Conference Reports

Mechanics of Composites Review

K. L. Reifsnider1

The Eighth Annual Mechanics of Composites Review sponsored by the Materials Laboratory, Nonmetallic Materials Division, Air Force Wright Aeronautical Laboratory, was held on 5-7 October 1982 at Stouffer's Dayton Plaza Hotel in Dayton, Ohio. The meeting was arranged to provide a review of mechanics of composites work throughout the U.S. Air Force and NASA, both in-house and contract programs. The titles and sponsors (in parentheses) of the programs discussed are recorded below. Readers wishing information regarding the activities and results of these programs should contact the individual investigators associated with them.

Postbuckling Behavior of Graphite/Epoxy Panels Loaded in Compression

J. H. Starnes, Jr., M. Rouse, M. Stein, and N. Knight, Jr., NASA Langley Research Center (in-house)

Objective—To study the postbuckling behavior of unstiffened and stiffened graphite/epoxy panels loaded in compression; to identify the failure modes of compressively loaded graphite/epoxy panels with postbuckling strength; to predict analytically the postbuckling response of graphite/epoxy panels loaded in compression; and to determine the effects of low-speed impact damage and circular holes on postbuckling strength.

Spectrum Fatigue Behavior of Postbuckled Shear Panels

B. L. Agerwall, Northrop Corporation (NADC)

Objective—To evaluate the effect of spectrum fatigue on postbuckling strength and to compare the behavior to constant-amplitude fatigue tests.

Development of Analysis for Predicting Compression Fatigue Life and Residual Strength in Composites

M. Ratwani and H. Kan, Northrop Corporation (NADC)

Objective—To develop models for compression fatigue and residual strength of composites incorporating the effects of ply orientations, stacking sequence, and loading conditions.

Microbuckling Initiated Failure in Tough Resin Laminates

J. Williams, NASA Langley Research Center (in-house)

Objective—To identify failure mechanisms that initiate failure in compression-loaded graphite/epoxy laminates and structural components; to understand why tough resins improve the compressive strength of graphite/epoxy laminates with impact damage but not with holes; and to develop ways to make compression-loaded laminates less notch-sensitive.

Summary of Impact Work in the Fatigue and Fracture Branch

W. Iilg, NASA Langley Research Center (in-house)

Objective—To establish, through slow transverse loading, the energy capabilities of various composites; to develop a simple analytic method to predict progressive impact damage in quasi-isotropic composite laminates; to determine the effect of deliberately fabricated partial bonding on the impact resistance of composite laminates under prestrain; and to predict the residual tensile strength of impacted laminates.

Characterization of Interlaminar Fracture Toughness in Composite Materials

J. Whitney, AFWAL/Materials Laboratory (in-house)

Objective—To develop test methods for characterizing interlaminar fracture of unidirectional and multidirectional fiber-reinforced polymeric matrix composites.

Composite Defect Significance

S. Chatterjee, Materials Sciences Corporation and R. B. Pipes, University of Delaware (NADC)

Objective—Review state of the art for nondestructive and analytic evaluation of defect criticality; test the validity of criticality criteria for disbonds in beam and plate type members subjected to quasi-static compression and transverse shear; study growth of isolated disbonds and delaminations near ply drops under cyclic loads; and develop analytical methodologies for calculation of energy release rates for multiple disbonds in plate or beam type members.

Superposition Method for Analysis of Free Edge Stresses

J. Whitcomb, NASA Langley Research Center and I. Raju, George Washington University (in-house)

Objective—To simplify free-edge stress analysis by using superposition principles; to develop a two-dimensional analysis for calculation of free-edge stresses in composite laminates; and to evaluate the accuracy of the two-dimensional analysis for mechanical, thermal, and hygroscopic loads.

Mechanics of Delamination Under Compressive Loads

A. S. D. Wang, Drexel University

Objective—To study the delamination mechanisms in graphite-epoxy laminates subjected to compressive static and fatigue loads; to formulate analytical models for the initiation and growth behavior of delamination cracking under both static and fatigue (compressive) loads.

1Virginia Polytechnic Institute and State University, Blacksburg, VA 24061.
A Cumulative Damage Model for Advanced Composite Materials
P. Chou, Dyna East Corporation (AFWAL/MLBM)

Objective—Development of a cumulative damage model to predict the failure modes, strength, and fatigue life of composite materials. The model will utilize fracture mechanics, random variables, and finite-element codes, as needed. The results must be verified by experiments.

Property Degradation Approach to Cumulative Damage Modeling of Advanced Composites
W. Stinchcomb, K. Reifsnyder, Virginia Polytechnic Institute and State University, and D. Ullman, General Dynamics/Fort Worth Division (AFWAL/MLBM)

Objective—To develop a cumulative damage model for advanced composite materials that is capable of predicting the strength, stiffness, and life of an arbitrary composite laminate when subjected to a variety of complex load histories.

Fatigue Damage-Strength Relationships in Composite Laminates
K. Reifsnyder, W. Stinchcomb, E. Henneke, II, J. Duke, Jr., and R. Jamison, Virginia Polytechnic Institute and State University (AFWAL/FIDEC)

Objective—To determine the nature of damage events, caused by cyclic (fatigue) loading, which are directly related to the fracture of composite laminates and to develop an understanding of how such damage events affect the strength of the laminates.

Lay-up and Frequency Effects on Fatigue Life of Composites
C. Saff, McDonnell Aircraft (NADC)

Objective—To determine sensitivity of life in graphite/epoxy to load frequency and to develop an analysis technique for identifying sensitive lay-ups.

Effect of Stress Ratio on Fatigue Life of Composites
G. Sendeckyj, AFWAL Flight Dynamics Laboratory (in-house)

Objective—To develop an understanding of the effect of stress ratio on fatigue life of resin-matrix composite materials and to develop a fatigue model that properly accounts for stress ratio dependence.

High-Load Transfer Joints for Wing Structures
S. Garbo and D. Buchanan, McDonnell Aircraft (NADC)

Objective—To design, select, and evaluate metal-to-composite bolted joints as an alternative to high-load transfer adhesive bonded step-lap joints.

Design Methodology for Bonded-Bolted Composite Joints
J. Hart-Smith, McDonnell Douglas Corporation (AFWAL/FIDEC)

Objective—Development of new analysis/design computer programs for composite joints (bonded, bolted, and bonded-bolted); illustration of analysis capabilities by sample solutions.

Interply Layer Progressive Weakening Effects on Composite Structural Response
C. Chamis, NASA Lewis Research Center (in-house)

Objective—To computationally determine and assess the effects of interply layer progressive degradation on the structural response of a layered composite beam, under bending/flexural, buckling, free vibration, periodic excitation, and impact loading.

Research on Composite Materials for Structural Design
R. Schapery, Texas A&M University (AFOSR)

Objective—To study deformation and fracture behavior of advanced structural composites with emphasis on polymer matrix dominated phenomena. (Most topics were selected so that work could be done as part of a one-year M.S. degree program.)

Imperfect Sensitivity of Fiber-Reinforced Composite Thin Cylinders
G. Simites, D. Shaw, and I. Sheinman, Georgia Institute of Technology (AFOSR)

Objective—To study the nonlinear response of geometrically imperfect, circular, cylindrical, thin shells of various constructions supported in various ways at the boundaries and subjected to static and sudden loads applied individually or in combination.

Research into the Design Technology of Advanced Composites
P. Lagace and J. Dugundji, Massachusetts Institute of Technology

Objective—To examine and predict from flat-plate data the effect of flaw size and stacking sequence on fracture stress (pressure) and mode for graphite/epoxy cylinders; to explore possible means of selectively reinforcing composite cylinders in order to arrest crack propagation; to study the effect of bending-torsion stiffness coupling in advanced composites, on the aeroelastic flutter and divergence behavior of unswept and forward swept wings; to explore aeroelastic behavior of wings at high as well as low angles of attack.

Nonlinear Transient Analysis of Composite Plates
J. Reddy, Virginia Polytechnic Institute and State University (AFOSR)

Objective—To develop a finite element for transient analysis based on shear-deformation theory including geometric nonlinearity (in the von Karman sense) and to develop analytical solutions for verification.

Improved Ceramic Fracture Behavior for High Temperature Turbine Applications
K. Buesking, S. Chatterjee, B. Rosen, Materials Sciences Corporation (AFOSR)

Objective—Determine feasibility of developing an analytical model to investigate fracture behavior and strength of ceramic composites; identify alternate analytical approaches for material model; fabricate whisker-reinforced ceramics and experimentally measure fracture toughness and tensile strength; compare experimental failure mechanisms to analytical methods to choose theory most representative of material behavior.
**Symposium on Mechanics of Composite Materials**

**K. L. Reifsnider**

The International Union of Theoretical and Applied Mechanics sponsored a Symposium on Mechanics of Composite Materials at Virginia Polytechnic Institute and State University on 16-19 August 1982. Five general lectures and 26 contributed papers were presented at the conference by scientists and engineers from seven countries. The Symposium cochairmen were Prof. Z. Hashin (Israel) and Prof. C. T. Herakovich (U.S.A.). Proceedings of the meeting will be published by Pergamon Press, New York. Edited versions of the abstracts of the papers follow. Further information regarding the work presented can be obtained from the authors. General information about the meeting can be obtained from C. T. Herakovich, Engineering Science and Mechanics Department, Virginia Polytechnic Institute & State University, Blacksburg, VA; telephone (703) 961-5372.

**Mechanical Properties of Composite Materials**

**R. M. Christensen, Lawrence Livermore National Laboratory**

Means of predicting the mechanical properties of composite materials in terms of microstructure properties are assessed. Various geometric models of microstructure characteristics are discussed. Primary emphasis is given to elasticity results, although some viscoelasticity and plasticity formulations are considered. Key theoretical results are compared with experimental data.

The results discussed are restricted to the case of small strain conditions, which are appropriate to many, if not most, composite material constitutions. The first two sections are concerned with the averaging process needed to obtain macroscopic properties in terms of those of the phases. Specific geometric models for the averaging process are then outlined, many static elasticity results are stated, and bounds, results, and some further elasticity property solutions are briefly discussed. The last three sections concern brief discussions of results for media containing cracks, dynamic characteristics, and inelastic effects.

**Influence of Microstructure on the Thermoelastic and Transport Properties of Particulate and Short-Fiber Composites**

**R. L. McCullough, Center for Composite Materials, University of Delaware, Newark, DE 19711**

A strong interest is developing in the use of discontinuous ("short") fiber or particulate reinforced polymeric materials or both that can be molded into load-bearing elements with complex shapes. These heterogeneous materials exhibit a wide range of properties which are dependent upon the composition and the particular microstructure developed during fabrication.

Modeling relationships must be based on identifying a limited number of quantitative descriptors of the microstructure which are susceptible to experimental evaluation. A minimal set of descriptors consists of (1) a measure of the state of fiber orientation and (2) a measure of the reinforcing geometry which can be described by an aspect ratio.

These structural descriptors were used in conjunction with results from bounding analyses to construct approximate model relationships to estimate thermoelastic and transport properties. The resulting estimates show good agreement with measured values of the Young’s moduli, shear moduli, Poisson’s ratios, and coefficients of thermal expansion obtained from specimens subjected to structural analyses that characterize the effective aspect ratio and intermediate states of fiber orientation.

**Further Applications of the Systematic Theory of Materials with Disordered Constitution**

**E. Kröner Institut für Theoretische und Angewandte Physik, Universität Stuttgart, Max-Planck-Institut für Metallforschung, Stuttgart**

In certain defined physical situations it is possible to describe the macroproperties of heterogeneous media (composites) with the help of a hypothetical homogeneous, so-called effective, medium. In the case of the linear properties such as (linear) elasticity, electrical and thermal conductivity, and so forth, in which the property is described by a tensor, there exist rigorous formulae giving the effective property tensor in terms of the Green’s function of the effective medium and the structural information about the constitution of the heterogeneous medium. This information is to be given in the form of the infinite set of n-point probability densities or n-point correlation functions ($n = 1, 2, 3, \ldots, \infty$). Rigorous bounds of the nth order can be constructed if only correlation functions up to order $n$ are available or tractable. A new branch of science, called mathematical morphology, provides methods for the calculation of correlation functions, in particular those of lower order, if the statistical information is given in different form.

The knowledge of the effective property tensor permits us to calculate average fields such as electric and magnetic fields, stress and strain, and so forth, if the causes producing these fields are known.

The methods indicated have applications to other kinds of problems. As examples, we discuss the plasticity of heterogeneous materials and the heat transmission through the contact interface between two bodies with rough surfaces, where the roughness is of stochastic nature.

**Finite Elastic-Plastic Deformation of Composites**

**S. Nemat-Nasser and T. Iwakuma, Department of Civil Engineering, The Technological Institute, Northwestern University, Evanston, IL 60201**

The objective is to estimate the overall instantaneous moduli of an elastic-plastic composite which consists of an elastic-plastic matrix containing randomly distributed ellipsoidal voids or elastic-plastic inclusions. Both the matrix and the inclusions may undergo finite deformations, and this may alter the shape of the inclusions during the course of flow. Full account is taken of the nonlinear nature of the involved kinematics and material properties. The interaction effects are included in a “self-consistent” manner, for each incremental deformation. The analysis is cast in terms of the nominal stress rate measured with respect to the current deformed state, and the corresponding instantaneous moduli that relate the overall uniform nominal stress rate to the corresponding uniform overall velocity gradient are estimated. The results are exemplified for the plane-strain case and uniaxial loading.
Effective Constitutive Equations for Fiber-Reinforced Viscoplastic Composites

J. Aboudi, Department of Solid Mechanics, Materials and Structures, School of Engineering, Tel-Aviv University, Ramat-Aviv, 69978, Israel

Effective elastic-plastic stress-strain relations are derived for fiber-reinforced composites whose constituents are elastic-viscoplastic work-hardening materials. The composite is made of unidirectional fibers which are embedded in the matrix in the form of a square array. The derivation is based on a higher order continuum theory with microstructure, which was developed recently by the author for the modeling of viscoplastic composites. A specific reduction of this theory gives the effective rate-dependent elastic-plastic behavior of the composite. In the special case of perfectly elastic constituents the approximate effective moduli of the fiber-reinforced material are obtained. Average stress-average strain rate-dependent curves are constructed for numerous modes of loading, from which the overall strength, rate-sensitivity, and hardening of the composite can be studied.

Metal Matrix Composites: Plasticity and Fatigue

J. Dvorak, University of Utah, Salt Lake City, UT 84112

The deformation behavior of unidirectional and laminated fibrous metal-matrix composites is characterized by certain distinct features which are usually not observed in unreinforced metals. Foremost among these is the large difference between the initial yield stress and the ultimate strength. The ratio of their magnitudes is typically equal to 0.20-0.25 in B-Al systems, and may be as low as 0.1 in fibrous silicon carbide materials. The plastic deformation range is thus much larger than the elastic range. However, the total strain at failure seldom exceeds 0.01. Therefore, development of theoretical models of elastic-plastic behavior must emphasize accuracy in the small strain region, yet the models must be simple enough to allow formulation of tractable constitutive equations.

This paper reviews recent theoretical studies of elastic-plastic behavior of fibrous composites and extends them to thermal loading problems. Also, certain applications of the plasticity theory are made to shakedown and fatigue of laminated B-Al plates.

Damping in Fiber Reinforced Laminates

Robert Plunkett, University of Minnesota

Linear damping is that for which the damping factor is independent of amplitude but not dependent in any particular way on frequency or environmental factors.

Amplitude-dependent damping necessarily makes linear superposition impossible and, indeed, a nonsinusoidal strain variation causes rather unexpected interaction.

Thermoelastic damping is an important mechanism for metals but not for composites. The published results show that the damping factor of reinforced composites is independent of strain amplitude up to about 0.1% but depends on frequency and temperature in a way that is consistent with the known behavior of polymers.

The simplest nonlinear damping mechanism is cyclic plastic hysteresis in soft metal-matrix materials. Another important mechanism for high strain damping is matrix damage associated with macrocracking in the transverse layers of laminates.

A reasonable physical mechanism for energy dissipation involving these cracks cannot be found. They open and close but not with a high enough velocity to cause impact loss; the material at the tips of the cracks is highly strained but the volume affected is small and so is the total energy dissipation. On the available evidence, only further microcracking in the high shear regions near each end of the microcracks can account for the observed phenomena.

Failure of Fiber Composite Laminates

B. Walter Rosen, Materials Sciences Corporation, Spring House, PA 19477

Laminates are the principal form of construction for advanced fiber composites used for structural applications. A major need in the design of these composite structures is the definition of acceptable stress levels based upon consideration of cyclic as well as static loads at operating temperatures. The development of these strength characteristics on a purely experimental basis is an overwhelming task because: the number of candidate materials and laminates is large; each configuration is anisotropic and requires directional properties, as well as data for combined stresses; and a statistically sound data base is required. For these reasons and others, analytical failure criteria are a necessary part of the definition of allowable stresses.

Failure analyses for composites have been developed at several levels. Analyses exist for the relationships between: strength of unidirectional fiber composites and the properties of their constituents; and the strength of laminates and the properties of their laminae. The present paper is a review of methods for defining the strength of laminates under various types of loads. Its objective is to provide an understanding of the factors of importance in establishing operating stress levels.

Probability Models for the Time and Temperature Dependent Failure of Unidirectional Composites: Understanding Stress-Rupture Data

S. L. Phoenix and E. M. Wu, Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY 14853; and Lawrence Livermore National Laboratory, Livermore, CA 94550, respectively

In this paper we present results from a probability model for the time- and temperature-dependent failure of a unidirectional composite material under a tensile load. We begin with a probability model for the failure of single fibers starting with considerations of molecular scission and slip. We then present results for the probability distribution for composite strength and lifetime that were derived in earlier work using accurate asymptotic techniques. For both strength and lifetime, we find that a Weibull distribution is a natural and accurate approximation, though the values of the various parameters differ dramatically for the two cases. In the next part of the paper we present experimental results on the strength and stress-rupture of Kevlar-49 fibers and their epoxy composites. And in the final part of the paper we discuss the extent to which the mathematical model and the experimental results agree. Most aspects of the experimental results are explainable but certain aspects clearly are not. In conclusion we discuss how the model might be modified in pursuit of understanding the anomalous experimental features.

Analysis of a Hybrid Unidirectional Laminate with Damage

L. R. Dharani and J. G. Goree, Graduate Student in Engineering Mechanics and Professor of Mechanics and Mechanical Engineering, re-
Modeling of the Failure Process in Notched Laminates

R. S. Sandhu, L. R. Gallo, and G. P. Sendeckyj, Structures & Dynamics Division, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio

Strength prediction procedures for composite laminates must successfully model the damage accumulation process as a function of the loading history. Damage accumulation consists of complex interaction of delaminations, matrix cracking, and fiber fractures.

In an attempt to model the failure process, we have developed a progressive ply failure, finite-element program. At present, the program assumes the absence of delaminations and models the effect of matrix cracking and fiber fractures through classical lamination theory. The laminae in the laminate are modeled by constant strain elements which have orthotropic nonlinearly elastic constitutive relations. Various models of element failure are used in the formulation. Double-edge notched graphite/epoxy specimens are analyzed and results compared with experimental data.

Variational Characterization of Waves in Fiber Reinforced Materials

J. R. Willis, School of Mathematics, Bath University, Bath BA2 7AY, England

The basic problem under consideration is to solve the equations of motion

$$\text{div} \sigma + g = \rho$$  \hspace{0.5cm} (1)

where $\sigma$ represents stress, $\rho$ momentum density, and $g$ body force, for a continuum with constitutive relations

$$\sigma = Le \text{ and } p = u$$  \hspace{0.5cm} (2)

where $e$ is strain and $u$ particle displacement. A variational principle is constructed using a dynamic generalization of the principle of Hashin and Shtrikman. The statistics of the medium enter through simple integrals of two-point probabilities. Results are sensitive to the choice of comparison materials. Illustrative examples are given, for a matrix reinforced by a single family of aligned circular cylindrical fibers, in the form of plots of estimates of wave speeds and attenuation factors $Q_N$, which show the dependence of the results both upon $L_o$ and upon the statistical properties assumed for the composite.

Harmonic Waves in a Periodically Laminated Medium

S. K. Datta, A. H. Shah, and H. M. Ledbetter, Department of Mechanical Engineering and CIRES, University of Colorado, Boulder, Colorado 80309; Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba R3T 2N2; and Fracture and Deformation Division, National Bureau of Standards, Boulder, Colorado 80303, respectively

The present paper addresses the dynamics of laminated media. Such a composite may be modeled as a laminated medium made up of alternate thin and thick layers of matrix and fiber-reinforced matrix materials, respectively. The fibers in the reinforced layers may be assumed to be randomly distributed.

In this paper we present results showing the effect of layering on wave propagation in a fiber-reinforced medium. A stiffness method is used in which an interpolation function is assumed for each lamina and is characterized by a discrete number of generalized coordinates at the interfaces. These generalized coordinates are the interface displacements and stresses, thus ensuring the continuity of these quantities across the boundary planes. By applying Hamilton’s principle and using Floquet’s theory the dispersion equation is obtained. The solution of this equation yields the frequency-wave number relation. Numerical results showing frequency-wave number dependence are compared with experiments.

Dynamic Behavior of Composites Studied by Caustics

P. S. Theocaris, Chair of Mechanics A’, National Technical University, S. K. Zographou, Athens (624), Greece

The fracture behavior of fibrous and particulate composites was studied by the method of dynamic caustics. The caustic created around the tip of a stationary or running crack carried all the information necessary to evaluate the instantaneous crack velocity, mode of deformation, and the variation of the stress field at the vicinity of the crack tip.

The fracture behavior of a specific fiber was simulated by studying the dynamic behavior of a crack approaching a bimaterial interface with one phase representing the matrix and the other representing the fiber material. A salient result of this work is the discovery that the interface between the two phases of a composite material is not a simple contact surface but rather a thin layer with mechanical properties not coinciding with those of the two phases. This third phase always exists, even in the case when no cementing material was used, and results in considerable modifications of the mechanical behavior of the whole composite system.

A model encountering the existence of the third phase is proposed which results in a better agreement with experimental data, as compared to those of the two-phase models, for both cases of either particulate or fibrous materials.

Computational Methods for Eigenvalue Problems in Composites

Cornelius O. Horgan, Professor of Mechanics, Department of Metallurgy, Mechanics and Materials Science, Michigan State University, East Lansing, MI 48824
Nonlinear Effects of Elastic Coupling in Unsymmetric Laminates

The paper summarizes studies aimed at understanding the behavior of composite laminates which exhibit bending-stretching coupling. The specific goal of the studies is to achieve an understanding of the mechanics of unsymmetric laminates which are flat at their elevated cure temperature but warp out-of-plane as they cool to room temperature.

The accuracy of this model for elastic stress field analysis of composite laminates is examined by comparison of solutions with this model to those given by purely local models developed in previous work. Emphasis is placed on free-edge laminates under interlaminar normal stresses of small magnitude since they present the most severe challenge to the model. This leads to a good understanding of the range of validity of the model. The global-local model is used in conjunction with experimental data to examine a proposed failure criterion for delamination and to define the range where significant influence of the interlaminar stresses on free-edge laminate failure response is present.

Failure Characteristics of Graphite-Epoxy Structural Components Loaded in Compression

James H. Starnes, Jr. and Jerry G. Williams, NASA Langley Research Center, Hampton, VA 23665

Structurally-efficient graphite/epoxy structural components have been shown to satisfy both strength and buckling design requirements when loaded in compression. For some applications, structural efficiency can be improved by permitting the skins of stiffened graphite/epoxy panels to buckle at loads below the expected failure loads. Experience has shown, however, that the compressive strength of graphite/epoxy structural components can be reduced significantly by low-speed impact damage and by the strain concentrations near holes. Experience has also shown that compressive strength can be limited by failures in the highly strained and deformed regions of a buckled panel. Many of the failure mechanisms that limit structural performance of compressively loaded components are unique to composites. Some of these mechanisms and their effects on performance are described.

The effect of low-speed impact damage on the compressive
strength of laminates loaded to a constant compressive strain level is discussed. The effect of circular holes on compressive strength is also investigated and successfully modeled by a point-stress criterion. Results showing the effect of aspect ratio on the postbuckling response of laminates are also presented.

Optimization of Composite Structures

W. Jefferson Stroud, NASA-Langley Research Center, Hampton, VA

The paper provides a brief introduction to structural optimization and focuses on its application to composite structures. Two early approaches to systematic structural design are described, then basic concepts and definitions for modern optimization procedures are presented and contrasted with them. Several examples illustrate factors that must be considered when using optimization techniques to design composite structures. These factors are:

1. Optimized structures that are tailored to a specific set of design conditions (loads, temperatures, failure criteria, and so forth) can perform poorly in a design condition not considered in the original design.
2. Optimized structures tend to have multiple modes of failure occurring simultaneously. Such structures are sensitive to imperfections.
3. Compared with metal materials, composite materials provide additional design variables (ply orientation and ply thickness) for more refined tailoring and more extensive optimization, but may also be more sensitive to "off-design" conditions.

One of the examples illustrates that optimized structural panels tend to have multiple simultaneous buckling modes and that small initial geometric imperfections in these panels can cause a substantial reduction in their buckling load.

Mechanics of Bimodular Composite Structures

C. W. Bert and J. N. Reddy, School of Aerospace, Mechanical and Nuclear Engineering, University of Oklahoma, Norman, OK 73019; and Department of Engineering Science and Mechanics, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, respectively

This paper is a survey of the mechanics of beam and plate structures laminated of fiber-reinforced composite materials having different elastic and thermoelastic properties in tension and compression. Examples of such materials include tire cord-rubber, wire-reinforced solid propellants, and soft biological materials. Specific topics covered include: mathematical models of fiber-reinforced bimodular materials and their experimental verification; static and dynamic analysis of laminated and sandwich beams; plane elasticity; analysis of deflection and free and transient vibration of laminated plates and shells. In all of these analyses, thickness-shear deformation and rotatory inertia are included. The solution methods used include closed-form, transfer-matrix, and finite-element techniques.

Initial emphasis is placed on the mechanics of fiber-reinforced composites with bimodular action on two different levels: micromechanics to explain the physical phenomena involved and anisotropic elastic continuum theory for use in structural mechanics. This is followed by applications to laminated and sandwich beams, plane elasticity, plate bending, and shells.

Stresses Around Pin-Loaded Holes in Composite Materials

Th. de Jong, Department of Aerospace Engineering, Delft University of Technology, Delft, Netherlands

The prediction of the stresses around a fastener hole in composite materials is of fundamental interest for the prediction of the bearing strength. All published theoretical work is confined to problems in which the load direction is parallel to one of the principal material axes.

This paper presents a theoretical solution for the general case using Lekhnitskii's method of complex stress functions. The relevant functions for a pin-loaded hole in an infinite plate are evaluated from a boundary condition of the first kind. The hole is loaded on a part of its edge by an infinitely rigid pin of the same diameter. The load is carried over by radial and friction forces, represented by sine series with unknown coefficients. These coefficients are solved from a boundary condition of the second kind for a number of points of the contact area.

Stress distributions and theoretical bearing strength values are presented for a number of laminates of carbon-fiber-reinforced plastics. The results indicate that friction has a strong influence on the contact pressure and on the induced tangential stresses. In all cases the bearing strength has a maximum value for the coefficient of friction.

Optimization of Laminated Composite Plates and Shells

Y. Hirano, Institute of Interdisciplinary Research, Komaba Campus, Faculty of Engineering, University of Tokyo, 4-6-1 Komaba, Meguroku, Tokyo 153, Japan

This paper is concerned with the optimum design of laminated flat plates and circular cylindrical shells with orthotropic layers under axial compression. The design criterion is the buckling stress. Each layer of the plates and the shells is assumed to have the same thickness and an equal number of the same kind of fibers in the +a directions and --a directions with respect to the x coordinate in the same type of matrix. The directions of fibers considered are not necessarily constant through the thickness. The present problem is to find the fiber directions of all the layers that give the highest axial buckling stress. The objective function and the design variables are the critical buckling stress and the fiber directions of all layers, respectively. The plates considered are under uniaxial or biaxial compression. Published buckling differential equations are simplified for the present problem and solved for the simply supported conditions. For shells, the published buckling differential equations of circular cylindrical shells under axial compression are rewritten for the present problem and solved for the simply supported conditions. The buckling stresses calculated for the axisymmetrical and unsymmetrical buckling deformations are compared and the smaller one is selected for the critical buckling stress.

An Endochronic Model for the Response of Unidirectional Composites Under Off-Axis Tensile Load

Marek Jerzy Pindera and Carl T. Herakovich, Materials Sciences Corporation, Spring House, PA 19477; and Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, respectively

A methodology of modeling both nonlinear elastic and dissipative response of unidirectional fiber composites has been developed and illustrated with the aid of the observed response of graphite/
polyimide off-axis coupons. The approach is based on the internal variable formalism employed within the text of classical irreversible thermodynamics and entails extension of Valanis' endochronic theory to transversely isotropic media. The developed model fulfills an existing need of depicting observed nonlinear response of unidirectional fibrous composites (modeled as transversely isotropic continuum) in a rational manner that is sufficiently general to predict the following types of material response often observed in these advanced, man-designed materials: linear or nonlinear elastic response along fiber directions, dissipation in shear and transverse tension, dissimilar "strain-hardening" in shear and transverse tension characterized by markedly different exponents in commonly employed power-law approximations, influence of transverse as well as longitudinal stress on the nonlinear shear strain and vice versa, and highly nonlinear response along particular material directions, for example, shearing parallel to fibers.

Curved Thermal Crack Growth in the Interfaces of a Unidirectional Carbon-Aluminum Composite

K. P. Herrmann, Institute of Mechanics, Department of Mechanical Engineering, Paderborn University, Federal Republic of Germany

This paper considers the curved thermal crack growth in the interfaces of a self-stressed unidirectionally reinforced carbon-aluminum composite with circular fibers in a hexagonal array. The quasi-static thermal crack extension in the fiber-matrix interface of a composite microcomponent (circular unit cell) is caused by a thermal shock. The corresponding nonstationary temperature distribution developing in the cross section of such a cracked unit cell is obtained by the solution of a boundary value problem of the stationary heat-conduction equation for a plane inhomogeneous domain containing a slit in the circular interface.

Further, the data that govern the fracture behavior of the inhomogeneous and linearly elastic microcomponents are determined by using the concepts of linear elastic fracture mechanics. Numerical results were obtained for the strain energy release rates $G_j (j = 1, II)$ in dependence on time and with the crack opening angle $\phi_0$ as a parameter.

Damage Mechanics and NDE of Composite Laminates


This paper deals with "damage mechanics" as a body of philosophies and analytical formulations based on principles of mechanics associated with states of stress and states of material peculiar to high-modulus fibrous composite laminates that endure loading histories known to cause changes in laminate stiffness, strength, and life caused by microfailure events collectively called "damage." It also discusses "nondestructive evaluation" as an activity associated with experimental schemes used to interrogate materials for the purpose of determining states of stress and states of material without influencing either. Load histories to be considered will be chosen so as to correspond to long but finite life. Our approach is to attempt to develop a systematic rational philosophy that emphasizes the associations between events, in contrast to a desultory recitation of observables and listing of events.

Fatigue Failure Mechanism of Composite Laminates

Assa Rotem, Technion-Israel Institute of Technology, Haifa 32000, Israel

In general, it has been observed that multidirectional laminates fail by progressive initiation and propagation of many cracks which accumulate until the final fracture.

There are five different modes of failure which may occur either separately or simultaneously: fiber failure, in-plane tension, in-plane shear, interlaminar tension, and interlaminar shear. The progressive failure occurring within the laminate alters the initial state of stress in each lamina within the laminate and causes a cumulative fatigue situation, even when the external applied load amplitude is constant. Fatigue functions, associated with the five failure modes, enable one to describe the fatigue strength of the laminate. Viewing the laminae as having nonlinear but continuous stress-strain relations up to failure gives an accurate strain to failure when using the strength criteria. The static-failure criteria could be extended to cover fatigue failure.

Typical results are shown for several laminates. Although these laminates, when loaded statically, fail by fiber fracture of the $0^\circ$ lamina, the fatigue failure mode is of the matrix (in plane) as predicted by the calculations and verified by the experiments.

The Role of Matrix Cracking in the Continuum Constitutive Behavior of a Damaged Composite Ply

R. J. Nuismer and S. C. Tan, Department of Mechanical and Industrial Engineering, University of Utah, Salt Lake City, UT 84112

The existence of microdamage before ultimate failure in fiber-reinforced composite materials is well known. Although a number of studies have been made seeking to characterize the initiation and growth of this subcritical damage, little work has been done on incorporating these microdamage mechanisms into a tractable model of continuum laminate behavior. One exception has been the work of Nuismer in which a continuum formulation of damaged ply behavior based on simple physical models of microdamage was developed and used to predict stress-strain and failure behavior of composite laminates.

In the present paper, more explicit modeling of the matrix cracking damage mechanism in composite plies is developed and incorporated into the authors' existing continuum formulation. Discretely spaced matrix cracks are modeled using a straightforward fracture-mechanics approach in conjunction with an approximate elasticity solution for the cracked body.

Using the newly developed damage model, the effect of changes in laminate lay-up and ply thickness on the softening of a ply caused by damage is investigated. It is found that the softening of a ply as damage grows is not a unique function of applied strain and ply properties. The implications of this to continuum constitutive models of damaged ply behavior are discussed.

A Damage Approach to the Fatigue of Composites

A. Poursartip and P. W. R. Beaumont, Cambridge University, Engineering Department, Trumpington Street, Cambridge CB2 1PZ, England

During fatigue loading of a fiber composite, damage accumulates within it. The damage may have several components: fiber breakage, matrix cracking, decohesion between fiber and matrix, and so
Energy Release Rates of Various Microcracks in Short-Fiber Composites

M. Taya and T. W. Chou, Department of Mechanical and Aerospace Engineering, University of Delaware, Newark, DE 19711

It has been reported that the stress-strain curve of a short-fiber composite consists of three stages, a linear stage followed by two nonlinear stages. One can conclude that the nonlinearity in the second and third stages is mainly because of the development of various microcracks in composite. In order to predict the nonlinear region of the stress-strain curve, we have developed a number of analytical models. In this paper we will focus on the energy release rate of various microcracks in composite. In order to predict the nonlinear region of the stress-strain curve, we have developed a number of analytical models. In this paper we will focus on the energy release rate of various microcracks in composite. In particular, (1) penny-shaped cracks in infinite matrix, (2) penny-shaped cracks in the matrix of a short-fiber composite, (3) a penny-shaped crack at a fiber end, (4) a penny-shaped crack arrested by the adjacent fibers, and (5) an interface crack between a rigid fiber and incompressible matrix.

The analytical tool in our study for the first three problems mentioned is the Eshelby's equivalent-inclusion method modified for a finite volume fraction of inhomogeneity. The fourth problem is based on the modified Kendall's model. The last problem is based on the mixed variation principle proposed by Washizu.

Experimental Mechanics of Composite Materials

I. M. Daniel, Mechanical Engineering Department, Illinois Institute of Technology, Chicago, IL

The complexity of loading conditions, structure geometry, and the inhomogeneity, anisotropy, and inelasticity of composite materials make the use of experimental methods indispensable for stress and failure analysis. In the case of failure analysis, the need for experimentation is even greater since existing failure theories are not always capable of predicting static strength and fatigue life under a variety of loading and environmental conditions. Specific applications of experimental methods to mechanics of composite materials include the following:

1. Characterization of constituent materials, that is, fiber and matrix, for use in micromechanics analyses.
2. Verification of micromechanics analyses.

3. Qualification and characterization of the basic unidirectional lamina, for use in lamination theory.
4. Strain and stress distributions.
5. Fracture characterization, including identification of fracture mechanisms and modes, initiation, and propagation.
6. Assessment of structural integrity and reliability.
7. Life prediction through accelerated testing.

Although experimental techniques which can be used for these determinations, especially methods which measure deformations or strains, are discussed, special attention is given to biaxial stress situations.

14th National SAMPE Technical Conference

J. W. Maxted and L. J. Cohen

The 14th National Society of Aerospace Material and Process Engineers (SAMPE) Technical Conference was held at the Sheraton Hotel in Atlanta, Georgia on 12-14 October 1982. Approximately 450 people attended the conference. A total of 69 presentations were made in 16 different sessions on various subjects that included coatings, adhesives, corrosion, applied technology, resins, composites, new materials, and metal matrix composites.

The keynote speaker was George P. Peterson, Director of Materials Laboratory at the Air Force Wright Aeronautical Laboratories. Mr. Peterson spoke on the importance to future systems of computer-aided design and manufacturing and composite technology.

Of particular interest were a series of presentations that summarized NASA-sponsored activity to improve Space Shuttle performance through the use of graphite/epoxy and graphite polyimide and tile repair. A paper was presented by Thomas R. Berkel entitled "Damage and Repair of the APS Graphite/Epoxy Composite Skins due to Columbia First Flight April 12-14, 1981." During the first flight of the Space Shuttle, missing thermal protection tile on the Orbital Maneuvering System pods created concern for the underlying graphite/epoxy composite skins. High-temperature testing of laminates and composite sandwich panels were performed while the Shuttle was in orbit to predict the effects of reentry heating on exposed pod areas. After landing, local inspection revealed overheated areas displaying various degrees of surface discoloration and composite degradation. Unacceptably degraded graphite/epoxy structure required removal and replacement, and the original graphite/epoxy composite strength of the overheated areas required restoration. Where pod damage was limited to surface discoloration and paint blistering, a repair for tile rebonding was designed. The final phase of work involved the on-site repair to the overheated areas. Replacement honeycomb core, precured graphite/epoxy plugs, and doublers were bonded to damaged areas as required in individual bonding operations using a field-type repair previously demonstrated and verified. All bonded repairs were inspected by ultrasonics and radiography for integrity, and all repairs were acceptable.

W. H. Morita and S. R. Graves's paper, "Graphite/Polyimide Technology Overview and Space Shuttle Orbiter Applications," described the early Space Shuttle orbiter studies that identified several structural items for which the application of advanced com-
Composites could achieve significant orbiter weight reduction and performance gain. Many of these structural components were included in the baseline design, including the graphite/polyimide payload bay doors. Other components, such as the vertical tail, elevons, and aft body flap, were identified for application of graphite/polyimide. Weight savings totaling 20 to 30% of the baseline aluminum structure and thermal protection system can be achieved with graphite/polyimide. Advanced structure and thermal protection system design concepts were presented with the corresponding benefits to the orbiter. Process development, nondestructive evaluation techniques and anomaly effects, material properties and fatigue effects, design, analysis fabrication, and testing of the graphite/polyimide body flap segment, repair development, and chopped graphite fiber molding development were discussed.

In addition, “Celion/Larc-160 Graphite/Polyimide Composite Processing Techniques and Properties,” by J. S. Jones, presented structural and thermal analyses that showed that there is the potential for a 25 to 35% weight savings for Space Shuttle orbiter components if a graphite/polyimide composite material system that is capable of 315°C service could replace the baseline aluminum structural material. To achieve this goal, the Composites for Advanced Space Transportation Systems project was initiated by NASA's Langley Research Center in 1976 for the purpose of developing materials, processes, and manufacturing technology for a new generation of polyimide resin systems reinforced with graphite fiber. The processing and test data were directly applied in the design and fabrication of a full-scale graphite/polyimide segment of the orbiter aft body flap.

A paper of interest by R. K. Frost and D. H. Wykes, “Fabrication of Bonded Graphite/Polyimide Structures for Advanced Aerospace Applications,” described manufacturing approaches of graphite/polyimide structures. Since 1978, several NASA CASTS programs for Langley have been directed to the structural development of graphite/polyimide composite material systems for the Space Shuttle Orbiter and future space transportation systems. Tooling concepts and manufacturing techniques developed to produce subelement and full-scale bonded test articles for two of the CASTS programs were presented. Self-tooling and low-cost aluminum tooling concepts, applied to subassembly and assembly bonding of the test articles, eliminated the need for complex and expensive tools.
Calendar on Composites

9–14 May 1983
2nd European Symposium on Flywheel Energy Storage
Torino, Italy
Contact: G. Genta
Politecnico Di Torino
I 10100 Torino, Italy

17–19 May 1983
5th Metal Matrix Composite Technology Conference
Naval Surface Weapons Center, Silver Spring, MD
Contact: Kaman Tempo
816 State Street, P.O. Drawer QQ, Santa Barbara, CA 93102
(805) 963-6455, ext. 6497

23–25 May 1983
ASCE Engineering Mechanics Specialty Conference
W. Lafayette, IN
Contact: J. T. P. Yao
School of Civil Engineering
Purdue University, W. Lafayette, IN 47907

30 May–3 June 1983
CANCAM83
Saskatoon, Saskatchewan, Canada
Contact: V. V. Neis
Civil Engineering, University of Saskatchewan,
Saskatoon, Saskatchewan, Canada S7N0W0

6–8 June 1983
2nd Japan-U.S. Conference on Composite Materials
NASA-Langley Research Center, Hampton, VA
Contact: Kathy Greene
ASTM, 1916 Race Street, Philadelphia, PA 19103
(215) 299-5414

12–13 July 1983
Environmental Effects on Fiber Reinforced Plastics
London, England
Contact: F. L. Matthews
Aeronautics Department
Imperial College, London SW7 2BY, England

18–21 July 1983
First International Symposium on Acoustic Emission from Reinforced Composites
San Francisco, CA
Contact: T. J. Fowler
Monsanto Company, 800 North Lindberg Boulevard
St. Louis, MO 63166

15–19 Aug. 1983
4th International Symposium on Mechanical Behavior of Materials
Stockholm, Sweden
Contact: N. G. Ohlson
Royal Institute of Technology, S-100 44 Stockholm, Sweden

14–15 Sept. 1983
Testing, Evaluation, and Quality Control of Composites
Surrey University, Guildford, England
Contact: Tim Feest, Conference Organizer
IPC Science and Technology Press,
Guildford, Surrey, GU2 5BH, England

14–16 Sept. 1983
2nd International Conference on Composite Structures
Paisley, Scotland
Contact: I. H. Marshall
Department of Mechanical and Production Engineering
High Street, Paisley, Scotland

8–9 Nov. 1983
Delamination and Debonding of Materials
Pittsburgh, PA
Contact: Kathy Greene
ASTM, 1916 Race Street, Philadelphia, PA 19103
(215) 299-5414

9–10 November 1983
Symposium on Delamination and Debonding of Materials
Pittsburgh, PA
Contact: Kathy Greene
ASTM, 1916 Race Street, Philadelphia, PA 19103
(215) 299-5414

13–18 Nov. 1983
ASME Winter Annual Meeting
Boston, MA
Contact: ASME
United Engineering Center, 345 East 47th Street
New York, NY 10017

16–20 Jan. 1984
39th Conference and Trade Show
Houston, TX
Contact: Wilda Roman
SPI, 355 Lexington Avenue, New York, NY 10017
(212) 573-9400