j^{M+k} \; f_k\,(r) \cos 2j\,\theta$$

$$f_k\,(r) = r^{2(k-M)+1} \qquad \text{for } k = 1, \ldots\ldots, M$$

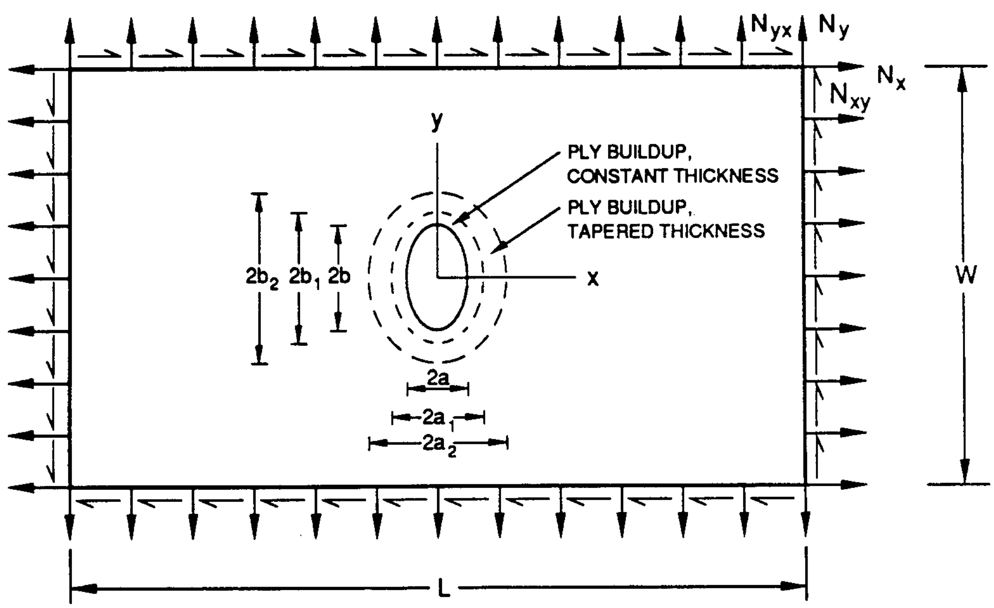
  - Solution of Linear Algebraic Equations

$$[K]\,\{q\} = \{T\}$$

V91-3/46

Analysis Geometry

Integral Padups/Reinforcements



V91-3/47

Analysis Methodology

Integral Padups/Reinforcements

- GEOMETRICAL FEATURES
  - Ply Build-Up Adjacent to Cutout
  - Reinforced Thickness Symmetric With Respect to Laminate Midplane
  - Ellipse Shaped Padup Regions

- CALCULATION PROCEDURE
  - No Modification of Unreinforced Panel Displacement Fields
  - Linear Variation of Extensional Stiffness in Tapered Region

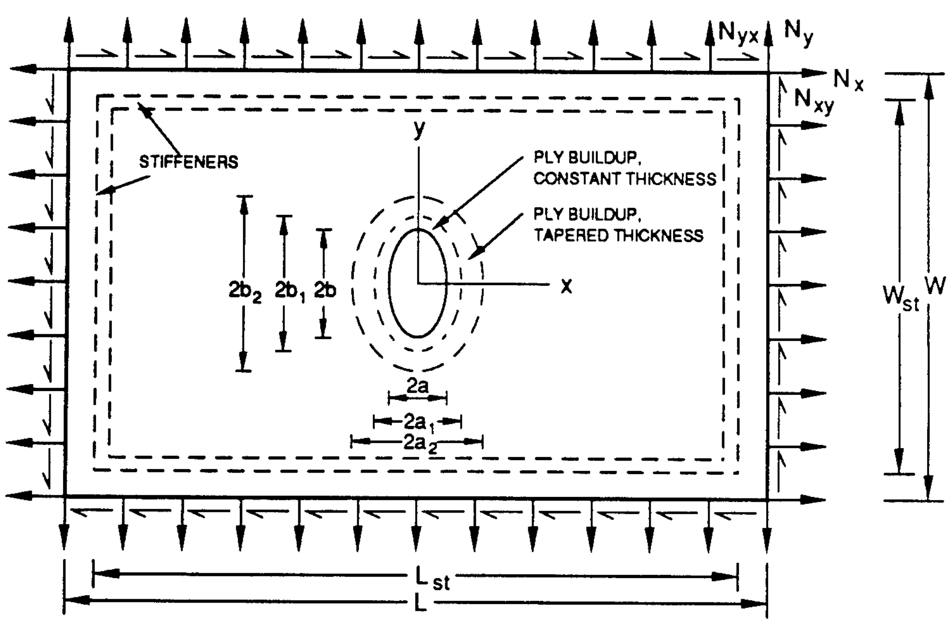
$$A_{jk}^{(2)} = \frac{(r - R_2)}{(R_1 - R_2)} A_{jk}^{(1)} + \frac{(r - R_1)}{(R_2 - R_1)} A_{jk}^{(3)} \; ; \; R_1 = R_1(\theta), \; R_2 = R_2(\theta)$$

  - Modified Stiffness Matrix [K]

V91-3/48

Analysis Geometry

Stiffened Panels



V91-3/49

Analysis Methodology

Stiffened Panels

- MODIFIED VIRTUAL WORK STATEMENT

$$\int_A \delta\{\varepsilon\}^T\{N\}\,dA + \int_{V_{st}} \delta\{\varepsilon\}^T\{\sigma\}\,dV - \int_{S_T} \delta\{u\}^T\{t\}\,ds = 0$$

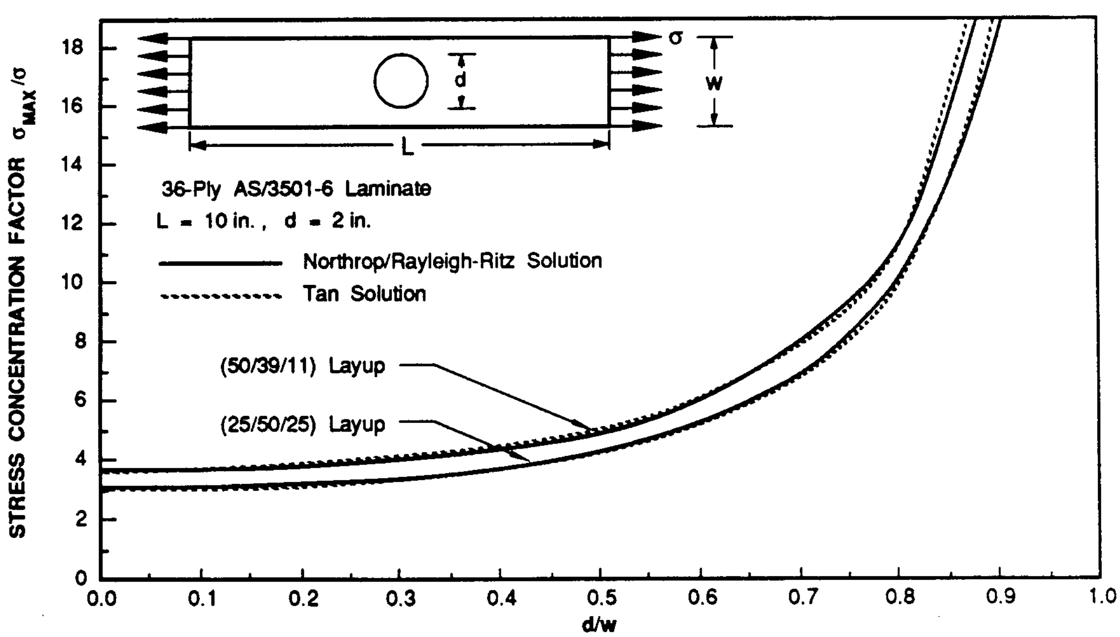
- STRAIN COMPATIBILITY BETWEEN PANEL AND STIFFENERS
  - — Stiffeners Provide One-Dimensional Axial Load Transfer
  - — Stiffener Bending Deformation Neglected

- STRESS ANALYSIS BASED ON MODIFIED STIFFNESS MATRIX [K]

V91-3/50

Benchmark Results

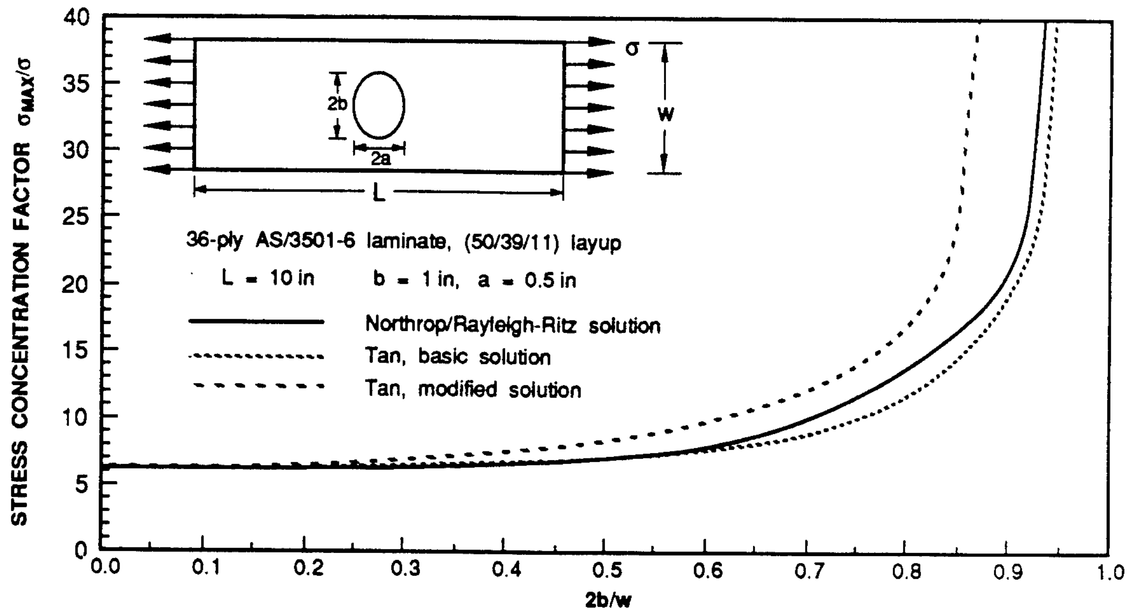
Stress Concentration Factor at Circular Holes



V91-3/51

Benchmark Results

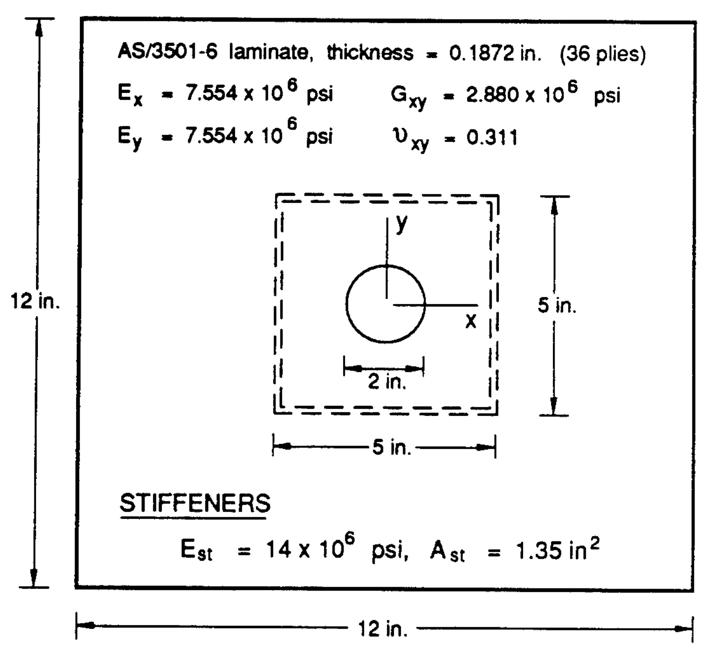
Stress Concentration Factor at Elliptical Holes



V91-3/52

Benchmark Results

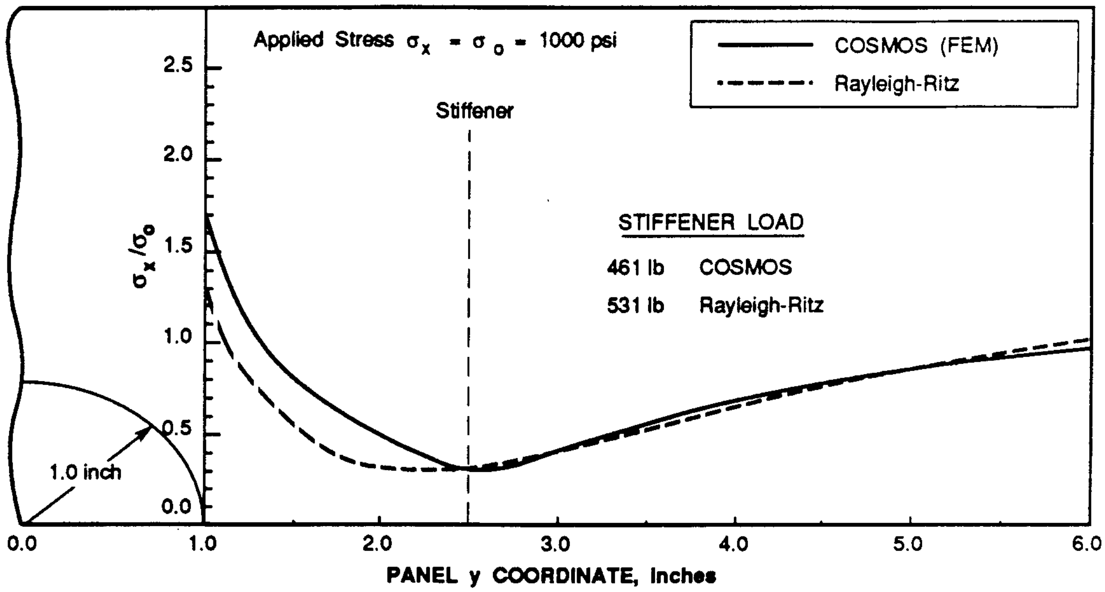
Stiffened Panel Test Problem



V91-3/53

Benchmark Results

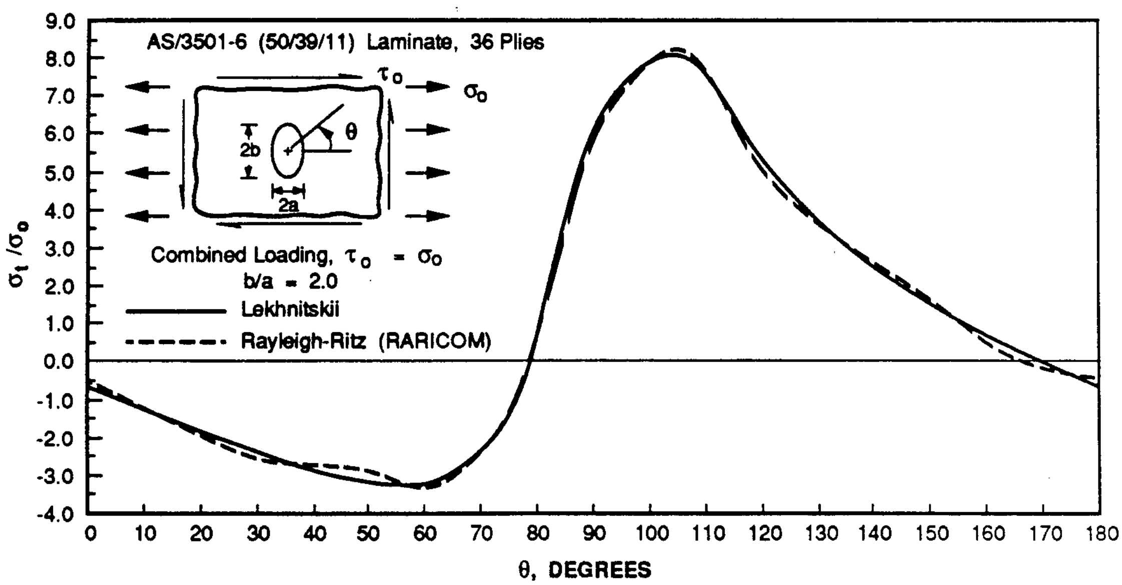
Calculated Stiffened Panel Stresses



V91-3/54

Benchmark Results

Stress Around an Elliptical Cutout Under Combined Loading



V91-3/55

Related Work

- FAILURE ANALYIS PROCEDURE
  - Generalized Average Stress Criterion for Panel Failure
  - Maximum Strain Criterion for Stiffener Failure
- RARICOM COMPUTER PROGRAM
  - Stress Analysis for Prescribed Panel Loads
  - Failure Analysis for Fixed Load Ratios
- DESIGN PROCEDURES
  - Padup/Reinforcement Sizing
  - Stiffener Sizing

V91-3/56

APPENDIX A: PROGRAM LISTINGS

NASA LANGLEY RESEARCH CENTER

IN-HOUSE

ADVANCED CONCEPTS FOR COMPOSITE HELICOPTER FUSELAGE STRUCTURES
83 April 1 - 92 January 1

Project Engineer: Mr. Donald J. Baker
Mail Stop 190
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3171 FTS 928-3171

Objective: To investigate new design concepts for composite materials on lightly loaded helicopter fuselage structures. Trade studies will be performed using the various computer codes. A 4-year task assignment contract was awarded in Fiscal Year 1989 to fabricate selected designs that will be tested at NASA Langley.

POSTBUCKLING AND CRIPPLING OF COMPRESSION-LOADED COMPOSITE STRUCTURAL COMPONENTS
79 March 1 - 92 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

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 AND SHELLS
79 October 1 - 92 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

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

POSTBUCKLING OF FLAT STIFFENED GRAPHITE/EPOXY SHEAR WEBS
81 July 1 - 92 September 30

Project Engineer: Mr. Marshall Rouse
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3182 FTS 928-3182

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

BUCKLING AND STRENGTH OF THICK-WALLED COMPOSITE CYLINDERS
86 October 1 - 92 September 30

Project Engineer: Ms. Dawn C. Jegley
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3185 FTS 928-3185

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

ADVANCED COMPOSITE STRUCTURAL CONCEPTS
84 October 1 - 92 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

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

FAILURE MECHANISMS FOR COMPOSITE LAMINATES WITH DAMAGE AND LOCAL DISCONTINUITIES
76 October 1 - 92 September 30

Project Engineer: Dr. Mark J. Shuart
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3170 FTS 928-3170

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

MECHANICS OF ANISOTROPIC COMPOSITE STRUCTURES
86 October 1 - 92 September 30

Project Engineer: Dr. Michael P. Nemeth
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3184 FTS 928-3184

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

CRASH CHARACTERISTICS OF COMPOSITE FUSELAGE STRUCTURES
82 July 1 - 91 September 30

Project Engineer: Mr. Huey D. Carden
Mail Stop 495
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4151 FTS 928-4151

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

EXPERIMENTAL AND ANALYTICAL CHARACTERIZATION OF THE MECHANICAL BEHAVIOR OF METAL MATRIX COMPOSITES
80 June 1 - 92 September 30

Project Engineer: Dr. W. Steven Johnson
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3463 FTS 928-3463

Objective: To experimentally investigate the fatigue, fracture, and thermomechanical behavior of MMC's to insure airframe structural integrity at elevated temperatures. Both continuously reinforced laminates and discontinuous particulate and whisker reinforced MMC's will be included in the study.

DEVELOPMENT OF ANALYTICAL MODELS OF THE THERMOMECHANICAL BEHAVIOR OF METAL MATRIX COMPOSITES
87 June 1 - 92 September 30

Project Engineer: Dr. C. A. Bigelow
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3462 FTS 928-3462

Objective: To develop finite-element codes, laminate-analysis codes, and micromechanics models necessary to analytically investigate mechanics issues related to the fatigue, fracture, and thermomechanical behavior of MMC's.

DELAMINATION MICROMECHANICS ANALYSIS
85 October 1 - 92 September 30

Project Engineer: Dr. John H. Crews, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3457 FTS 928-3457

Objective: To develop stress analysis for region near a delamination front, including microcracks and fiber bridging.

MECHANICS MODELS OF ADVANCED TEXTILE COMPOSITES
88 June 1 - 94 September 30

Project Engineer: Mr. Clarence C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3449 FTS 928-3449

Objective: To develop finite-element models of the deformation and local stress states that reflect the local fiber curvature of advanced textile composites. Mathematical descriptions of the unit cell architecture will be the basis for the models. Failure criteria will be developed to optimize these materials with regard to in-plane and out-of-plane strength. Experiments will be conducted to support model development and verify predictions.

INTERLAMINAR SHEAR FRACTURE TOUGHNESS
89 May 1 - 92 September 30

Project Engineer: Ms. Gretchen B. Murri
Mail Stop 188E
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3466 FTS 928-3466

Objective: Cyclic end-notched flexure tests will be used to measure the mode II strain energy release rate of two materials in fatigue. Results will be used to develop ASTM test standards for strain energy release rate under fatigue loading.

DELAMINATIONS IN TAPERED COMPOSITE LAMINATES WITH INTERNAL PLY DROPS
88 October 1 - 92 September 30

Project Engineer: Ms. Gretchen B. Murri
Mail Stop 188E
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3466 FTS 928-3466

Objective: To characterize delamination failures in tapered composites containing internal ply-drops. Experimental results from a variety of materials and lay-ups will be compared with finite element and closed-form solutions.

STUDY OF DAMAGE TOLERANCE OF THERMOPLASTIC COMPOSITES
88 December 1 - 92 December 31

Project Engineer: Mr. C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3467 FTS 928-3467

Objective: To develop an analysis that can also be used as a design tool for predicting the complete damage state during and after impact and the residual properties in thermoplastic and thermoset matrices.

IMPACT RESPONSE AND DAMAGE IN THREE-DIMENSIONAL BRAIDED GRAPHITE FIBER COMPOSITES
87 October 1 - 94 October 31

Project Engineer: Mr. C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3467 FTS 928-3467

Objective: To characterize damage in three-dimensional braided composites subjected to hard object impact at low energy levels.

MIXED-MODE DELAMINATION TESTING
87 September 1 - 92 September 30

Project Engineer: Mr. James R. Reeder
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3456 FTS 928-3456

Objective: To measure the delamination fracture toughness of laminated composites material subjected to combined mode I and mode II loadings and thereby develop a mixed mode delamination failure criterion. The new mixed-mode-bending specimen will be used for testing.

HIGH TEMPERATURE LONG-TERM APPLICATIONS OF POLYMERIC COMPOSITES
90 January 1 - 98 September 30

Project Engineer: Dr. W. S. Johnson
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3463

Objective: To assess the influence of thermal-mechanical fatigue and long term durability on the mechanical properties of polymeric matrix composites for use on advanced supersonic commercial transports. Temperatures will approach 450°F for 60,000 flight hours.

TIME DEPENDENT COMPOSITE CHARACTERIZATION FOR POLYMER COMPOSITES
90 January 1 - 95 September 30

Project Engineer: Dr. Thomas S. Gates
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3400 FTS 928-3400

Objective: To develop constitutive models for nonlinear, rate dependent behavior. Theanalysis will be supported by experimental data to account for creep, relaxation, and physical aging.

EXPERIMENTAL EVALUATION OF ADVANCED COMPOSITE MATERIAL FORMS
84 June 1 - 92 June 1

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3094 FTS 928-3094

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

MICROMECHANICS MODELING OF COMPOSITE THERMOELASTIC BEHAVIOR
86 October - 92 June 30

Project Engineer: Dr. David E. Bowles
Mail Stop 191
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3095 FTS 928-3095

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.

THERMAL DEFORMATIONS AND STRESSES IN COMPOSITE PANELS FOR PRECISION OPTICAL BENCHES
89 June 1 - 92 May 31

Project Engineer: Dr. David E. Bowles
Mail Stop 191
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3095 FTS 928-3095

Objective: Analytically and experimentally investigate the effects of constituent properties (fiber, matrix, core, adhesive) on thermally induced deformations and stresses in composite honeycomb panels for precision optical bench applications.

ADVANCED COMPOSITE MATERIALS FOR ULTRA-HIGH PRECISION REFLECTOR HONEYCOMB PANELS
88 October 1 - 95 September 30

Project Engineer: Dr. Stephen S. Tompkins
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3096 FTS 928-3096

Objective: Develop advanced structural graphite reinforced composite material systems that are dimensionally stable and durable in the LEO and GEO space environments. Using these material systems, fabricate ultra high precision, light weight, core reinforced panels for reflectors and optical benches. Critical requirements for the panels are: a) high inplane and flectural stiffness, b) low moisture distortion, c) near zero thermal expansion, and, d) panel facesheet material replicate high accurate mold surface (surface accuracy less than 1 micron RMS).

THERMAL AND MECHANICAL STABILITY OF COMPOSITE MATERIALS
83 October 1 - 93 September 30

Project Engineer: Dr. Stephen S. Tompkins
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3096 FTS 928-3096

Objective: Develop and evaluate structural composite materials (resin-, metal-, and glass-matrix) that are dimensionally stable and/or have stable thermal and mechanical properties when subjected to simulated long-term LEO and GEO space service environments.

ULTRASONIC NDE OF CARBON-CARBON MATERIALS FOR NASP

Project Engineer: Dr. Eric I. Madaras
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665
(804) 864-4993 FTS 928-4993

Objective: To develop ultrasonic measurement techniques for characterizing the integrity of carbon-carbon composite materials under consideration for use in the NASP project.

EFFECTS OF THROUGH-THE-THICKNESS REINFORCEMENT ON ULTRASONIC INSPECTION OF COMPOSITE LAMINATES

Project Engineer: Dr. Patrick H. Johnston
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665
(804) 864-4966 FTS 928-4966

Objective: To measure the spatial variations of sound velocity in stitched and other three-dimensional fiber architecture composites and to relate these to measurement artifacts in ultrasonic measurements of these composites resulting from them, with a focus toward developing detection methods which are insensitive to these phase-distortions.

CHARACTERIZATION OF COMPOSITES BASED ON ANALYSIS OF THE FREQUENCY DEPENDENCE OF ULTRASONIC ATTENUATION

Project Engineer: Dr. Patrick H. Johnston
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665
(804) 864-4966 FTS 928-4966

Objective: To measure the ultrasonic attenuation coefficient of composites as a function of frequency and to relate these results to models of the flaw types present, such as porosity or delaminations due to impact damage.

NONDESTRUCTIVE EVALUATION OF PULTRUSION PROCESSING

Project Engineer: Mr. F. Raymond Parker
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665
(804) 864-4965 FTS 928-4965

Objective: To instrument a pultrusion die with ultrasonic sensors to enable one to monitor the cure properties of the composite in the die by measuring the change in ultrasonic velocity in the composite and to detect the presence of porosity in the composite by measuring the attenuation of the ultrasonic signal in the composite.

PROPAGATION OF PLATE MODES IN ACOUSTIC EMISSION SIGNALS IN COMPOSITE PLATES

Project Engineer: Mr. William Prosser
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804)864-4960 FTS 928-4960

Objective: To characterize the propagation of plate mode acoustic waves in thin composite plates by measuring the velocity of the extensional mode and the dispersion of the flexural mode as well as the effect of source orientation on the amplitude of the two modes, allowing a better understanding of the propagation of acoustic emission (AE) signals in composite structures.

EFFECT OF STRESS ON THE ENERGY FLUX DEVIATION OF ULTRASONIC WAVES IN GRAPHITE-EPOXY COMPOSITES

Project Engineer: Mr. William Prosser
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804)864-4960 FTS 928-4960

Objective: To model the shift in the energy flow of ultrasonic waves due to the application of stress and nonlinear elastic effects in composite materials to serve as the basis of a new NDE technique to characterize stress in a composite.

THERMAL NDE OF COMPOSITE ROTORCRAFT STRUCTURES

Project Engineer: Mr. Joe Zalameda
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665
(804) 864-4793 FTS 928-4793

Objective: To develop NDE systems for rapid, inexpensive, and efficient inspection of composite rotorcraft structures in both industrial and field environments, including investigations toward combining thermal and ultrasonic NDE techniques for the inspection of composite impact damage.

THERMOGRAPHIC NDE OF COMPOSITES

Project Engineer: Dr. William P. Winfree
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804)864-4963 FTS 928-4963

Objective: To develop thermographic techniques for characterization of defects in composite materials and structures with particular emphasis on impact damage and porosity detection.

THERMOGRAPHIC CHARACTERIZATION OF STRESS INDUCED DAMAGE IN COMPOSITES

Project Engineer: Ms. D. Michele Heath
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665
(804) 864-4964 FTS 928-4964

Objective: To develop a remote thermographic technique for monitoring stress induced damage in composite materials during cyclic fatigue testing and during static loading.

SMART MATERIALS AND STRUCTURES

Project Engineer: Dr. Robert Rogoswki
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804)864-4990 FTS 928-4990

Objective: Investigate methods for embedding and interrogating optical fiber sensors for health monitoring of composite materials and structures.

CONTRACTS

COLLAPSE AND FAILURE MODES IN ADVANCED COMPOSITE STRUCTURES
NSG-1483
78 January 15 - 92 January 14

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

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

Objective: To experimentally and analytically study time-dependent effects on buckling and failure of composite structures with discontinuities.

STRUCTURES AND MATERIALS TECHNOLOGIES FOR AIRCRAFT COMPOSITE PRIMARY STRUCTURES
NAS1-19347
91 September 1 - 98 August 31

Project Engineer: Mr. Marshall Rouse
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3182 FTS 928-3182

Principal Investigator: Dr. Ravi Deo
M.S. 3853/MF
Northrop Corporation
1 Northrop Ave
Hawthorne, CA. 90250-3277
(213) 332-2134

Objective: To develop and validiate structures and materials technologies for wing and fuselage structures that would be applicable to subsonic and/or supersonic commercial transport aircraft.

ADVANCED COMPOSITE STRUCTURAL DESIGN TECHNOLOGY FOR COMMERCIAL TRANSPORT AIRCRAFT
Pending
91 September 1 - 98 August 31

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: TBD

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

STRUCTURAL OPTIMIZATION FOR IMPROVED DAMAGE TOLERANCE
NAG-1-168
81 September 1 - 92 October 15

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: Dr. Raphael T. Haftka
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
(703) 231-4860

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 - 90 December 30

Project Engineer: Dr. Damodar R. Ambur
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3174 FTS 928-3174

Principal Investigator: Mr. R. E. Barrie
Lockheed Aeronautical Systems Co.
D/73-C1 Zone 0150
86 South Cobb Drive
Marietta, GA 30063
(404) 494-8161

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

ANISOTROPIC SHELL ANALYSIS
NAG-1-901
88 October 1 - 92 September 30

Project Engineer: Dr. Michael P. Nemeth
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3184 FTS 928-3184

Principal Investigator: Dr. Michael W. Hyer
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
(703) 231-5372

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

THICKNESS DISCONTINUITY EFFECTS
NAG-1-537
85 October 1 - 92 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: Dr. Eric R. Johnson
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
(703) 231-6126

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

STRUCTURAL DESIGN CRITERIA FOR FILAMENT-WOUND COMPOSITE SHELLS
NAG-1-982
89 May 15 - 92 May 15

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: Dr. H. T. Hahn
Pennsylvania State University
University Park, PA 16802
(814) 865-4523

Objective: To develop structural design criteria that can be used to scale-up filament wound composite shells.

COMPOSITE FUSELAGE TECHNOLOGY
NAG-1-982
89 April 7 - 92 April 7

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: Dr. P. A. Lagace
Massachusetts Institute of Technology
Cambridge, MA 02139
(617) 253-3628

Objective: To conduct experimental and analytical studies of pressurized composite fuselage shells subjected to damage.

FIBER BUCKLING IN LAMINATED PLATES
NAG-1-1040
89 October 1 - 92 September 30

Project Engineer: Dr. Mark J. Shuart
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3170 FTS 928-3170

Principal Investigator: Dr. A. Waas
University of Michigan
Ann Arbor, MI 48109-1248
(313) 764-8227

Objective: Conduct experimental and analytical studies to isolate and observe in-situ failure mechanisms for composite structures.

STIFFNESS TAILORING OF COMPOSITE PLATES FOR IMPROVED STABILITY AND STRENGTH UNDER COMBINED LOADING
NAG-1-1141
90 June 1 - 92 November 1

Project Engineer: Dr. Mark J. Shuart
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3170 FTS 928-3170

Principal Investigator: Dr. S. B. Biggers
Clemson University
Clemson, SC 29634
(803) 656-0139

Objective: Conduct experimental and analytical studies to tailor membrane and bending stiffnesses for a composite plate that will result in improved buckling resistance and/or postbuckling strength.

MECHANICAL PROPERTIES OF 3-D WOVEN FABRIC
NCC-1-130
88 August 1 - 92 May 1

Project Engineer: Dr. Gary L. Farley
Mail Stop 190
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3091 FTS 928-3091

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

Objective: Establish the mechanical response and damage tolerance characteristics of 3-D woven fabrics.

PROGRESSIVE FAILURE MODEL FOR LAMINATED COMPOSITES
NAG-1-979
89 March 1 - 92 February 28

Project Engineer: Dr. Charles E. Harris
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3449 FTS 928-3449

Principal Investigator: Dr. David H. Allen
Aerospace Engineering Department
Texas A&M University
College Station, TX 77843

Objective: To develop a damage-dependent constitutive model as the mechanics foundation for a progressive failure methodology to predict the residual strength and life of laminates.

THERMAL VISCOPLASTICITY IN METAL MATRIX COMPOSITES
L-24457C
87 July 1 - 92 January 31

Project Engineer: Dr. W. S. Johnson
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3463 FTS 928-3463

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 thermal viscoplasticity stresses and strains in continuous fiber-reinforced metal matrix composites due to fabrication and/or subsequent thermal cycling and mechanical loadings.

ANALYSIS OF INTERLAMINAR FRACTURE IN COMPOSITES UNDER COMBINED LOADING
NAG-1-637
89 October 1 - 92 September 30

Project Engineer: Ms. Gretchen B. Murri
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Mail Stop 188E
Hampton, VA 23665-5225
(804) 864-3466 FTS 928-3466

Principal Investigator: Dr. E. A. Armanios
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

Objective: The objective of this program is to extend an existing sublaminate analysis method to model tapered ply-drop configurations under bending and combined tension-bending loads. The analyses are intended for use on personal-class computers.

DEVELOPMENT OF ADVANCED WOVEN COMPOSITE MATERIALS AND STRUCTURAL FORMS
NAS1-18358
86 August 29 - 92 June 30

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3094 FTS 928-3094

Principal Investigator: Ms. Janice Maiden
Textile Technologies, Inc.
2800 Turnpike Drive
Hatboro, PA 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.

VISCOELASTIC RESPONSE OF COMPOSITE/HONEYCOMB PANELS FOR PRECISION REFLECTORS
NAG-1-343
88 August 16 - 92 December 31

Project Engineer: Dr. D. E. Bowles
Mail Stop 191
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3095 FTS 928-3095

Principal Investigator: Dr. M. W. Hyer
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
(703) 231-5372

Objective: Analytically and experimentally investigate the viscoelastic response of sandwich panels fabricated from composite facesheets and honeycomb cores.

ADVANCED COMPOSITE FABRICATION AND TESTING
NAS1-18954
89 August - 94 August

Project Engineer: Mr. Marvin B. Dow
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3090 FTS 928-3090

Principal Investigator: Mr. Anthony Falcone
Boeing Aerospace
Seattle, WA 98124
(206) 234-2678

Objective: To process and test experimental composite materials and state-of-the-art systems including woven, braided, knitted, and stitched fiber forms. Processing shall include resin transfer molding, pultrusion, and thermoforming.

DEVELOPMENT OF FILAMENT WINDING PROCESS FOR GR/TP COMPOSITE LAMINATES
NAS1-18624
89 April 27 - 91 September 30

Project Engineer: Mr. Jerry W. Deaton
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3087 FTS 928-3087

Principal Investigator: Mr. G. E. Walker, Jr.
Hercules Aerospace Company
Composite Products Group
Bacchus Works
Magna, UT 84044-0098
(801) 251-4194

Objective: Development of consolidation processes for Gr/TP filament-wound/fiber-placement laminates and demonstration of laminate quality through nondestructive evaluation/inspection and mechanical testing. Mechanical testing of specimens is currently underway at NASA Langley.

ADVANCED COMPOSITE STRUCTURAL CONCEPTS AND MATERIAL TECHNOLOGIES FOR PRIMARY AIRCRAFT STRUCTURES
NAS1-18888
1989 April - 1995 May

Project Engineer: Dr. Randall C. Davis
Mail Stop 241
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-5435 FTS 928-4535

Principal Investigator: Mr. A. Jackson
Lockheed Aeronautical Systems Company
D/73-C1 Zone 0150
86 South Cobb Drive
Marietta, GA 30063
(404) 494-8164

Objective: To develop and verify innovative textile preform concepts and fabrication processes that exploit the full potential of integrated design/manufacturing procedures to achieve light-weight and cost-effective primary structures; and to develop a strong structural mechanics technology base to predict the performance of advanced concepts.

NOVEL MATRIX RESINS WITH IMPROVED PROCESSABILITY AND PROPERTIES FOR PRIMARY AIRCRAFT STRUCTURES
NAS1-18841
1989 April - 1992 April

Project Engineer: Dr. P. Hergenrother
Mail Stop 226
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4270 FTS 928-4270

Principal Investigator: Dr. E. P. Woo
Dow Chemical Company
1712 Building
Midland, MI 48674
(517)-636-1072

Objective: Develop new high performance resins with improved durability, toughness and processability. The resins will be targeted for aircraft structural applications with maximum use temperatures ranging from 180°F to 450°F. New resins such as toughened cyanates, modified epoxies, acetylene chromenes, bisbenzocyclobutenes and cyclic oligomers will be synthesized. Composites of the new resins will be fabricatd via resin transfer molding or conventional prepreg and evaluated.

ADVANCED MATERIALS AND PRODUCT FORMS
NAS1-18834
1989 April - 1995 May

Project Engineer: Dr. N. Johnston
Mail Stop 188M
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3493 FTS 928-3493

Principal Investigator: Mr. J. T. Hartness
BASF
13504-A South Point Blvd.
Charlotte, NC 28217
(704)-588-7976

Objective: Develop improved matrix resins and unique material forms that offer increased performance and improved processability over state-of-the-art structural composite materials. Two prepreg concepts will be developed and evaluated. The first will use either thermoplastic or thermoset polymer powders to impregnate fiber tows or woven preforms. The second will employ thermoplastics spun into fibers and intimately blended with the reinforcing fibers.

EFFECTS OF MATRIX AND INTERPHASE ON CARBON FIBER COMPOSITE COMPRESSION STRENGTH
NAS1-18883
1989 April - 1995 May

Project Engineer: Mr. James Reeder
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3456 FTS 928-3456

Principal Investigator: Dr. Willard D. Bascom
M.S. 304 EMRO
University of Utah
Salt Lake City, UT 84112
(801)-581-7422

Objective: There is evidence from previous work conducted at Boeing that fiber tensile strength is not being fully translated into unidirectional coupons fabricated by tow placement. This program aims to examine the difference between tape layup and tow placement, along with two other materials variables: fiber type and resin toughness. Failures in unnotched, notched, open hole and impacted panels will be characterized in detail. The result will be a better understanding of damage progression and residual strength in multiaxially-loaded structures.

CHARACTERIZING THE FRACTURE TOUGHNESS OF ADVANCED COMPOSITE STRUCTURES
NAS1-18833
1989 December 1 - 1991 December 31

Project Engineer: Dr. John Crews
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3457 FTS 928-3457

Principal Investigator: Dr. John A. Nairn
M.S. 304 EMRO
University of Utah
Salt Lake City, UT 84112
(801) 581-3413

Objective: Develop fracture mechanics analyses for predicting matrix microcracks and microcrack-induced delaminations. Conduct tests to identify the parameters that govern microcracking and microcrack-induced delaminations. Then, develop strain energy release rate (G) analyses for observed damage initiation modes and growth modes. Finally, interpret composite stiffness degradation and fracture toughness in terms of critical strain energy release rates for damage initiation and growth.

THE MICROMECHANICS OF FATIGUE FAILURE IN WOVEN AND STITCHED COMPOSITES
NAS1-18840
1989 April - 1995 May

Project Engineer: Mr. C. C. Poe
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3467 FTS 928-3467

Principal Investigator: Dr. Brian Cox
P.O. Box 1085
Rockwell International
1049 Camino Dos Rios
Thousand Oaks, CA 91360
(805)-373-4128

Objective: Develop experimental techniques to characterize the initiation and growth of fatigue amage. Determine the effect of damage on the internal stresses and the global composite stiffness. Based on damage characterization, develop micromechanical model for predicting fatigue behavior of new material architectures.

DAMAGE TOLERANCE OF COMPOSITE PLATES
NAS1-18778
1989 April - 1995 May

Project Engineer: Mr. W. C. Jackson
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3468 FTS 928-3468

Principal Investigator: Dr. G. S. Springer
Department of Aeronautics and Astronautics
Stanford University
Stanford, CA 94305
(415)-723-4135

Objective: Develop an analysis to predict the complete damage state during and after low-velocity impact and to predict the residual properties. The analysis will be sufficiently general to account for the unique properties of thermoplastic matrix materials while applying to other matrices as well. A three-dimensional finite element model will be developed to calculate stresses, strains, and displacements in a composite during impact based on Hertzian contact forces. The model will define impactor position, velocity, and force as a function of time and will be general regarding material properties and composite layup. The model will predict fiber and matrix damage and trace delamination growth. The analysis will be verified through impact tests wherein the impact force and the extent of damage will be measured. Both destructive and nondestructive techniques will be used to determine the extent of damage.

ADVANCED FIBER PLACEMENT FUSELAGE TECHNOLOGY PROGRAM
NAS1-18887
1989 April - 1995 May

Project Engineer: Mr. W. T. Freeman
Mail Stop 241
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-2945 FTS 928-2945

Principal Investigator: R. L. Anderson
M.S. X11K4
Hercules Incorporated
P.O. 98
Magna, Utah 84044
(801)-251-2077

Objective: To develop breakthrough technology for cost effective fabrication of damage tolerant composite fuselage structures. A seven-axis tow placement technique will be used to achieve low cost manufacturing of highly efficient complex structural forms. Major emphasis shall be on innovative manufacturing methods that may offer options for highly efficient primary aircraft structures. A variety of crown, windowbelt, and keel panels will be manufactured at Hercules and delivered to the Boeing Commercial Airplane Group for evaluation.

INNOVATIVE FABRICATION PROCESSING OF ADVANCED COMPOSITE MATERIALS CONCEPTS FOR PRIMARY AIRCRAFT STRUCTURE
NAS1-18799

1989 May 9 - 1992 August 9

Project Engineer: Mr. Jerry W. Deaton
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-30870 FTS 928-3087

Principal Investigator: Mr. S. P. Garbo
United Technologies
Sikorsky Aircraft Division
6900 Main Street
Stratford, Conn. 06601-1381
(203)-386-4576

Objective: Develop unique and innovative design concepts for complex fuselage structure that are amenable to the Therm-X pressure molding fabrication process. Concept drivers include innovative structural arrangement, improved structural efficiency, damage resistance, maintainability and repairability, and lower fabrication costs. Integrated design and Therm-X fabrication process to produce fuselage structure with frame/stringer intersections in a single cure operation.

MODELING AND DESIGN ANALYSIS METHODOLOGY FOR COMPOSITE PRIMARY STRUCTURE
NAS1-18754
1989 April - 1995 May

Project Engineer: Dr. Damodar R. Ambur
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3174 FTS 928-3174

Principal Investigator: Dr. L. W. Rehfield
Dept. of Mechanical Engineering
University of California
Davis, CA. 95616
(916)-752-0580

Objective: Develop and validate new structural models for aeroelastically tailored wings. Nonclassical effects will be incorporated into these analytical models as appropriate. Emphasis will be given to identifying mechanisms that are useful for tailoring, with particular attention being devoted to elastically produced chordwise camber deformations. The models will be simple, useful for preliminary deisgn and trade-off studies and adequate for representing the essential physical behavior of the structure. Validation of analytical models by extensive finite element simulation and selected experiments is conducted as well.

STUDY OF TAILORED COMPOSITE STRUCTURES OF ORDERED STAPLE THERMOPLASTIC MATERIALS
NAS1-18758
1989 April - 1995 May

Project Engineer: Ms. D. C. Jegley
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3185 FTS 928-3185

Principal Investigator: Dr. M. H. Santare
Dept. of Mechanical Engineering
University of Delaware
Newark, DE. 19716
(302)-451-2246

Objective: Develop and verify an analysis method to predict the response of curved beam structures that accounts for beams with various cross sections, microstructures, anisotropy and position-dependent material properties. Design curved beam test specimens made of ordered staple thermoplastic materials. Develop a methodology for fabrication of these test specimens that makes use of cost-effective manufacturing and sheet-forming technology.

ADVANCED TECHNOLOGY COMPOSITE AIRCRAFT STRUCTURES
NAS1-18889
1989 April - 1995 May

Project Engineer: Mr. W. T. Freeman
Mail Stop 241
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-2945 FTS 928-2945

Principal Investigator: Dr. Larry Ilcewicz
Boeing Commercial Airplanes
M.S. 31C-65
P.O. Box 3707
Seattle, WA 98124
(206) 393-9630

Objective: To support NASA's goal to revitalize the nation's capacity for aeronautical innovation over the next decade by developing technology needed to apply composites to primary structures on commercial transport aircraft by the late 1990's. The technology shall provide a high level of technical confidence and demonstrate acceptable cost effectiveness for these specific objectives: (1) Develop basic technologies required to support cost effective damage tolerant pressurized fuselage structural designs and verify breakthrough technology results with mechanical tests. (2) Demonstrate advanced material placement processes and flexible automation for low cost assembly of pressurized transport fuselage structures. (3) Demonstrate the use of thermoplastic materials with advanced manufacturing techniques for fuselage clips, fittings, frames, and window belt reinforcements. (4) Develop the associated design, analysis and process technologies so that commercial application readiness and cost effectiveness can be realistically assessed. (5) Since the fuselage has the highest percentage of corrosion and fatigue problems on transport aircraft, composites will be evaluated for their potential to reduce repair and maintenance costs associated with airline life-cycle supportability. (6) Composite center fuselage elements will be developed because weight reductions at the airplane centerline are more effective in increasing payload, due to the offsetting dead-weight relief effects. The contract was modified in 1991 to include development of a Designer's Cost Model.

INNOVATIVE COMPOSITE AIRCRAFT PRIMARY STRUCTURES (ICAPS)
NAS1-18862
89 March 31 - 94 September 30

Project Engineer: Mr. Marvin B. Dow
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3090 FTS 928-3090

Principal Investigator: Mr. Alan Markus
McDonnell Douglas Corporation
Douglas Aircraft Company
3855 Lakewood Blvd.
Long Beach, CA 90846
(213) 593-4880

Objective: Develop and demonstrate innovative woven/stitched fiber preforms and resin matrix impregnation concepts for transport wing and fuselage structures. Demonstrate tow placement processes for transport fuselage structures. Conduct a study of materials and structures for high speed transport aircraft. For such future aircraft, perform long-term, elevated temperature evaluations of polymeric matrix composite materials, investigate accelerated testing methodology, and develop structural panel concepts.

NOVEL COMPOSITES FOR WING AND FUSELAGE APPLICATIONS
NAS1-18784
89 April 28 - 93 July 31

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3094 FTS 928-3094

Principal Investigator: Mr. James Suarez
Grumman Aerospace Corporation
Aircraft Systems Division
South Oyster Bay Road
Bethpage, NY 11714-3582
(516) 575-6552

Objective: Integrate innovative design concepts with cost-effective fabrication processes to achieve damage tolerant structures that can perform at a design ultimate strain level of at least 6000 micro in./in. Integral structures will be fabricated using weaving and knitting/stitching concepts. Resin transfer molding will be used for low cost resin application and consolidation.

INNOVATIVE COMPOSITE FUSELAGE STRUCTURES
NAS1-18842
1989 April - 1995 May

Project Engineer: Mr. M. Rouse
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3182 FTS 928-3182

Principal Investigator: Dr. R. B. Deo
M.S. 3853/MF
Northrop Corporation
1 Northrop Ave
Hawthorne, CA. 90250-3277
(213) 332-2134

Objective: Develop innovative concepts for fighter aircraft fuselage structures that will improve structural efficiency while reducing manufacturing costs. Analysis methods and structural mechanics methodologies appropriate for the new structural concepts will also be developed and validated through tests of elements and components. Analysis techniques will be developed in three major areas: (1) structural details, (2) structural stability, and (3) scaling laws. This contract was redirected in 1991 to develop structural concepts and materials technology of future supersonic commercial transports.

FIBER WAVEGUIDE SENSORS FOR INTELLIGENT MATERIALS
NAG -1-895
1988 SEPTEMBER – 1991 OCTOBER

Project Engineer: Dr. Robert Rogoswki
IRD, Nondestructive Evaluation Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804)864-4990 FTS 928-4990

Principal Investigator: Dr. Richard O. Claus
Department of Electrical Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Objective: Development of fiber-optic based opto-electronic sensing instrumentation for the characterization of materials and structures.

ULTRASONIC NONDESTRUCTIVE CHARACTERIZATION OF COMPOSITES WITH 3-DIMENSIONAL ARCHITECTURES
NSG-1-601
1981 September – 1992 March

Project Engineer: Dr. Patrick H. Johnston
IRD, Nondestructive Evaluation Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665
(804) 864-4966 FTS 928-4966

Principal Investigator: Dr. James G. Miller
Department of Physics
Washington University
St. Louis, MO 33130

Objective: The overall goal of our research program is the development and application of quantitative ultrasonic techniques to problems of nondestructive evaluation of composite materials. We specifically are focused on applications of frequency analysis of ultrasonic propagation to determine material properties in composite laminates and more complex fiber geometries.

INVESTIGATION OF ACOUSTIC PROPERTIES OF COMPOSITE MATERIALS
NAG -1-1063
1983 September – 1991 October

Project Engineer: Dr. Patrick H. Johnston
IRD, Nondestructive Evaluation Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665
(804) 864-4966 FTS 928-4966

Principal Investigator: Dr. Barry T. Smith
Department of Physics
College of William and Mary
Williamsburg, VA 23185

Objective: The research involves an investigation of the ultrasonic properties of composite materials in order to characterize and assess damage. Current focus lies upon impact damage in carbon-carbon and stitched and woven laminates.

NONDESTRUCTIVE EVALUATION OF CARBON-CARBON COMPOSITES
1989 September – 1995 September

Project Engineer: Dr. Eric I. Madaras
IRD, Nondestructive Evaluation Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665
(804) 864-4993 FTS 928-4993

Principal Investigator: Dr. Ron Kline
Department of Aerospace and Mechanical Engineering
University of Oklahoma
Norman, OK 73019

Objective: The research involves methods of measuring the elastic moduli of carbon-carbon materials and integrating the results with FEM codes to predict the behavior of components. Also, research related to nondestructive evaluation of carbon-carbon coatings is being conducted.

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

IN-HOUSE

NONE

GRANTS AND CONTRACTS

DEVELOPMENT AND CHARACTERIZATION OF TOUGH CERAMIC MATRIX COMPOSITES
AFOSR-87-0307
1 Mar 91 - 30 Apr 94

Principal Investigator: Prof Peter W R Beaumont
Engineering Department
Cambridge University
Trumpington Street, Cambridge CB2 1PZ
011-44- 223-332600

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: The proposed research program aims at directly observing and modeling the underlying physical processes and microstructure-property relationships of model metal-reinforced brittle matrix systems, as well as Glass - SiC and polymer-carbon fiber laminates. A key objective of this work is to quantify the toughening effect of each microstructural feature, so as to guide the development of damage tolerant brittle matrix composites.

NUCLEATION AND GROWTH IN CHEMICAL VAPOR DEPOSITION
AFOSR-ISSA
1 Oct 91 - 30 Sep 92

Principal Investigator: Dr Theodore M Besmann
Oak Ridge National Laboratory
Metals and Ceramics Division
Oak Ridge TN 37831-6063
(615) 574-6852

Program Manager: Lt Col Larry W Burggraf
AFOSR/NC
Bolling AFB DC 20332-6448
(202) 767-4960

Objective: The objective of the proposed research is to acquire a basic understanding of nucleation and growth in CVD necessary to control the microstructure; and thus the properties of the composite. This understanding will involve the effects of both processing conditions (temperature, pressure, concentrations, flow rate, etc.) and the characteristics of the substrate.

SITE SPECIFIC REACTIONS OF CARBON WITH OXYGEN AND SILICON IN GRAPHITE, CARBON FIBERS AND CARBON-CARBON COMPOSITES
AFOSR-91-0103
1 Dec 90 - 30 Nov 93

Principal Investigator: Prof Dawn A Bonnell
Dept of Materials Science & Engineering
University of Pennsylvania
Philadelphia PA 19104-3246
(215) 898-8337

Program Manager: Lt Col Larry W Burggraf
AFOSR/NC
Bolling AFB DC 20332-6448
(202) 767-4960

Objective: The objective of this research is to investigate the reactions of carbon with oxygen, boron and silicon at a fundamental level by direct observation (imaging) and spectroscopic analysis that exploits the spatial localization of information obtained by scanning tunneling microscopy (STM).

INTERFACIAL STUDIES OF COATED FIBER/GLASS CERAMIC MATRIX COMPOSITES
F49620-88-C-0062
1 May 88 - 30 Apr 91

Principal Investigator: Dr John J Brennan
United Technologies Research Center
East Hartford CT 06108
(203) 727-7220

Program Manager: Lt Col Larry W Burggraf
AFOSR/NC
Bolling AFB DC 20332-6448
(202) 767-4960

Objective: The objective of the proposed program is to develop an understanding of the relationships between the fiber, the fiber coating, and the glass-ceramic matrix that will lead to a composite system exhibiting high strength, high toughness, and high thermal and environmental stability to temperatures of 1200°C.

DAMAGE TOLERANCE OF LAMINATED COMPOSITES TO IMPACT
AFOSR-89-0554
1 Sep 89 - 31 Aug 92

Principal Investigator: Prof Fu-Kuo Chang
Dept of Aeronautics and Astronautics
Stanford University
125 Panama Street
Stanford, CA 94305-4125
(415) 723-3466

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: The objectives of the proposed research are (1) to identify and describe the fundamental damage mechanisms induced by impact in composite laminates, (2) to predict the extent of damage as a function of impact momentum, material properties, etc., and (3) to predict the residual strength and stiffness in the laminate after impact.

3D ANALYSIS AND VERIFICATION OF FRACTURE GROWTH MECHANISMS IN FIBER-REINFORCED CERAMIC COMPOSITES
AFOSR-89-0005
1 Sep 88 - 31 Aug 91

Principal Investigator: Prof Michael P Cleary
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139
(617) 253-2308

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To model the fracture mechanisms in mechanical systems representative of existing and proposed ceramic composites. Emphasis is placed on the roles of the fibers and the interface in generating, arresting, or retarding the growth of fractures.

MICROMECHANICAL PREDICTION OF TENSILE DAMAGE FOR CERAMIC-MATRIX COMPOSITES UNDER HIGH TEMPERATURE
AFOSR-90-0341 (URI)
15 Aug 90 - 14 Aug 93

Principal Investigator: Professor Feridun Delale
Department of Mechanical Engineering
City College - CUNY
New York NY 10031
(212) 650-5224

Program Manager: Lt Col Larry W Burggraf
AFOSR/NC
Bolling AFB DC 20332-6448
(202) 767-4960

Objective: The aim of the research is to generate a model to predict the non-linear behavior of ceramic matrix composites at high temperatures. The experiments are designed to observe and record in situ the progression of tensile damage at high temperature. An analytical model based on micromechanics will be developed to predict the expected non-linear damage behavior.

DYNAMICS AND AEROELASTICITY OF COMPOSITE STRUCTURES
F49620-86-C-0066
1 Jul 86 - 30 Sep 90

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

Program Manager: Dr Spencer Wu
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-6962

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

FIBER COATINGS BY SPUTTERING FOR HIGH TEMPERATURE COMPOSITES
F49620-89-C-0066 (DARPA)
15 May 89 - 14 May 92

Principal Investigator: Dr M Emiliani
Pratt & Whitney Aircraft Group
West Palm Beach FL 33410-9600
(407) 796-6311

Program Manager: Lt Col Larry W Burggraf
AFOSR/NC
Bolling AFB DC 20332-6448
(202) 767-4960

Objective: The objective of this program is to provide high quality, well characterized sputtered coatings for chemical and mechanical studies of the interface in fiber reinforced intermetallic and ceramic matrix composites.

FAILURE CRITERIA IN LAMINATES BASED ON A 3-D MICROMECHANICS CONSIDERATION
AFOSR-90-073
15 Jun 90 - 14 Jun 92

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

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To use analytically determined three-dimensional stress fields derived for laminated composites to establish failure criteria based on micromechanics considerations.

DEVELOPMENT OF AN ADVANCED CONTINUUM THEORY FOR COMPOSITE LAMINATES
F49620-91-C-0019 (SBIR)
30 Sep 90 - 31 Aug 92

Principal Investigator:
Dr G R Ghanimati
Berkeley Applied Science & Engineering
P. O. Box 10104
Berkeley, CA 94709-0104
(415) 653-2323

Program Manager:
Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: The objective of the proposed research is the development of a continuum model for laminated composite materials which is physically and mathematically accurate and accounts for the effects of the microstructure, both geometric and material nonlinearities, and curved geometry. The model will consist of a set of constraint equations, a set of global/local equations of motion, and response functions (constitutive equations). The model will be applied to composites with flat and curved layers and the predictions will be compared with those of existing models. The specific objectives of the current effort are (1) explicit derivation of constitutive relations, (2) application of the theory to practical problems, (3) further development of the theory, and (4) finite element formulation and development of a computer code.

CERAMIC FIBER COATING DEVELOPMENT AND DEMONSTRATION
F49620-89-C-0078 (DARPA)
15 May 89 - 31 Dec 91

Principal Investigator:
Dr Terry D Gulden
General Atomics
San Diego CA 92121-1194
(619) 455-2893

Program Manager:
Lt Col Larry W Burggraf
AFOSR/NC
Bolling AFB DC 20332-6448
(202) 767-4960

Objective: The objective of the proposed work is to address the critical issues in the coating selection/processing for continuous ceramic filament yarns and to carry through to production kilogram quantitites of coated fiber and fabrication and testing of composites from the coated fiber.

COMPOSITE MATERIAL INTERFACE MECHANICS
AFOSR-MIPR-89-0022 (Co-funded with ONR)
1 Mar 89 - 28 Feb 91

Principal Investigator:	Prof Zvi Hashin Department of Mechanical Engineering and Applied Mechanics University of Pennsylvania Philadelphia, PA 19104-3246 (215) 898-8504
Program Manager:	Dr Walter F Jones AFOSR/NA Bolling AFB DC 20332-6448 (202) 767-0470
Objective:	To assess the effects of realistic interface conditions due to elastic, inelastic, and damaged interphase on the thermoelastic properties and failure of composite materials.

MECHANISMS OF ELEVATED TEMPERATURE FATIGUE DAMAGE IN FIBER-REINFORCED CERAMIC MATRIX COMPOSITES
AFOSR-91-0106
1 Dec 90 - 30 Nov 92

Principal Investigator:	Prof John W Holmes Ceramic Composites Research Laboratory University of Michigan 1065 G.G. Brown Laboratory Ann Arbor, MI 48109-2125 (313) 763-5969
Program Manager:	Dr Walter F Jones AFOSR/NA Bolling AFB DC 20332-6448 (202) 767-0470
Objective:	The objective of this research is to explore and identify the microstructural damage mechanisms that occur during high temperature fatigue and creep loading of fiber reinforced CMC materials.

HIGH TEMPERATURE HETEROGENEOUS MATERIALS
AFOSR-90-0237 (URI)
1 Dec 89 - 30 Nov 92

Principal Investigator:	Prof Leon M Keer Department of Civil Engineering Northwestern University Evanston, IL 60208 (708) 491-4046

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To study the high-temperature behavior of ceramic fiber-reinforced, ceramic matrix composites. The types, severity, and growth of damage mechanisms under various loading conditions will be experimentally established and analytically described.

MECHANICS OF FAILURE OF HIGH TEMPERATURE METAL-MATRIX COMPOSITES
AFOSR-89-424 (URI)
15 Mar 90 - 14 Mar 93

Principal Investigator: Prof D A Kouris
Department of Mechanical and Aerospace Engineering
Arizona State University
Tempe, AZ 85287
(602) 965-4977

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To establish the damage mechanisms mainly responsible for the degradation of metal matrix composite materials under high-temperature fatigue conditions and to describe those mechanisms analytically so that predictions of the expected behavior can be made. Experimental work (to be carried out by Rockwell International Science Center) will establish physical damage mechanisms by direct observation and will also verify analytical damage-growth rate predictions.

HIGH PERFORMANCE LAMINATED COMPOSITES
AFOSR-90-0132 (URI)
1 Jan 90 - 31 Dec 92

Principal Investigator: Prof F A Leckie
Department of Mechanical Engineering
University of California
Santa Barbara, CA 93106
(805) 961-2652

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To establish the mechanics framework which will allow the analysis and interpretation of the mechanical behavior of laminated systems consisting of thin alternating layers of brittle and ductile materials.

INTERFACES IN INORGANIC MATRIX COMPOSITES: EXPERIMENT AND ATOMISTIC SIMULATION
AFOSR-91-0285
15 May 92 - 14 May 96

Principal Investigator: Dr Janez Megusar
Materials Processing Center
Massachusetts Institute of Technology
Cambridge MA 02139
(617) 253-6917

Program Manager: Lt Col Larry W Burggraf
AFOSR/NC
Bolling AFB DC 20332-6448
(202) 767-4960

Objective: The objective of this proposed research is to advance the understanding of interfacial phenomena in CMC materials by a combination of atomistic simulation, experimental study of interfaces, and CMC processing in an interdisciplinary research program. A graphic fiber/silicon carbide bi-material is proposed as the model system. Specimens will be fabricated by coating graphite fibers with a layer of silicon carbide using plasma enhanced chemical vapor deposition. The specimens will be subjected to a series of heat treatments in which the annealing time and temperature will be systemically varied in order to establish a basis for studying the kinetics of the interface reactions and a detailed characterization of interface structures. The characterization of the graphite/SiC interfaces will include high-resolution transmission electron microscopy and analytical electron microscopy. Limited testing of the interface strength and toughness will be performed for the sole purpose of verifying the predictions of the atomistic simulation. The experiments will contribute toward optimizing interface structure and properties of the proposed model system and will furthermore ensure that the parallel atomistic simulation will relate to real systems.

MICROMECHANICS OF INTERFACES IN HIGH-TEMPERATURE COMPOSITES
AFOSR-89-0269
1 Feb 89 - 31 Jan 92

Principal Investigator: Prof Toshio Mura
Department of Civil Engineering
Northwestern University
Evanston, IL 60208
(312) 491-4003

Program Managers: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To establish the microstructural variables which promote toughness in brittle matrix composites by means of analytical and experimental perspectives, and to construct the mechanics/material sciences based model for predicting the behavior of such materials.

OPTIMUM AEROELASTIC CHARACTERISTICS FOR COMPOSITE SUPER-MANEUVERABLE AIRCRAFT
AFOSR-89-0055
1 Oct 88 - 30 Sep 91

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

Program Manager: Dr Spencer Wu
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-6962

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

FINITE ELEMENT ANALYSIS OF COMPOSITE SHELLS
AFOSR-PD-88-0010
1 Apr 89 - 30 Sep 90

Principal Investigator: Dr Anthony Palazotto
Air Force Institute of Technology
Wright-Patterson AFB OH 45433-6583
(513) 255-2998, AUTOVON 785-2998

Program Manager: Dr Spencer Wu
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-6962

Objective: A general nonlinear shell theory has been developed to analyze the static and dynamic characteristics of composite shells. A finite element program is being developed. Perturbation and boundary integral techniques are also being used for baseline and comparison purposes.

MESOMECHANICAL MODEL FOR FIBRE COMPOSITES: THE ROLE OF THE INTERFACE
AFOSR-89-0365
1 Jun 89 - 31 May 92

Principal Investigator: Prof M R Piggott
University of Toronto
Ontario, Canada M5S 1A4
(416) 978-4745

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: The objective of this program is to establish the relationship between the interface/interphase parameters and composite properties. Particular attention is paid to the role of interphase failure.

THE OVERALL RESPONSE OF COMPOSITE MATERIALS UNDERGOING LARGE ELASTIC DEFORMATIONS
AFOSR-91-0161
1 Jan 91 - 31 Aug 92

Principal Investigator: Prof Pedro Ponte-Castaneda
Department of Mechanical Engineering
University of Pennsylvania
School of Engineering & Applied Sciences
Philadelphia, PA 19104-3246

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: The objective of this research effort is to establish the limits of the overall constitutive behavior starting with limited statistical information about the distribution of phases in the composite.

PRESSURELESS DENSIFICATION OF CERAMIC MATRIX COMPOSITES
AFOSR-90-0267 (URI)
1 Mar 90 - 28 Feb 93

Principal Investigator: Professor Mohamed N Rahaman
Department of Ceramic Engineering
University of Missouri
Rolla MO 65401-0249
(314) 341-4406

Program Manager: Lt Col Larry W Burggraf
AFOSR/NC
Bolling AFB DC 20332-6448
(202) 767-4960

Objective: The objective of this research is to study and model the sintering of ceramic particles around hard inclusions. The limits for pressureless sintering will be evaluated and the responsible impediments will be identified through model theoretical studies. It is also proposed to study the in situ formation of reinforcements during reaction sintering.

EVOLUTION MECHANICS
AFOSR-89-0216
1 Dec 88 - 30 Nov 91

Principal Investigator: Prof K L Reifsnider
Virginia Polytechnic Institute & State University
Blacksburg, VA 24061
(703) 961-5316

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To develop methods for predicting the long-term behavior of composite materials, especially their remaining strength and life after periods of service which includes exposure to time-variable thermomechanical and chemical loading.

EIGENSENSITIVITY ANALYSIS OF COMPOSITE LAMINATES: EFFECT OF MICROSTRUCTURE
F49620-89-C-0003
1 Nov 88 - 31 Oct 90

Principal Investigator: Prof Robert Reiss
Howard University
Washington DC 20059
(202) 636-6608

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To assess the sensitivity of composite laminates' natural (for elastic models) and complex (for viscoelastic models) frequencies to small changes in the properties of their constituents.

FLAW SENSITIVITY IN CERAMIC-MATRIX COMPOSITES
AFOSR-89-0548
1 Sep 89 - 31 Aug 92

Principal Investigator: Prof Paul Steif
Department of Mechanical Engineering
Carnegie-Mellon University
Pittsburgh, PA 15213-3890
(412) 268-3507

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: The objective of the proposed research is to develop an analytical model which will predict whether or not cracks propagating in the matrix will spare or break the fibers as they approach. The model will be developed in terms of physical parameters such as the crack geometry, the strength and moduli of fibers and matrix, and in particular, the character of the fiber-matrix interface.

A STUDY OF THE CRITICAL FACTORS CONTROLLING THE SYNTHESIS OF CERAMIC-MATRIX COMPOSITES FROM PRECERAMIC POLYMERS
F49620-91-C-0017
15 Dec 90 - 14 Dec 93

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

Program Manager: Lt Col Larry W Burggraf
AFOSR/NC
Bolling AFB DC 20332-6448
(202) 767-4960

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.

DAMAGE ACCUMULATION IN ADVANCED METAL-MATRIX COMPOSITES UNDER THERMAL CYCLING
AFOSR-89-0059
15 Oct 88 - 14 Oct 91

Principal Investigator: Prof M Taya
University of Washington
Seattle, WA 98195
(206) 545-2850

Program Manager: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To characterize the mechanisms of the damage accumulation process in metal-matrix composites subjected to creep and/or thermal cycling, including the nucleation and growth of interface damage.

ANISOTROPIC DAMAGE MECHANICS MODELLING IN METAL MATRIX COMPOSITES
AFOSR-90-0227 (URI)
1 Apr 90 - 31 Mar 93

Principal Investigator: Prof G. Z. Voyiadjis
Department of Civil Engineering
Louisiana State University
Baton Rouge, LA 70803
(504) 388-8668

Program Manger: Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To formulate a constitutive model for ductile fracture and finite strains in metal matrix composites, using the anisotropic theory of continuum damage mechanics. A damage tensor derived with respect to the unstressed damaged state will be utilized.

A COMPREHENSIVE STUDY OF MATRIX FRACTURE MECHANISMS IN FIBER-REINFORCED CERAMIC MATRIX COMPOSITES
AFOSR-90-0172 (URI)
15 Feb 90 - 14 Feb 93

Principal Investigator:

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

Program Manager:

Dr Walter F Jones
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0470

Objective: To establish both a fabrication and a material characterization capability for a class of high-temperature ceramic matrix composites as an integrated effort.

PRESSURELESS SINTERING OF CERAMIC COMPOSITES
AFOSR-90-0265 (URI)
1 Apr 90 - 31 Mar 93

Principal Investigator:

Professor Martin W Weiser
Department of Mechanical Engineering
University of New Mexico
Albuquerque NM 87131
(505) 277-2831

Program Manager:

Lt Col Larry W Burggraf
AFOSR/NC
Bolling AFB DC 20332-6448
(202) 767-4960

Objective: The objective of this research is to study and model the sintering of ceramic matrix composites. This work intends to examine the pressureless sintering and densification of two sequences of model ceramic composites in order to determine the range of suitability of each of the two current theories and to allow the formulation of a theory to describe the densification of real short fiber composites.

ARMY PROGRAM INPUT

Sixteenth Annual Mechanics of Composites Review
Dayton, Ohio
12-13 November 1991

Submitted By
Dr. Bruce P. Burns
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-IB-M
Aberdeen Proving Ground, MD 21005-5066

U.S. ARMY
ARMY RESEARCH OFFICE

CONTRACTS

TITLE: Large-Amplitude Forced Response of Dynamic Systems

RESPONSIBLE INDIVIDUAL: Dr. Anderson
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211
(919) 549-4317

PRINCIPAL INVESTIGATOR: Ali H. Nayfeh
Department of Engineering Science & Mechanics
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

OBJECTIVE: TO INVESTIGATE THE RESPONSE AND STABILITY OF NON-LINEAR DYNAMICAL SYSTEMS IN THE PRESENCE OF BOTH PARAMETRIC AND EXTERNAL EXCITATIONS. RELEVANCE: NON-LINEAR EFFECTS ARE KNOWN TO INFLUENCE HINGELESS AND BEARINGLESS ROTOR STABILITY. THE NON-LINEAR RESPONSE OF ROTORCRAFT IN FORWARD FLIGHT MAY BE OF PARTICULAR IMPORTANCE. THE PROPOSED INVESTIGATION COULD BE HIGHLY RELEVANT IN STUDYING CHANGES OF DYNAMIC RESPONSE OF COMPONENTS, SUCH AS ROTOR BLADES, WHOSE STIFFNESS AND INERTIAL PARAMETERS VARY WITH TIME AS A RESULT OF ENVIRONMENTAL AND/OR BALLISTIC EFFECTS.

TITLE: Stability of Elastically Tailored Rotor Systems

RESPONSIBLE INDIVIDUAL: Dr. Anderson
U.S. Army Research Office
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Research Triangle Park, NC 27709-2211
(919) 549-4317

PRINCIPAL INVESTIGATOR: D. H. Hodges and L.W. Rehfield
Department of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

OBJECTIVE: TO DEVELOP MATHEMATICAL MODELING AND ANALYSIS PROCEDURES TO DETERMINE THE AEROELASTIC STABILITY CHARACTERISTICS OF BEARINGLESS HELICOPTER ROTORS ON ELASTIC SUPPORTS IN AXIAL FLOW AND TILT ROTOR AIRCRAFT WITH ELASTIC WINGS IN AXIAL FLIGHT IN THE HELICOPTER MODE AND IN THE AIRPLANE MODE. RELEVANCE: THE INVESTIGATION IS A NECESSARY STEP IN THE DESIGN OF TAILORED COMPOSITE ROTORS.

TITLE: Severe Edge Effects & Simple Complimentary Interior Solutions for Anisotropic & Composite Structures

RESPONSIBLE INDIVIDUAL: Dr. Anderson
U.S. Army Research Office
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PRINCIPAL INVESTIGATOR: C. O. Horgan and J. G. Simmonds
Applied Mathematics
University of Virginia
Charlottesville, VA 22904

OBJECTIVE: TO INVESTIGATE THE DEFORMATION, STABILITY, AND VIBRATION CHARACTERISTICS OF THIN WALLED STRUCTURES, NAMELY (1) THE INTERIOR WHERE THERE ARE NO STEEP STRESS GRADIENTS AND (2) THE EDGE ZONES, WHERE STRESS GRADIENTS ARE HIGH. RELEVANCE: THIS RESEARCH OF SEVERE EDGE EFFECTS COULD BE VERY SIGNIFICANT IN STRESS BASED DESIGNS OF COMPOSITE STRUCTURES. IT IS RELEVANT TO THE MISSIONS OF SEVERAL ARMY LABORATORIES SINCE HIGH STRESS LEVELS CAN OCCUR NEAR THE EDGES OF STRUCTURES SUCH AS GUN BARRELS, ROCKET MOTOR CASINGS, HELICOPTER ROTOR BLADES, AND CONTAINMENT VESSELS WHICH MUST REMAIN ELASTIC WHEN SUBJECTED TO MECHANICAL, INERTIAL, OR THERMAL LOADS. IN PARTICULAR, END EFFECTS IN COMPOSITE STRUCTURES HAVE DIRECT BEARING ON HELICOPTER ROTOR BLADES, WITH SUCH EFFECTS BEING IMPORTANT NEAR THE ROTOR HUB.

TITLE: Smart Materials & Structures Incorporating Electro-rheological Fluids Analytical & Experimental Investigation

RESPONSIBLE INDIVIDUAL: Dr. Anderson
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211
(919) 549-4317

PRINCIPAL INVESTIGATOR: Mukesh V. Gandhi and Brian S. Thompson
Department of Mechanical Engineering
Michigan State University
East Lansing, MI 48823

OBJECTIVE: TO DEVELOP THE ABILITY TO CHANGE IN A RAPID AND SIGNIFICANT MANNER THE VIBRATIONAL CHARACTERISTICS OF STRUCTURES FABRICATED FROM ADVANCED SMART COMPOSITE MATERIALS IN WHICH ELECTRO-RHEOLOGICAL MATERIALS ARE EMBEDDED BY CHANGING IN A CONTROLLED FASHION THE ELECTRICAL FIELD IMPOSED UPON THE FLUID DOMAINS. RELEVANCE: THE GENERIC RESEARCH PROGRAM OFFERS THE POTENTIAL OF ACCELERATING THE DEVELOPMENT OF A NEW GENERATION OF ADVANCED HELICOPTER AND ROTORCRAFT SYSTEMS, BATTLE FIELD ROBOTIC AND AMMUNITION SUPPLY SYSTEMS, AND VEHICULAR SUSPENSIONS AND MATERIEL HANDLING SYSTEMS.

TITLE: Damage-Survivable & Damage-Tolerant Laminated Composite with Optimally Placed Piezoelectric Layers

RESPONSIBLE INDIVIDUAL: Dr. Anderson
U.S. Army Research Office
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PRINCIPAL INVESTIGATOR: Shiv P. Joshi
Department of Aerospace Engineering
University of Texas at Arlington
Arlington, TX 76010

OBJECTIVE: TO PRODUCE A SMART LAMINATED COMPOSITE STRUCTURE BY EMBEDDING PIEZOELECTRIC SENSORS AND ACTUATORS IN IT, DETERMINING THE OPTIMAL PLACEMENT OF PIEZOELECTRIC LAYERS IN A LAMINATED COMPOSITE AND THE DURABILITY (FATIGUE LOADING) AND SURVIVABILITY (IMPACT LOADING) OF EMBEDDED SENSORS AND ACTUATORS. DEVISE MEANS OF ESTIMATING THE EXTENT OF DAMAGE, LOCATING IMPACT DAMAGE, ACTIVELY SUPPRESSING DAMAGE, AND CONTROLLING STRUCTURAL DYNAMICS. RELEVANCE: THE DEVELOPMENT OF THE ABILITY TO ENHANCE THE DURABILITY AND THE DAMAGE SURVIVABILITY OF COMPOSITE STRUCTURES AND TO SUPPRESS STRUCTURAL DAMAGE IN AN ACTIVE MANNER HAS CONSIDERABLE POTENTIAL APPLICATION TO THE DESIGN OF VARIOUS HELICOPTER COMPONENTS.

TITLE: Active Control of NITINOL-reinforced Smart Structural Composites

RESPONSIBLE INDIVIDUAL: Dr. Anderson
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(919) 549-4317

PRINCIPAL INVESTIGATOR: Amr M. Baz
Department of Mechanical Engineering
Catholic University of America
Washington, DC 20017-1575

OBJECTIVE: TO DEVELOP THE ABILITY TO CHANGE THE VIBRATIONAL CHARACTERISTICS OF STRUCTURES FABRICATED FROM ADVANCED COMPOSITE MATERIALS IN WHICH SHAPE MEMORY NICKEL-TITANIUM ALLOY (NITINOL) WIRES ARE EMBEDDED TO SENSE AND CONTROL THE STATIC AND DYNAMIC CHARACTERISTICS OF THE COMPOSITE STRUCTURE. RELEVANCE: THE GENERIC RESEARCH PROGRAM OFFERS THE POTENTIAL OF ACCELERATING THE DEVELOPMENT OF A NEW GENERATION OF ADVANCED HELICOPTER AND ROTORCRAFT SYSTEMS, BATTLE FIELD ROBOTIC AND AMMUNITION SUPPLY SYSTEMS, AND VEHICULAR SUSPENSIONS AND MATERIEL HANDLING SYSTEMS.

TITLE: Damage Evaluation of Structures from Changes of Complex Eigenvalues & Mode Shapes Using Interferometer Data

RESPONSIBLE INDIVIDUAL: Dr. Anderson
U.S. Army Research Office
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Research Triangle Park, NC 27709-2211
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PRINCIPAL INVESTIGATOR: Roberto A. Osegueda
Department of Civil Engineering
University of Texas at El Paso
El Paso, TX 79902-3333

OBJECTIVE: TO UTILIZE OPTICAL INTERFEROMETRIC MEASUREMENTS OF COMPLEX EIGENVALUES AND MODE SHAPES OF VIBRATIONALLY EXCITED STRUCTURES TO RELATE CHANGES OF COMPLEX EIGENVALUES AND COMPLEX MODE SHAPES TO CHANGES IN STRUCTURAL PARAMETERS DENOTING DAMAGE IN VISCOUSLY DAMPED STRUCTURES. RELEVANCE: THE RESEARCH IS DIRECTLY RELEVANT TO STRUCTURAL INTEGRITY, EXTENDED LIFETIME, REDUCED MAINTENANCE AND LOGISTICS MANAGEMENT FOR ALL ARMY MOBILITY SYSTEMS SUCH AS HELICOPTERS, TANKS, APC'S, ETC.

TITLE: Use of Shape Memory Alloys in the Robust Control of Smart Structures

RESPONSIBLE INDIVIDUAL: Dr. Anderson
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PRINCIPAL INVESTIGATOR: Vittal S. Rao and Thomas J. O'Keefe
Electrical Engineering
University of Missouri at Rolla
Rolla, MO 65401

OBJECTIVE: TO DEVELOP APPROPRIATE ELECTRODEPOSITION TECHNIQUES FOR THE PROCESSING OF SHAPE MEMORY ALLOYS CHARACTERIZED BY ULTRA-FINE SIZES THAT ARE AMENABLE TO MANUFACTURING PROCESSES (THE PREPARATION OF LAYERED SMART STRUCTURES IS FORESEEN). IDENTIFY OPTIMUM DEPOSITION PARAMETERS FOR THE BEST PROPERTIES OF THE ELECTRODEPOSITED FILM. ESTABLISH MATHEMATICAL MODELS FOR PHASE TRANSITIONS (CONSTITUTIVE RELATIONS). DEVELOP ROBUST CONTROLLER DESIGN METHODOLOGY FOR SMART STRUCTURES WITH RIGID AND FLEXIBLE MODELS THROUGH THE USE OF REDUCED ORDER MODELS. RELEVANCE: THE RESEARCH PROGRAM OFFERS THE POTENTIAL OF ACCELERATING THE DEVELOPMENT OF A NEW GENERATION OF ADVANCED ROTORCRAFT SYSTEMS, BATTLE FIELD ROBOTIC AND AMMUNITION SUPPLY SYSTEMS, AND VEHICULAR SUSPENSION AND MATERIEL HANDLING SYSTEMS. THE SHAPE MEMORY ALLOYS BASED SMART STRUCTURES WITH ROBUST CONTROL SYSTEMS FROM THE BASIS OF EFFECTIVE VIBRATION SUPPRESSION SYSTEMS.

TITLE: Smart Composite Structures Featuring Embedded Hybrid Actuation and Sensing Capabilities

RESPONSIBLE INDIVIDUAL: Dr. Anderson
U.S. Army Research Office
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PRINCIPAL INVESTIGATOR: Mukesh V. Gandhi and Brian S. Thompson
Department of Mechanical Engineering
Michigan State University
East Lansing, MI 48823

OBJECTIVE: TO INVESTIGATE THE POSSIBILITY OF APPLYING A HYBRIDIZATION OF ELECTRORHEOLOGICAL FLUID AND PIEZOELECTRIC ACTUATOR SYSTEMS TO ACCOMPLISH IN REAL TIME WITH MINIMAL ENERGY CONSUMPTION THE VIBRATION TAILORING AND CONTROL OF BEAM AND PLATE STRUCTURES FABRICATED FROM COMPOSITE MATERIALS. RELEVANCE: THE GENERIC RESEARCH PROGRAM OFFERS THE POTENTIAL OF ACCELERATING THE DEVELOPMENT OF A NEW GENERATION OF ADVANCED ROTORCRAFT SYSTEMS, BATTLE FIELD ROBOTIC AND AMMUNITION SUPPLY SYSTEMS, AND VEHICULAR SUSPENSION AND MATERIEL HANDLING SYSTEMS. SOME NATIONAL DEFENSE PROGRAMS THAT MAY ALSO BENEFIT FROM THE PROPOSED RESEARCH INCLUDE THE STRATEGIC DEFENSE INITIATIVE, THE NATIONAL AEROSPACE PLANE, NASA SPACE STATIONS, THE B-2 BOMBER, AND VARIOUS WEAPONS SYSTEMS.

TITLE: Development of "Smart" Piezothermo-Elastic Laminae: Theory and Applications

RESPONSIBLE INDIVIDUAL: Dr. Anderson
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PRINCIPAL INVESTIGATOR: Horn S. Tzou
Department of Mechanical Engineering
University of Kentucky
Lexington, KY 40506-0999

OBJECTIVE: (1) DEVELOP A PIEZOTHERMOELASTIC LAMINATION THEORY FOR MULTILAYERED COMPOSITE SHELLS (EACH LAYER OF WHICH CAN BE EITHER ELASTIC, PIEZOELECTRIC, THERMOELASTIC, OR PIEZOTHERMOELASTIC); (2) DEVISE A NEW FINITE ELEMENT TO ANALYZE A DISTRIBUTED MODAL SENSOR ACTUATOR THEORY; AND (3) CONDUCT A THEORETICAL AND EXPERIMENTAL VALIDATION OF PROTOTYPE STRUCTURES, WITH ONE OR MORE PIEZOELECTRIC LAYERS SERVING AS A DISTRIBUTED SENSOR AND ANOTHER LAYER SERVING AS A DISTRIBUTED ACTUATOR. RELEVANCE: THE DEVELOPMENT OF SMART STRUCTURES THAT CONSIST OF MULTILAYERED COMPOSITE SHELLS WITH EMBEDDED PIEZOELECTRIC SENSORS AND ACTUATORS OFFERS THE POTENTIAL OF SUPPRESSING STRUCTURAL VIBRATIONS AND REDUCING THE NOISE OCCURRING INSIDE ROTORCRAFT CONSTRUCTED WITH THESE MATERIALS. THE RESULTS OF THIS RESEARCH ARE RELEVANT TO THE MISSION OF THE AEROSTRUCTURES DIRECTORATE.

TITLE: Two-Dimensional Modeling of Composite Links in High-Speed Machinery

RESPONSIBLE INDIVIDUAL: Dr. Anderson
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PRINCIPAL INVESTIGATOR: Behrooz Fallahi
Department of Mechanical Engineering
North Carolina Agricultural and
Technical State University
Greensboro, NC 27401-3209

OBJECTIVE: TO DEVELOP AND VALIDATE A TWO-DIMENSIONAL MODEL TO PREDICT THE STRESS DISTRIBUTION IN FLEXIBLE COMPOSITE LINKS OF HIGH-SPEED MACHINERY. RELEVANCE: THE RESEARCH ADDRESSES THE IMPORTANT PROBLEM OF APPLICATION OF COMPOSITE MATERIALS IN ROBOTIC MECHANISMS WHICH IS VERY RELEVANT TO ARMY VEHICULAR KSYSTEMS SUCH AS AUTOMATED LOADERS, FIELD MATERIAL HANDLERS AND MANIPULATORS.

TITLE: Programmable Materials and Structures

RESPONSIBLE INDIVIDUAL: Dr. Anderson
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PRINCIPAL INVESTIGATOR: Daniel J. Inman
Department of Mechanical & Aerospace Engineering
State University of New York at Buffalo
Buffalo, NY 14260

OBJECTIVE: TO EXAMINE THE POSSIBILITY OF USING MICROPROCESSORS EMBEDDED IN COMPOSITE BEAM AND PLATE STRUCTURES COMBINED WITH EMBEDDED SENSORS AND ACTUATORS FOR BOTH VIBRATION SUPPRESSION AND DAMAGE DETECTION, ADDRESSING ISSUES OF MODELLING, EXPERIMENTAL VERIFICATION, OPTIMAL DESIGN OF VARIOUS LAYERS, MATHEMATICAL MODELING, AND CONTROL. RELEVANCE: THE DEVELOPMENT OF SMART STRUCTURES THAT CONTAIN EMBEDDED SENSORS, ACTUATORS, AND MICROPROCESSORS WILL LEAD TO THE ABILITY TO REALIZE (1) VIBRATION SUPPRESSION, (2) GEOMETRIC SHAPE CHANGE, AND (3) DAMAGE CONTAINMENT IN COMPOSITE STRUCTURES THAT COULD SERVE AS COMPONENTS IN ROTORCRAFT AND LAND BASED VEHICLES. THE RESULTS OF THIS RESEARCH ARE OF POTENTIAL VALUE AT THE AFDD, WHERE THERE IS AN INTEREST IN CONTROLLING AT WILL THE CAMBER AND/OR TRAILING EDGE OF A HELICOPTER ROTOR BLADE FOR PURPOSES OF INCREASING LIFT.

TITLE: Inelastic Deformation & Failure Analysis of Filament-Wound Composite Structures

RESPONSIBLE INDIVIDUAL: Dr. Iyer
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211
(919) 549-4258

PRINCIPAL INVESTIGATOR: Gerald A. Wempner and Wan-Lee Yin
Department of Civil Engineering
Georgia Institute of Technology
Atlanta, GA 30332

OBJECTIVE: TO DEVELOP ANALYTICAL MODELS FOR DESCRIBING INELASTIC DEFORMATIONS AND FAILURE BEHAVIOR OF FILAMENT-WOUND COMPOSITE STRUCTURES. RELEVANCE: THERE ARE SEVERAL CRITICAL APPLICATIONS OF THIS TECHNOLOGY NEEDED TODAY IN, E.G., THE ANALYSIS AND EVALUATION OF ROCKET MOTOR CASINGS AND LAUNCH TUBES.

TITLE: Wave Propagation & Dynamic Response of Laminated Structures

RESPONSIBLE INDIVIDUAL: Dr. Iyer
U.S. Army Research Office
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PRINCIPAL INVESTIGATOR: R. K. Kapania and J. N. Reddy
Department of Aerospace & Ocean Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

OBJECTIVE: TO INVESTIGATE WAVE PROPAGATION AND NONLINEAR DYNAMIC RESPONSE OF LAMINATED STRUCTURES UNDER IMPACT AND OTHER SHORT DURATION (TRANSIENT) LOADS, PLACING SPECIAL EMPHASIS ON TRANSIENT WAVE PROPAGATION IN THE PRESENCE OF RESIDUAL STRESSES.
RELEVANCE: THIS RESEARCH HAS BEEN IDENTIFIED AS BEING QUITE RELEVANT TO WORK CONDUCTED BY THE APPLIED TECHNOLOGY DIRECTOR IN THE AREA OF COMPOSITE STRUCTURES AND WEAPONS INTERFACING. THE DEVELOPMENT OF A SPACE-TIME FINITE ELEMENT WHICH WOULD ACCOUNT FOR UNSYMMETRIC LAMINATES AND NONLINEAR RESPONSE IS PARTICULARLY RELEVANT TO THE NOISE TRANSMISSION, STRESS ANALYSIS, FATIGUE, AND DYNAMIC RESPONSE ACTIVITIES OF THE AEROSTRUCTURES DIRECTORATE.

TITLE: Effect of Nose Shape & Mass of the Impactor on Impact Damage of Laminated Composite Shells

RESPONSIBLE INDIVIDUAL: Dr. Iyer
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PRINCIPAL INVESTIGATOR: Fu-Kuo Chang
Department of Aeronautics & Astronautics Engineering
Stanford University
Stanford, CA 94305

OBJECTIVE: TO INVESTIGATE IMPACT DAMAGE IN THIN TO THICK SHELLS FABRICATED FROM FIBER REINFORCED POLYMER BASED MATRIX COMPOSITES SUBJECTED TO LOW VELOCITY IMPACT UNDER DIFFERENT TYPES OF IMPACTORS. DETERMINE THE EFFECT OF THE IMPACTOR'S MASS AND NOSE SHAPE ON IMPACT DAMAGE IN LAMINATED COMPOSITES AS A FUNCTION OF PLY ORIENTATION, THICKNESS, AND LAMINATE CURVATURE. RELEVANCE: STRENGTH DEGRADATION OF CARBON REINFORCED COMPOSITES DUE TO LOW SPEED IMPACT CONTINUES TO BE A PROBLEM AREA. THIS RESEARCH ADDRESSES PARTICULAR ASPECTS OF THE PROBLEM THAT ARE IMPORTANT BUT THAT HAVE NOT BEEN ADDRESSED ELSEWHERE.

TITLE: High Velocity Impact of Composite Laminates

RESPONSIBLE INDIVIDUAL: Dr. Iyer
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PRINCIPAL INVESTIGATOR: C.T. Sun
Department of Aerospace &
Astronautical Engineering
Purdue University
Lafayette, IN 47907

OBJECTIVE: TO CONDUCT THEORETICAL AND EXPERIMENTAL STUDIES TO CONTRIBUTE TO THE UNDERSTANDING OF THE KEY ELEMENTS IN HIGH VELOCITY IMPACT OF COMPOSITE LAMINATES AND TO MODEL THE PENETRATION, PERFORATION, AND DELAMINATION PROCESSES DURING IMPACT. RELEVANCE: THIS RESEARCH HAS DIRECT IMPLICATIONS ON MISSION OBJECTIVES IN THE TERMINAL BALLISTIC DIVISION AT BRL. TECHNOLOGICAL DEVELOPMENT IN HIGH VELOCITY IMPACT OF COMPOSITES IS NEEDED AND WOULD REPRESENT A SIGNIFICANT CONTRIBUTION TO MANY BALLISTIC ARMOR PROGRAMS. SOME OF THE BASIC ISSUES ADDRESSED IN THE PROPOSED PROJECT ARE IMPORTANT TO PROGRAMS AT THE ASTD, PARTICULARLY THE MODELING OF THE CONTACT-PENETRATION PROBLEM AND ANALYSIS OF THE PROGRESSIVE FAILURE THROUGH THE THICKNESS OF COMPOSITE LAMINATES.

TITLE: Assessment of Damage in Composite Materials by a Real-time Nondestructive Laser Technique

RESPONSIBLE INDIVIDUAL: Dr. Iyer
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PRINCIPAL INVESTIGATOR: M. A. Seif
Department of Mechanical Engineering
Tuskegee University
Tuskegee, AL 36083

OBJECTIVE: TO DEVELOP A LASER SPECKLE SHEARING INTERFEROMETRY TECHNIQUE FOR THE CHARACTERIZATION OF NUCLEATION AND PROPAGATION OF MICROCRACKS IN COMPOSITES. RELEVANCE: LASER SPECKLE SHEARING INTERFEROMETRY OFFERS THE POTENTIAL FOR DYNAMICALLY CHARACTERIZING THE FORMATION AND SUBSEQUENT PROPAGATION OF MICROCRACKS UNDER SPECIFIC LOAD ENVIRONMENTS. WHEN CORRELATION WITH DEFECT CHARACTERISTICS ARE ESTABLISHED, LOAD CARRYING CAPACITY AND REMAINING SERVICE LIFE OF COMPONENTS COULD BE ASSESSED NONDESTRUCTIVELY. THE TECHNIQUE COULD ALSO BE A POWERFUL TOOL IN THE DEVELOPMENT OF COMPOSITES FOR SPECIFIC APPLICATIONS.

TITLE: Penetration Mechanics of Fiber Laminate Composites

RESPONSIBLE INDIVIDUAL: Dr. Iyer
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PRINCIPAL INVESTIGATOR: Stephan Bless
Department of Impact Physics
University of Dayton
Dayton, OH 45407-3002

OBJECTIVE: TO INVESTIGATE THE MECHANICS OF PROJECTILE PENETRATION OF FIBER-REINFORCED COMPOSITES. RELEVANCE: FIBER-REINFORCED PLASTICS ARE OF GREAT RELEVANCE TO THE ARMY SCIENCE. THEY ARE BEING IMPLEMENTED IN AN INCREASING NUMBER OF WEAPONS AND SYSTEMS. DATA DEVELOPED AND MODELS PRODUCED WILL BE HELPFUL IN MATERIAL SELECTION AND APPLICATION TO COMBAT VEHICLES. EVALUATIONS OF PENETRATION MECHANISMS OF FRP ARE BEING CARRIED OUT AT BRL, AND MTL IS DEVELOPING FRP BODY FOR A FIGHTING VEHICLE.

TITLE: Micromechanisms of Deformation & Fracture in Aluminum Based MMC'S -Interface Effects

RESPONSIBLE INDIVIDUAL: Dr. Simmons
U.S. Army Research Office
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Research Triangle Park, NC 27709-2211
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PRINCIPAL INVESTIGATOR: John J. Lewandowski
Department of Metallurgy & Materials Science
Case-Western Reserve University
Cleveland, OH 44106-4931

OBJECTIVE: THE ROLE OF REINFORCEMENT CLUSTERING, THE INTERFACE AND THE MICROSTRUCTURE OF THE MATRIX IN THE SILICON CARBIDE WHISKER AND PARTICLE REINFORCED ALUMINUM ALLOY COMPOSITES WILL BE INVESTIGATED. RELEVANCE: THIS RESEARCH IS VERY IMPORTANT FOR DEVELOPING LIGHT WEIGHT METAL MATRIX COMPOSITES, NEEDED FOR APPLICATION IN A VARIETY OF WEAPON COMPONENTS, INCLUDING ADVANCED GUN BARRELS, ENGINE HOUSING OF ARMY HELICOPTERS, AND ARMOR/ANTI-ARMOR SYSTEMS.

TITLE: Enhanced Computational/Modeling Capabilities for Dynamic Material Behavior

RESPONSIBLE INDIVIDUAL: Dr. Simmons
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PRINCIPAL INVESTIGATOR: James Lankford, Jr. and Charles E. Anderson
Southwest Research Institute
San Antonio, TX 78228-0510

OBJECTIVE: DEVELOP AN IMPLEMENT INTO A HYDROCODE A CONSTITUTIVE MODEL WHICH INCLUDES DAMAGE FOR THE CLASS OF METAL MATRIX COMPOSITES REPRESENTED BY LIQUID PHASE SINTERED TUNGSTEN ALLOYS, WHEN MODIFIED TO VERY HIGH STRAIN RATES. RELEVANCE: THE RESEARCH IS EXTREMELY IMPORTANT FOR THE DEVELOPMENT OF ANTIARMOR MATERIALS AND DESIGN OF HYPERVELOCITY PROJECTILES FOR THE DEFEAT OF ADVANCED THREATS IN THE ARMY 21 SCENARIO.

TITLE: Measurement of Interface Strength, Intrinsic Toughness & Their Dependence on Interfacial Segregants

RESPONSIBLE INDIVIDUAL: Dr. Simmons
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211
(919) 549-4329

PRINCIPAL INVESTIGATOR: Vijay Gupta
Thayer School of Engineering
Dartmouth College
Hanover, NH 03755

OBJECTIVE: TO DEVELOP AND IMPLEMENT A LASER SPALLATION TECHNIQUE TO INVESTIGATE THE MECHANICAL PROPERTIES OF SELECTED INTERFACE SYSTEMS. RELEVANCE: THE DETERMINATION AND CONTROL OF INTERFACIAL STRENGTH IS OF GREAT IMPORTANCE TO THE DEVELOPMENT OF COATINGS AND COMPOSITES NEEDED IN THE DESIGN AND PROTECTION OF ARMY WEAPONS AND VEHICLES.

TITLE: Effect of Processing Parameters on the High Temperature Creep of SiC Whisker- Reinforced Alumina

RESPONSIBLE INDIVIDUAL: Dr. Simmons
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211
(919) 549-4329

PRINCIPAL INVESTIGATOR: Terence G. Langdon
Department of Materials Science
University of Southern California
Los Angeles, CA 90089-1452

OBJECTIVE: TO DETERMINE THE INFLUENCE OF PROCESSING PARAMETERS ON THE HIGH TEMPERATURE CREEP BEHAVIOR OF SILICON CARBIDE WHISKER-REINFORCED ALUMINA COMPOSITES. RELEVANCE: THE RESEARCH WILL CONTRIBUTE TO THE UNDERSTANDING OF HIGH TEMPERATURE CREEP IN CERAMIC AND CERAMIC COMPOSITES AND PROVIDE GUIDELINES FOR PROCESS CONTROL FOR OPTIMUM PROPERTIES. ADVANCED CERAMIC COMPOSITES ARE NEEDED IN HIGH TEMPERATURE APPLICATIONS SUCH AS THERMAL BARRIERS FOR PISTONS IN ADIABATIC ENGINES, TURBINE BLADES, AND MISSILE PARTS.

TITLE: Manufacturing Science, Reliability and Maintainability Technology

RESPONSIBLE INDIVIDUAL: A. Crowson
Army Research Office
P.O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641

PRINCIPAL INVESTIGATORS: T.W. Chou and R.L. McCullough
Center For Composite Materials
University of Delaware
Newark, DE 19716

OBJECTIVE: This University Research Initiative Program consists of the following elements: cure characterization and monitoring, on-line intelligent non destructive evaluation for in-process control of manufacturing, process simulation, computer aided manufacturing by filament winding, structural property relationships, mechanics of thick section composite laminates, structure performance and durability and integrated engineering for durable structures.

U.S. ARMY LABORATORY COMMAND
MATERIALS TECHNOLOGY LABORATORY

TITLE: Demonstration Composite Hull Program

PROJECT MANAGER: Wm. E. Haskell III
U.S. Army Materials Technology Laboratory
Attn: SLCMT-MEC
Watertown, MA 02172-0001
DSN 955-5172 COMM: 617-923-5172

MTL CONTRACT DAAL04-86-C-0079
PROJECT MANAGER: Dr. Farro Kaveh
FMC Corporation
Ground Systems Division
Santa Clara, CA 95108

OBJECTIVE: Develop and demonstrate the benefits of the replacement of metallic hull structures with composite materials. Primary payoffs are weight reduction, survivability enhancement, corrosion resistance, signature reduction and reduced manufacturing and life-cycle costs. Significant achievements have been made in materials and process procedures of thick composite structural armor systems. This 6.3 program involves a 60 month, three phase contract with FMC Corporation.

PROGRESS: Phase I and II have been completed and successfully demonstrate the application of composites for light and medium weight armored vehicles. An operational Composite Infantry Fighting Vehicle (CIFV) was designed, fabricated and completed a 6000 mile field durability test. A 25% weight reduction in hull and armor weight was achieved compared to a similar aluminum hulled vehicle. This program gave the Army confidence to begin the new TACOM Composite Armored Vehicle (CAV) effort.

The on-going Phase III effort is developing and demonstrating composite hull technology for 55 ton and heavier armored vehicles. A full scale composite hull concept has been designed to resist heavy armor inertial loads, blast loads and gun firing loads. This composite hull will be subjected to static and dynamic testing to verify the design.

TITLE: ANALYTIC METHODOLOGY FOR ADHESIVE JOINTS AND THICK COMPOSITES

RESPONSIBLE INDIVIDUAL: S.C. Chou
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5427

PRINCIPLE INVESTIGATOR: E. Saether
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001

OBJECTIVE: The program objective is to develop improved analytical and numerical methods for analyzing adhesively bonded joints and thick composites.

Research of bonded joints focus on the development of special finite element formulations to accurately and efficiently model bonded joints of arbitrary 3-D geometry. Efforts in this area include: (1) The investigation of novel displacement-based and hybrid stress-based finite element formulations to best simulate adhesive layer stresses; (2) research of appropriate material models to represent nonlinear adhesive response.

Efforts directed towards developing analytical methodology for thick composites include: (1) Development of higher-order plate and shell theories for static and dynamic analysis of thick composite laminates; (2) formulation of finite plate and shell elements based on developed higher-order theories.

U. S. ARMY MISSILE COMMAND

TITLE: Determination of Mechanical Material Properties for Filament Wound Structures
RESPONSIBLE INDIVIDUAL: Dr. Larry C. Mixon
Army Missile Command
PRINCIPAL INVESTIGATOR: Terry L. Vandiver
Army Missile Command
(205) 876-1015

OBJECTIVE: The objective of this task is to develop test standards for the determination of mechanical material properties for filament wound composite structures. The initial task is to develop uniaxial material properties. Future plans include biaxial and triaxial material property determination. This effort is being performed by the Joint-Army-Navy-NASA-Air Force (JANNAF) Composite Motor Case Subcommittee through a round robin test effort. This task is coordinated with MIL-HDBK-17, ASTM, National Bureau of Standards, and DoD CMPS Composites Technology Program.

TITLE: Composite Materials Evaluation for Filament Winding
RESPONSIBLE INDIVIDUAL: Lawrence W. Howard
Army Missile Command
PRINCIPAL INVESTIGATOR: Terry L. Vandiver
Army Missile Command
(205) 876-1015

OBJECTIVE: The object of this task is to evaluate new fibers for filament winding. Delivered strengths are determined via strand tests and 3-inch diameter filament wound pressure vessels with different stress ratios. The experimental data is used in the design of composite rocket motor cases, launchers, pressure vessels and other filament wound structures.

TITLE: Composite Wing Design and Fabrication
RESPONSIBLE INDIVIDUAL: Lawrence W. Howard
Army Missile Command
PRINCIPAL INVESTIGATORS: J. Frank Wlodarski
Terry L. Vandiver
Army Missile Command
(205) 876-0398

OBJECTIVE: The objective of this task is to design and fabricate an all composite wing with an elliptical planform. The materials used are s-glass cloth and uni-directional tape. These materials were selected because of their strength, stiffness and low radar cross-section. The method of fabrication is hand layup in a clamshell mold made of composite tooling. The wings are tested to determine what structural properties are achieved with this method of manufacture and if they are accurately predicted in the design.

U.S. ARMY LABORATORY COMMAND
BALLISTIC RESEARCH LABORATORY

TITLE: Lightweight Structures for Interior Ballistics

PRINCIPAL INVESTIGATOR: W.H. Drysdale
AMC LABCOM
Ballistic Research Laboratory
Aberdeen Proving Ground
MD 21005-5066
(301) 278-6123

OBJECTIVE: Composite materials represent a portion of this effort. The objective of this project is to develop failure criteria, architecture transition technology, and optimum design technology for thick ballistic structures. Rate of loading and layup transition studies are being addressed at 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 Lawrence Livermore National Lab (LLNL). They are also sponsoring studies at the University of Utah and 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.

U.S. ARMY AVIATIONS SYSTEMS COMMAND
FT. EUSTIS

TITLE: Damage Tolerance Testing of the ACAP Roof
RESPONSIBLE INDIVIDUAL: Dan Good
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TV-ATS
Ft. Eustis, VA 23604-5577
(804) 878-5921
PRINCIPAL INVESTIGATOR: B. Spigel

OBJECTIVE: A forward roof subcomponent from the Bell Advanced Composite Airframe Program (ACAP) helicopter will be tested to verify the damage tolerance design criteria developed under contract by Bell Helicopter Textron, Inc. (Final Report: USAAVSCOM TR-87-D-3A, B, C). The roof will be subjected to an anticipated ACAP load spectrum, and manufacturing defects and in-service damage will be monitored by both laboratory and field nondestructive evaluation methods to determine the extent of damage growth.

TITLE: Ballistic Survivability of Generic Composite Main Rotor Hub Flexbeams
RESPONSIBLE INDIVIDUAL: Dan Good
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TV-ATS
Ft. Eustis, VA 23604-5577
(804) 878-5921
PRINCIPAL INVESTIGATOR: E. Robeson and K. Sisitka

OBJECTIVE: The goal of this effort is to quantify the ballistic survivability of typical composite main rotor hub flexbeams. Two different flexbeam designs will be impacted with various ballistic threats. One design will be tested under simulated centrifugal load while the other will be fatigue tested following ballistic impact in a no load condition. Fatigue testing of the first design will be considered after a damage assessment is made.
RESPONSIBLE INDIVIDUAL: Dan Good
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TV-ATS
Ft. Eustis, VA 23604-5577
(804) 878-5921
PRINCIPAL INVESTIGATOR: N. Calapodas and D. Kinney
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TV-ATS
Ft. Eustis, VA 23604-5577
(804) 878-3303

OBJECTIVE: A joint program among Army/NASA/Contractor is planned to conduct detail correlation of the Finite Element (FE) dynamic models of both ACAP airframes. AATD will perform all shake testing and the contractors will be responsible for analytical changes to the FE models. The FE dynamic models, generated under Army funding during the developmental phases of the ACAP program, were further improved under funding of the NASA DAMVIBS program. However, the thrust of shake testing performed during the developmental phase was oriented towards the usefulness of the models to 15 Hz and below. In the correlation to be performed., the test vehicles will be stripped down to the basic structure. The inertia of the components removed will be substituted with concentrated masses. Upon successful correlation of the basic configuration, components will be installed and correlation efforts repeated. The goal is to achieve satisfactory correlation at modal and force response frequencies up to 40 Hz.

TITLE: Composite Airframe Design for Weapons Interface
RESPONSIBLE INDIVIDUAL: Dan Good
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TV-ATS
Ft. Eustis, VA 23604-5577
(804) 878-5921
PRINCIPAL INVESTIGATOR: J. Moffatt
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TV-ATS
Ft. Eustis, VA 23604-5577
(804) 878-2377
OBJECTIVE: The effect of 20-30mm weapon firing in close proximity to composite airframe is investigated. Effects of weapon-induced pressure and thermal environments on weight tradeoffs for structural design are investigated.

AEROSTRUCTURES DIRECTORATE
U.S. ARMY AVIATION SYSTEMS COMMAND
NASA LANGLEY RESEARCH CENTER

TITLE: Basic research in Structures

RESPONSIBLE INDIVIDUAL: Dr. F. D. Bartlett, Jr.
U.S. Army Aerostructures Directorate
NASA Langley Research Center (MS 266)
Hampton, Virginia 23665-5225
(804) 864-3960

PRINCIPAL INVESTIGATORS: Dr. T. K. O'Brien, G. B. Murri,
Dr. R. L. Boitnott, Dr. K. E. Jackson,
Dr. G. L. Farley, V. L. Metcalf, M. Nixon

OBJECTIVE: The focus of the Army basic research in composites is to investigate and explore structures technologies which improve structural integrity of rotorcraft composite structures, develop superior analyses for composites design, exploit structural tailoring and smart structures potential to improve structural performance, and develop more effective nondestructive evaluation sciences for inspecting composite structures. The Army basic research is conducted jointly with NASA to provide the fundamental mechanics of composites knowledge needed to transition these technology developments to military and civil advanced rotorcraft applications.

TITLE: Structures Technology Applications

RESPONSIBLE INDIVIDUAL: Dr. F. D. Bartlett, Jr.
U.S. Army Aerostructures Directorate
NASA Langley Research Center (MS 266)
Hampton, Virginia 23665-5225
(804) 864-3960

PRINCIPAL INVESTIGATORS: Dr. R. L. Boitnott, Dr. K. E. Jackson,
Dr. G. L. Farley, V. L. Metcalf,
M. W. Nixon, D. J. Baker, J. N. Zalameda

OBJECTIVE: The goals of this applied research are to explore and demonstrate innovative structural concepts and design methodologies for composite structures so that the U. S. industries can build safe, durable, and affordable rotorcraft structures. The ultimate goal is to develop mature composites technology that can compete with metals in providing more durable structures at a lower cost and save weight. This research is conducted through jointly-sponsored Army/NASA investigations which establish reliable composite structures, validate new and improved analytical capabilities, and demonstrate faster and more effective field and manufacturing inspection methods for complex composite structures. The benefits of this research will provide proven technology to the rotorcraft industry and the U. S. Army for applications to future air vehicle systems.

OFFICE OF NAVAL RESEARCH
MECHANICS DIVISION
ARLINGTON VA 22217-5000

GRANTS AND CONTRACTS

FAILURE OF THICK COMPOSITE LAMINATES
N00014-90-F-0060
February 88 - January 93

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Dr. R. M. Christensen
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550
(415) 422-7236

Objective: Research will be conducted into the mechanics of failure of composite materials, with emphasis on physically-based failure criteria for thick composites laminates.

NONDESTRUCTIVE EVALUATION AND DAMAGE ACCUMULATION OF COMPOSITES
N00014-90-J-1724
April 87 - September 92

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 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 thick composite laminates subjected to complex loading states and fatigue. Nondestructive evaluation methods for damage characterization will be developed.

ENVIRONMENTAL EFFECTS AND ENVIRONMENTAL DAMAGE IN THERMOPLASTIC COMPOSITES
N00014-90-J-1556
January 90 - December 92

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. Y. Weitsman
University of Tennessee
Dept. of Engineering Science & Mechanics
Knoxville, TN 37996-2030
(615) 974-5460

Objective: Research will be conducted into the effects of constant and cyclic pressure on moisture absorption and moisture-induced damage in thermoplastic composites. The development of residual stresses during processing will be investigated.

DYNAMIC MATRIX CRACKING AND DELAMINATION IN COMPOSITE LAMINATES SUBJECTED TO IMPACT LOADING
N00014-90-J-1666
July 90 - November 92

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 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, including the use of soft adhesive strips. Compression failure of thick composites will be investigated.

THERMOMECHANICAL BEHAVIOR OF HIGH TEMPERATURE COMPOSITES
N00014-89-J-3107
March 85 - November 91

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. G. J. Dvorak
Rensselaer Polytechnic Institute
Department of Civil Engineering
Troy, NY 12181
(518) 276-6943

Objective: Investigations of the thermomechanical response, damage growth and fracture in metal matrix composites and intermetallic matrix composites will be conducted using analytical and experimental techniques. Local stress states caused during fabrication and by thermal changes in service, inelastic time-dependent behavior, and static and fatigue damage will be explored.

QUANTITATIVE ULTRASONICS MEASUREMENTS IN COMPOSITES
N00014-90-J-1273
July 85 - September 92

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405

Principal Investigator: Prof. W. Sachse
Cornell University
Dept. of Theoretical and Applied Mechanics
Ithaca, NY 14853
(609) 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 composite materials.

DYNAMIC BEHAVIOR OF FIBER AND PARTICLE REINFORCED COMPOSITES
N00014-91-J-1297
October 90 - December 91

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 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, accounting for interfacial effects.

IMPACT RESPONSE AND QNDE OF COMPOSITE LAMINATES
N00014-90-J-1857
April 87 - April 92

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. A. K. Mal
University of California, Los Angeles
Dept. of Mechanical, Aerospace & Nuclear Engineering
Los Angeles, CA 90024
(213) 825-5481

Objective: Research will be conducted into wave propagation in composite laminates. The Leaky Lamb Wave technique will be utilized for the characterization of elastic properties and defects in composites. The use of ultrasonic techniques for interfaces and interfacial regions will be explored.

MICROMECHANICS OF COMPOSITES
N00014-90-J-1377
October 90 - August 92

Scientific Officer: Dr. Yapa D.S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. B. Budiansky
Harvard University
Division of Applied Science
Cambridge, MA 02138
(617) 495-2849

Objective: Research will be conducted into the enhancement of the fracture toughness of ceramics and intermetallics by the incorporation of toughening agents such as fibers, whiskers, ductile particles and phase-transforming particles. Models will be established for the compression failure of polymer matrix composites. Microbuckling and kink band models will be established.

MECHANICS OF INTERFACE CRACKS AND COMPOSITES
N00014-90-J-1380
November 87 - November 91

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. C. F. Shih
Brown University
Division of Engineering
Providence, RI 02912
(401) 863-2868

Objective: Research will be conducted to provide a fundamental understanding of the behavior of interface cracks in bimaterial elastic-plastic systems. The stress and strain fields around such cracks will be studied at both the continuum and polycrystalline slip theory levels. The effects of mode mixity and stress triaxiality will be investigated.

FRACTURE MECHANICS OF INTERFACIAL ZONES IN BONDED MATERIALS
N00014-89-J-3188
September 89 - August 92

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. F. Erdogan
Lehigh University
Dept. of Mechanical Engineering & Mechanics
Bethlehem, PA 18015
(215) 758-3020

Objective: Research will be conducted into the micromechanics aspects of failure of composites, accounting for realistic interfacial zones. Models will be established for crack propagation in interfacial regions with continuously varying mechanical properties.

FAILURE MECHANICS OF THICK COMPOSITES
N00014-91-J-1173
October 90 - September 93

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovn 226-4405

Principal Investigator: Prof. S. N. Atluri
Georgia Institute of Technology
Dept. of Civil Engineering
Atlanta, GA 30332
(404) 894-2758

Objective: Research will be conducted into three-dimensional aspects of deformation, damage and failure in composites. Compression failure in thick composites will be investigated.

OPTICAL MAPPING OF DEFORMATION FIELDS AROUND INTERFACE CRACKS
N00014-91-J-1380
January 90 - December 93

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. F. P. Chiang
State University of New York
Dept. of Mechanical Engineering
Stony Brook, NY 11794-2300
(516) 246-6768

Objective: The optical techniques of moire interferometry and laser speckle interferometry will be used to determine two-dimensional and three-dimensional deformations in the vicinity of interface cracks.

INVESTIGATION OF THE COMPRESSIVE FAILURE OF LONG FIBER COMPOSITES DUE TO MICROBUCKLING
N00014-91-J-1916
June 91 - May 94

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Dr. N. A. Fleck
University of Cambridge
Department of Engineering
Cambridge, U.K.

Objective: Research will be conducted into the mechanisms of compression failure in polymer matrix composites. The effects of fiber misalignment, material nonlinearity, multiaxial stress states, and specimen thickness will be investigated.

COMPRESSIVE RESPONSE OF DEBONDED THICK COMPOSITE SHELLS INCLUDING THE EFFECTS OF TRANSIENT MOISTURE SORPTION
N00014-91-J-1892
April 91 - March 93

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. G. A. Kardomateas
Georgia Institute of Technology
Dept. of Aerospace Engineering
Atlanta, GA 30332
(404) 894-8198

Objective: Research will be conducted into the effect of local delaminations on the stability of thick composite shells under external pressure. The influence of moisture on stress fields at the boundaries of debonded regions will be explored.

THE INFLUENCE OF HIGH PRESSURE AND STRAIN RATE ON THE MECHANICAL BEHAVIOR OF FIBER-REINFORCED COMPOSITES
N00014-91-J-1937
June 91 - May 93

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. G. J. Weng
Rutgers University
Dept. of Mechanics and Materials Science
Piscataway, NJ 08855
(201) 932-2223

Objective: The effects of high hydrostatic pressure states on the constitutive properties and compression failure of thick composites will be investigated. The effects of strain-rate on the mechanical properties will be investigated.

COMPRESSION FAILURE OF THICK FIBROUS COMPOSITES
N00014-91-J-1705
March 91 - March 93

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. A. M. Waas
University of Michigan
Dept. of Aerospace Engineering
Ann Arbor, MI 48109
(313) 764-8227

Objective: Compression failure mechanisms in composite laminates will be investigated using moire interferometry and holographic interferometry. Failure under uniaxial compression and under combined loading states will be investigated.

VISCOELASTIC BEHAVIOR OF THICK COMPOSITE LAMINATES
N00014-91-J-4091
April 91 - May 94

Scientific Officer: Dr. Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132SM
Arlington, VA 22217-5000
(703) 696-4405, Autovon 226-4405

Principal Investigator: Prof. R. A. Schapery
University of Texas at Austin
Dept. of Aerospace Engineering and Engineering Mechanics
Austin, TX 78712
(512) 471-7593

Objective: Research will be conducted into the time-dependent behavior of composites subjected to compressive static and fatigue loading. The effects of initial ply waviness on the response of composite laminates will be established.

NAVAL RESEARCH LABORATORY
WASHINGTON, DC 20375-5000

IN-HOUSE

SIMULATION OF STRUCTURAL RESPONSE OF DAMAGED COMPOSITE SHIP COMPONENTS
October 86 - September 92

Principal Invesigator: Dr. Phillip Mast
Naval Research Laboratory
Code 6383
Washington, DC 20375-5000
(202) 767-2165, Autovon 297-2165

Objective: Develop and apply an advanced simulation capability for predicting the effect of damage on the structural response of naval components made with fiber reinforced composites.

CONTRACTS

DYNAMIC BEHAVIOR OF COMPOSITES
N00014-86-C-2580
October 86 - March 92

Scientific Officer: Mr. Irvin Wolock
Naval Research Laboratory
Washington, DC 20375-5000
(202) 767-2567, Autovon 297-3567

Principal Investigator: Dr. Longin B. Greszczuk
McDonnell Douglas Astronautics Company
5301 Bolsa Avenue
Huntington Beach, CA 92647
(714) 896-3810

Objective: Develop a capability to predict the effects of large area dynamic loading, such as that due to an underwater explosion, on the mechanical response of composite materials and structures.

NAVAL AIR DEVELOPMENT CENTER
WARMINSTER, PA 19874-5000

IN-HOUSE

INVESTIGATION OF ADVANCED LIGHT-WEIGHT SANDWICH STRUCTURAL CONCEPTS
October 90 - August 91

Project Engineer: Dr. H. Ray
Naval Air Development Center
Warmister, PA 18974-5000
(215) 441-1149, Autovon 441-1149

Objective: To investigate advanced light-weight sandwich structures fabricated of composite materials, retaining no moisture and eliminating corrosion with improved damage tolerance.

ANALYTICAL MODELING OF COMPOSITE INTERFACE MECHANICS
April 88 - September 91

Project Engineer: Dr. H. C. Tsai
Naval Air Development Center
AVCSTD/6043
Warminster, PA 18974-5000
(215) 441-1287, Autovon 441-1287

Objective: To develop analytical methods which predict the transverse tensile failures of composite materials and to examine how various micromechanical parameters influence the transverse tensile strength and failure modes.

CONTRACTS

DELAMINATION METHODOLOGY FOR COMPOSITE STRUCTURES
N62269-90-C-0282
September 90 - September 92

Project Engineer: Dr. E. Kautz
Naval Air Development Center
Warminster, PA 18974-5000
(215) 441-1561, Autovon 441-1561

Principal Investigator: Dr. H. P. Kan
Northrop Corporation
One Northrop Avenue
Hawthorne, CA 90250
(213) 332-5285

Objective: To develop a methodology to evaluate the significance of delaminations that occur during assembly of composite structures and to establish criteria for acceptance, rejection, or repair of the delaminated structure.

ASSEMBLY INDUCED DELAMINATIONS IN COMPOSITE STRUCTURES
N62269-90-C-0281
September 90 - September 92

Project Engineer: Dr. E. Kautz
Naval Air Development Center
Warminster, PA 18974-5000
(213) 441-1561, Autovon 441-1561

Principal Investigator: Dr. J. Goering
McDonnell Aircraft Co.
Box 518
St. Louis, MO 63166
(314) 233-9622

Objective: To analytically predict and experimentally verify the initiation/resistance of delaminations around fastener holes during mechanical assembly due to poorly mating skins to substructure.

DAVID TAYLOR RESEARCH CENTER
BETHESDA, MD 20084-5000
ANNAPOLIS, ND 21842

IN-HOUSE

COMPRESSION RESPONSE OF THICK-SECTION COMPOSITE MATERIALS
October 86 - September 92

Principal Investigator: Dr. E. T. Camponeschi, Jr.
David Taylor Research Center, Code 2844
Annapolis, MD 21842
(301) 267-2165, Autovon 281-2165

Objective: Develop an understanding of compression failure for thick section composites.

NONLINEAR MECHANICS FOR THICK SECTION COMPOSITES
October 89 - September 92

Principal Investigator: Ms. K. Gipple
David Taylor Research Center, Code 2844
Annapolis, MD 21842
(301) 267-5218, Autovon 281-5218

Objective: Develop three-dimensional nonlinear material models for thick section composites.

COMPOSITE STRUCTURES FOR SUBMARINES
October 85 - September 95

Principal Investigator: Dr. W. Phyillaier
David Taylor Research Center
Bethesda, ND 20084-5000
(301) 227-1707, Autovon 287-1707

Objective: Develop the basic technology to support the applications of composites to submarine structures including methods of analysis and design for thick composite structures, design concepts for joints and penetrations in thick section composites, and failure prediction and residual strength after damage due to impact. Demonstrate the feasibility of using FRP composites for submarine applications such as control surfaces, air flasks, foundations, and ballast tank structures.

COMPOSITE STRUCTURES FOR SURFACE SHIPS
October 85 - September 95

Principal Investigator: Dr. M. Critchfield
David Taylor Research Center
Bethesda, MD 20084-5000
(301) 227-1769, Autovon 287-1769

Objective: Develop the basic technology to support the applications of composites to naval ship structures including static and dynamic analysis of hybrid fiber reinforced laminates, joints and attachments, failure prediction and residual strength after damage due to fire insult. Demonstrate the feasibility of using FRP composites for surface ship structural applications such as deckhouses, stacks and masts, and secondary structures.

BEHAVIOR OF HYBRID GLASS/GRAPHITE REINFORCED THICK-SECTION COMPOSITE CYLINDERS UNDER HYDROSTATIC LOADING
October 89 - September 92

Principal Investigator: Dr. H. Garala
David Taylor Research Center
Bethesda, MD 20084-5000

Objective: Determine the failure mechanisms and hydrostatic strength of commingled glass/graphite reinforced composite cylinders.

WRIGHT LABORATORY
MATERIALS DIRECTORATE

IN-HOUSE

ADVANCED COMPOSITES
WORK UNIT DIRECTIVE (WUD) NUMBER 45
91 October - 92 October

WUD Leader: Steven L. Donaldson
Materials Directorate
Wright Laboratories
WL/MLBM
Wright-Patterson AFB OH 45433-6533
(513) 255-9096, DSN: 785-9096

Objective: The long-term objective for the in-house research effort is to develop an understanding of deformation and failure in composite materials. The short-term objectives include the following: (a) understanding of failure mechanisms in polymer matrix composites, particularly under compression loading; (b) intelligent on-line processing of composites, including sensor development; (c) the development of advanced carbon-carbon materials; (d) failure of brittle matrix ceramic composites.

CONTRACTS

IMPROVED COMPOSITE MATERIALS
F33615-91-C-5618
16 Sep 91 - 15 Sep 95

Project Engineer: Ken Johnson
Materials Directorate
Wright Laboratory
WL/MLBC
Wright-Patterson AFB OH 45433-6533
(513) 255-6981, DSN: 785-6981

Principal Investigator: Allen Crasto
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 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.

MICROMECHANICS OF COMPOSITE FAILURE
F33615-88-C-5420
1 Oct 88 - 30 Sep 92

Project Engineer: Capt David Rose
Materials Directorate
Wright Laboratory
WL/MLBM
Wright-Patterson AFB OH 45433-6533
(513) 255-9097, DSN 785-9097

WRIGHT LABORATORY
MATERIALS DIRECTORATE

IN-HOUSE

ADVANCED COMPOSITES
WORK UNIT DIRECTIVE (WUD) NUMBER 45
91 October - 92 October

WUD Leader: Steven L. Donaldson
Materials Directorate
Wright Laboratories
WL/MLBM
Wright-Patterson AFB OH 45433-6533
(513) 255-9096, DSN: 785-9096

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CONTRACTS

IMPROVED COMPOSITE MATERIALS
F33615-91-C-5618
16 Sep 91 - 15 Sep 95

Project Engineer: Ken Johnson
Materials Directorate
Wright Laboratory
WL/MLBC
Wright-Patterson AFB OH 45433-6533
(513) 255-6981, DSN: 785-6981

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MICROMECHANICS OF COMPOSITE FAILURE
F33615-88-C-5420
1 Oct 88 - 30 Sep 92

Project Engineer: Capt David Rose
Materials Directorate
Wright Laboratory
WL/MLBM
Wright-Patterson AFB OH 45433-6533
(513) 255-9097, DSN 785-9097

Principal Investigator: Som R. Soni
AdTech Systems Research Inc
1342 N Fairfield Road
Dayton OH 45432

Objective: The objective of this program is to provide exploratory development in thermomechanical response, model material system development composite processing, and failure mechanism investigations of composite and related constituent materials.

MECHANICS OF ADVANCED COMPOSITE
F33615-91-C-5600
1 Mar 91 - 1 Aug 95

Project Engineer: Capt David Rose
Materials Directorate
Wright Laboratory
WL/MLBM
Wright-Patterson AFB OH 45433-6533
(513) 255-9097, DSN 785-9097

Principal Investigator: Som R. Soni
AdTech Systems Research Inc
1342 N Fairfield Road
Dayton OH 45432

Objective: The objective of this program is to develop mathematical models which describe the behavior of advanced composite materials with emphasis on micromechanics and to transition the models to industry through the development of a series of user friendly computer programs.

DEVELOPMENT OF ULTRA-LIGHTWEIGHT MATERIALS-N
F33615-88-C-5447
29 Apr 88 - 1 Jun 92

Project Engineer: Lt Suzanne Guihard
Materials Directorate
Wright Laboratory
WL/MLBC
Wright-Patterson AFB OH 45433-6533
(513) 255-9728, DSN: 785-9728

Principal Investigator: Dr Anna Yen
Northrop Corporation
Aircraft Division
One Northrop Avenue
Hawthorne CA 90250

Objective: To demonstrate the potential for advanced ultra-lightweight (ULW) materials and associated processes that will permit a fifty percent reduction in the structural weight of state-of-the-art (SOTA) high-performance aircraft that currently utilize up to ten percent of advanced composite materials in their structures.

DEVELOPMENT OF ULTRA-LIGHTWEIGHT MATERIALS-M
F33615-88-C-5452
13 May 88-15 Mar 92

Project Engineer: Lt Suzanne Guihard
Materials Directorate
Wright Laboratory
WL/MLBC
Wright-Patterson AFB OH 45433-6533
(513) 255-9728, DSN: 785-9728

Principal Investigator: Mindy Schowengerdt
McDonnell Douglas Corporation
McDonnell Douglas Company
PO Box 516
St Louis MO 63166

Objective: To demonstrate the potential for advanced ultra-lightweight (ULW) materials and associated processes that will permit a fifty percent reduction in the structural weight of state-of-the-art (SOTA) high-performance aircraft that currently utilize up to ten percent of advanced composite materials in their structures.

ULTRALIGHTWEIGHT MATERIALS AND PROCES DEVELOPMENT
F33615-91-C-5617
16 Sep 91 - 16 Jan 95

Project Engineer: Lt Suzanne Guihard
Materials Directorate
Wright Laboratory
WL/MLBC
Wright-Patterson AFB OH 45433-6533
(513) 255-9728, DSN: 785-9728

Principal Investigator: Dr Anna Yen
Northrop Corporation
Aircraft Division
One Northrop Avenue
Hawthorne CA 90250

Objective: To develop advanced ultralightweight (ULW) materials and processes which will enable innovative approaches to design ULW aircraft structures that are at least 50% lighter and offer reduced life cycle costs and improved system performance when compared with current state-of-the-art (SOTA) aircraft structures utilizing up to 10% advanced composite materials in their structures.