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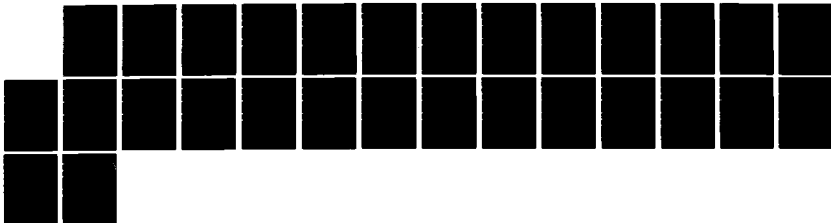
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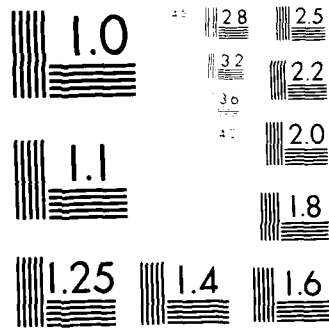
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FAILURE PROCESSES IN
ADVANCED COMPOSITE STRUCTURES

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INTRODUCTION

This research is divided into four phases of activity, which are denoted A1, A2, R1 and R2. Phases A1, "Computational Methods for Fatigue and Fracture Analysis" and A2, "Complementary Energy Approaches for Non-linear Stability," are directed by Prof. S. N. Atluri, School of Civil Engineering. Phases R1 and R2 are under the direction of Prof. L. W. Rehfield, School of Aerospace Engineering. Phase R1 is entitled "Static and Dynamic Behavior of Advanced Composite Structures". Phase R2, "Behavior of Advanced Composite Isogrid Structures", is an effort involving cooperation between the School of Aerospace Engineering and McDonnell Douglas Astronautics Company-St. Louis.

For convenience, this report contains a separate section devoted to each phase.

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PHASE A1

"Computational Methods for Fracture and Fatigue Analyses"

S. N. Atluri

Objectives:

The objectives of this phase of research were: (i) to develop efficient and accurate finite element procedures for stress and fracture analyses of angle-ply laminates, (2) to develop efficient procedures for analysis of fatigue crack growth and fracture in homogeneous metallic materials, and (3) to develop analysis procedures for cracks near fastener holes in adhesively bonded metallic laminates.

Accomplishments:

A new assumed stress hybrid finite element method, based on a complementary energy principle, has been developed for stress as well as fracture analyses of angle-ply laminates. The loading cases can include inplane as well as general bending loads. In this method, the fully three-dimensional stress-state (including the transverse shear and normal stresses) in each lamina is accounted for; the mixed-mode stress and strain singularities near the crack front, the intensities of which vary within each ply in the thickness direction of the laminate, are embedded in special elements near the crack-front; the inter-laminar traction reciprocity conditions are satisfied a priori; and the interelement traction reciprocity conditions in the finite element mesh are satisfied through a Lagrange Multiplier technique. In the present procedure, each finite element consists of the entire stack of lamina, each of which is treated as an anisotropic medium. The mixed-mode stress-intensity factors $K_I(t)$, $K_{II}(t)$, and $K_{III}(t)$ in each lamina (and their variation with thickness t) are

computed directly in the present procedure.

In the above development, a new theoretical method to study the effects of the free-surfaces on stress-intensity factors has been formulated. In the analytical solutions for embedded flaws, in either isotropic or anisotropic media, it is found that the asymptotic stress solution obeys the plane-strain constraint. However, when a crack intersects a stress-free surface, say at a right angle, it is noted that the solution in the vicinity of the free surface must necessarily be of a plane-stress type. The transition from this plane-stress state to a plane-strain state in the interior region of the crack, has been a subject of much controversy in literature. In the present research, the constraints of either plane-stress or plane-strain along the crack-border for cracks in general multi-layer anisotropic media, that satisfies the equilibrium equations only, a priori, has been derived. The principle of complementary energy is then used to force the above stress-solution to satisfy compatibility of deformation. The numerical solution thus automatically predicts conditions of plane-stress or plane-strain along the crack border, as the case may be.

Analysis procedures were also developed for problems of stress-concentration near fastener holes in angle-ply laminates. In this approach, analytical asymptotic solutions for an elliptical hole in a general two-dimensional anisotropic solid, subjected to far-field tensile stresses along the principal directions of material orthotropy as well as far-field shear stresses, are employed. From these two-dimensional solutions, a three-dimensional asymptotic solution which accounts for the variation of the stress-concentration factors through the thickness of the lamina (and hence of the laminate), and which accounts for the transverse shear and normal stresses, is generated by integration through the thickness of the laminate. The computer coding based on this approach has been

successfully completed. The obtained results for four ply and six ply symmetric angle-ply laminates agree excellently with those in prior literature and more over indicate the relative efficiency and accuracy of the presently developed procedure.

Thus the above approaches lead to multilayer, 3-dimensional special "crack" and "hole" elements for analysis of cracks and holes in angle-ply laminates. The unique features of these elements are that the crack-surface and hole-surface conditions are satisfied exactly a priori, and that stress-intensity factors, the stress-concentration factors, and their variation along the thickness direction of each lamina are solved for directly.

Based on the insights gained from the above 3-dimensional analyses, 2-dimensional procedures to estimate the stress-intensity and stress-concentration factors approximately, were also developed. These 2-dimensional estimation procedures were found to work remarkably well in a variety of carefully chosen test cases, as far as the inplane stresses and deformations are concerned. However, to predict delamination failures, in which case an accurate knowledge of interlaminar normal and shear stresses are necessary, the presently developed 3-dimensional analysis procedures are mandatory.

Several two dimensional problems of cracks in lamina wherein the matrix and fibers are modeled individually have been solved. The general case of a crack running at an angle to the fiber orientation was treated. Explorative studies into the feasibility of analysis of stable crack growth of a crack oriented at an angle to the fiber-direction and growing across the fiber, have been made.

Using the multilayer 'hole' and 'crack' elements as described above, analyses of cracks near fastener holes in adhesively bonded metallic

laminates have been performed. Several parametric studies were conducted, with the parameters that were varied include: (i) relative thickness of adherends and adhesive, (ii) relative material properties of adherend and adhesive, (iii) ratio of hole diameter to laminate thickness, (iv) ratio of crack length to hole diameter, (v) cracks in one of the metallic laminas, with and without debonding of the lamina near the crack.

Under objective (3) of Phase A1, the following studies were accomplished.

Analysis of fatigue crack growth of cracks in panels subject to Mode I and Mode II type cyclic loading have been performed. The cyclic load spectra that were considered are: (i) constant amplitude zero to tension, (ii) high-to-low spectrum, (iii) low-to-high spectrum and (iv) single overload in an otherwise constant amplitude spectrum. Quantitative results were obtained for effects of fatigue crack closure on the acceleration or retardation of crack growth due to stress-interaction. Some highlights of the conclusions from these studies were: (a) depending on the overload stress ratio, fatigue crack-growth can actually be stopped through the application of a single overload: (b) that fatigue cracks do not close under pure Mode II loading, unlike in the Mode I case. Thus, when considering fatigue growth of cracks in mixed-mode loading and in considering the effects of crack-closure on the growth rate of cracks under this loading, only Mode I component needs to be analyzed.

Analyses of the problem of fatigue growth of cracks near fastener holes have also been performed. Results have been obtained for sizes of plastic zones near fastener holes subjected to various levels of cold-working. The significant results from the analyses of fatigue-crack-growth near the fastener holes are: (a) the process of cold-working results in retardation of fatigue growth of cracks in cases where the crack is completely

embedded within the plastic zone created by cold-working and also when the crack is longer than the plastic zone due to cold-working; (b) in both the formentioned cases, the retardation effects are more significant during the initial phase of fatigue crack-growth than after sufficient number of load-cycles.

The methods of moving singular elements developed for the above analyses have been found to be extremely novel and useful in the analysis of more rapid crack propagation in which inertia plays a significant role. Work is underway in analyzing crack propagation under dynamic loading.

Papers, Reports and Presentations, Phase A1:

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- (2) T. Nishioka and S.N. Atluri, "An Efficient Assumed Stress Finite Element Procedure for the Analysis of Multilayer Anisotropic Laminates" in Recent Advances in Engineering Science, (Ed. R.H. Sierakowshi), University of Florida Press, pp 95-101.
- (3) T. Nishioka and S.N. Atluri, "Fracture-Stress Analysis of Through-Cracks in Angle-Ply Laminates: An Efficient Assumed Stress Finite-Element Approach - I" AIAA Paper No. 79-0810, Proceedings 20th AIAA/ASME/ASCE/AHS, Structures, Structural Dynamics and Materials Conference, St. Louis, Missouri, April 1979, pp 315-326.
- (4) S.N. Atluri, M. Nakagaki and K. Kathiresan, "Numerical Studies of Some Problems of Engineering Fracture Mechanics: Fatigue Crack Growth and Surface Flaws", International Conference on Fracture Mechanics Application, Bangalore, India, March 26-30, 1979, p. 59.
- (5) T. Nishioka and S.N. Atluri, "Analysis of a Through-Crack in $(-45^\circ/+45^\circ/+45^\circ/-45^\circ)$ Laminate Using a Complementary Energy Principle", paper submitted to Journal of Engineering Fracture Mechanics, August 1979.
- (6) S.N. Atluri, "Analytical Modeling of Free-Surfaces in 3-D Cracks in Laminates", Invited Presentation, Society for Experimental Stress Analysis, Spring Meeting, (Special Research Session), May 25-29, 1979.
- (7) T. Nishioka and S.N. Atluri, "An Assumed-Stress Finite Element Approach to Analysis of Edge-Effects and Holes in Laminates" 21st AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, Seattle, Wash., May 1980, pp 295-302.

- (8) T. Nishioka and S.N. Atluri, "A New Approach to Estimate Free-Surface Effects for Surface Flaws", prepared for submission to International Journal of Numerical Methods in Engineering.
- (9) S.N. Atluri and T. Nishioka, "Studies in Fracture of Composites", contribution to U.S.-U.S.S.R. Conference on Mechanics of Composites, Lehigh University, September 1980.
- (10) T. Nishioka and S.N. Atluri, "Efficient Finite Element Techniques for Computation of Mixed-Mode Stress Intensities for Cracks in Laminates", presented and published at, 2nd International Conference on Numerical Methods in Fracture Mechanics, Swansea, United Kingdom, July 1980.
- (11) T. Nishioka and S.N. Atluri, "Studies on Fracture of Angle-Ply Laminate", accepted for presentation and publication, 4th International Conference on Fracture, Cannes, France, March 1981
- (12) T. Nishioka and S.N. Atluri, "Assumed Stress Finite Element Analysis of Through-Cracks in Angle-Ply Laminates", AIAA Journal, to appear, September 1980, 45 pages.
- (13) T. Nishioka and S.N. Atluri, "Analysis of Through-holes in Composite Laminates: A Special Hole Element Approach" being submitted to AIAA Journal.
- (14) T. Nishioka and S.N. Atluri, "An Approximate 2-D Analysis of Stress Concentration Around Holes in Laminates", being submitted to Journal of Composite Materials.
- (15) M. Nakagaki and S.N. Atluri, "An Elastic-Plastic Analysis of Fatigue Crack Closure in Modes I and II", AIAA Paper No. 1 79-0758, 20th AIAA/ASME/ASCE/AHS DSM Conference, St. Louis, Missouri, April 1979, pp 221-232.
- (16) M. Nakagaki and S.N. Atluri, "Fatigue Crack-Closure and Delay Effects Under Mode - I Spectrum Loading", Proceedings Third International Conference on Mechanical Behavior of Materials, Cambridge University, United Kingdom, Pergamon Press, 12 pages.

The above has also appeared as an invited paper in the Journal, Fatigue of Engineering Materials & Structures, Pergamon, Vol. 14, 1979, pp 474-484.

- (17) S.N. Atluri, M. Nakagaki and K. Kathiresan, "Hybrid Finite Element Analysis of Some Nonlinear and 3-D Problems of Engineering Fracture Mechanics", in Engineering Application of the Finite Element Method, Vol. 1, Det Norske Veritas, Norway, 1979, pp 14.1-14.32.

Also to appear in Journal of Computers and Structures, 1980.

- (18) S.N. Atluri, "Numerical Modeling of Crack Growth", Invited Contribution in Proceedings, 3rd ASCE, Engineering Mechanics Specialty Conference, Austin, Texas, September 16-19, 1979.

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- (20) A.S. Kobayashi, J.S. Cheng, S.N. Atluri, A.F. Emery and W.J. Love, "Elastic-Plastic Analyses of a Three-Point Bend Specimen and a Fracturing Pipe", invited contributions, U.S.-Japan Seminar and Elastic-Plastic Fracture, Hyama, Japan, November 1979.
- (21) T. Nishioka, R.B. Stonesifer and S.N. Atluri, "Translating Singularity Method of Analysis of Rapid Crack Growth", invited paper, 2nd International Conference on Numerical Methods in Fracture, Swansea, U.K. July 1980.
- (22) S.N. Atluri, Higher-order, Special and Singular Elements, Invited Paper, Chapter 4 in Finite Element Methods, published by ASME, NY (to appear) 1980.
- (23) T. Nishioka and S.N. Atluri, "Analysis of Cracks in Adhesively Bonded Metallic Laminates", prepared for presentation and publication at 22nd AIAA/ASME/ASCE/AHS SDM Conference, Atlanta, April 1981.
- (24) M. Nakagaki and S.N. Atluri, "Elastic-Plastic Analysis of Fatigue Crack-Closure in Modes I and II", AIAA Journal, Vol. 18, No. 9, pp 1110-1118, Sept. 1980.

PHASE A2

"Complementary Energy Approaches for Nonlinear Stability"

S. N. Atluri

Objectives:

The objectives of this phase of research were: (1) to develop appropriate complementary energy principles, involving the unsymmetric first Piola-Kirchhoff stress tensor and rotation tensor, for finite deformation of and stability analyses of beams, plates, and shells, (2) to develop the appropriate complementary energy density expressions for beams, plates, and shells in terms of first Piola-Kirchhoff stress resultants, and moment resultants, invoking plausible deformation hypotheses, and (3) to solve certain chosen cases of large-deformation and post-buckling of structural members.

Accomplishments:

Making a fundamental departure from the currently well-established beam, plate, and shell theories, new approaches have been developed for developing the beam, plate, and shell equations based on the a priori polar-decomposition of deformation into pure stretch and rigid rotation of material elements. The plausible approximations to the deformation gradient for these "thin" bodies are thus reduced to appropriate approximations for the stretch tensor and the rigid rotation tensor. Thus for instance, the originally 3-dimensional stretch tensor is reduced to a 2-dimensional one for the case of plates and shells, and the variation of this 2-dimensional stretch tensor is assumed appropriately as being linear or quadratic in the thickness direction. Moreover, the rotation tensor which, in general, may have a 3-dimensional variation, now becomes only a function of only mid-surface coordinates for plates

and shells. Likewise, the usual stress-resultants and stress-couples of the well-known plate and shell theories are now reduced and redefined in terms of the first Piola-Kirchhoff stress-resultants and stress-couples, or the Jaumann-type stress resultants and stress-couples.

Using the stretch tensor, rotation tensor, displacement vector, the first Piola-Kirchhoff stress-resultants and stress-couples as variables, a general variational principle of the Hu-Washizu type is developed. This general variational principle leads to a new set of plate and shell equations in terms of the forementioned variables. These new equations offer some fundamentally novel advantages for finite-deformation and buckling analysis of structures, over the currently popular ones.

Expressions for complementary energy density of plates and shells, in terms of first-Piola-Kirchhoff stress-resultants and stress-couples are newly developed. Using this, and satisfying the force equilibrium equations a priori, certain new and novel complementary energy principles for plates and shells are developed from the above mentioned general variational principle.

The above complementary energy principle was cast into an appropriate incremental form. By introducing the interelement stress-resultant reciprocity as an a posteriori constraint, a modified variational principle, from which a hybrid-finite element procedure can be developed, was generated.

The above procedures have been successfully tested in the cases of finite deformation and post-buckling of plates. These results do point to remarkable advantages of the presently developed procedures over the existing ones. This exciting line of new inquiry into plate and shell behavior is ongoing.

Papers, Reports and Presentations, Phase A2:

- (1) S.N. Atluri, "Complementary Rate Principles for Nonlinear Structural Analysis", Invited Contribution, International Conference on Theory Practice of Finite Elements, Chalmers Institute of Technology, Goteborg, Sweden, August 27-29, 1979.
- (2) S.N. Atluri, "Finite Strain Inelasticity. Complementary Energy, and Finite Elements: Some Recent Computational Studies", Invited Paper, U.S.-Europe Conference on Finite Elements in Nonlinear Structural Mechanics, Bochum, West Germany, July 1980.
- (3) S.N. Atluri, H. Murakawa and K.W. Reed. "Stability Analysis Via a New Complementary Energy Principle", presented at 2nd International Conference on Nonlinear Mechanics and Finite Elements, JIAFS and GWU Washington, DC, October 1980. (Also to appear in Journal of Computers & Structures, Pergamon).
- (4) H. Murakawa and S.N. Atluri, "Complementary Energy Analysis of Large Deformations and Post-Buckling of Plates" being prepared for presentation and publication at 22nd AIAA/ASME/ASCE/AHS SDM Conference, Atlanta, April 1981.
- (5) S.N. Atluri and H. Murakawa, "Studies in Hybrid Methods: Fluid Flow and Elastic Stability" Invited Paper, 17th SES Meeting, Atlanta, Georgia, December 1980.
- (6) S.N. Atluri and H. Murakawa, "Advances in Hybrid Methods in Non-linear Mechanics", International Symposium on Hybrid and Mixed Methods, Atlanta, Georgia, April 1981.

PHASE R1

"Static and Dynamic Behavior of Advanced Composite Structures"

L. W. Rehfield

Introductory Remarks

As the research work unfolded, two dominant areas emerged as the primary foci. The first, hygrothermal effects on resin matrix composite structures, is a continuation of work begun under a previous grant. The second, development of a new bending theory, is a serendipitous outgrowth of work related to the first. While the first task was dominantly experimental in nature, the latter is exclusively theoretical.

Objectives

Hygrothermal Effects on Dynamic Behavior. This research has three objectives. The first is to establish a data base to facilitate confident use of graphite/epoxy composites in dynamic applications. The second is to determine the extent to which viscoelastic factors influence dynamic behavior. This is reflected in the frequency dependence of response to time dependent excitation. The third objective is to determine the effects of moisture absorption and elevated temperature on dynamic behavior over a wide range of exciting frequencies.

These objectives have been accomplished by performing flexural vibration tests on graphite/epoxy beams. Dynamic behavior in the dry, room temperature state 25°C (77°F) is contrasted with the following four elevated temperature states:

- a. 82°C (180°F), dry
- b. 60°C (140°F), moisture saturated
- c. 82°C (180°F), moisture saturated
- d. 93°C (200°F), moisture saturated

New Bending Theory. Significant new theoretical developments emerged in the course of work done on hygrothermal effects. The original intent of the work was to study the influence of hygrothermal effects on the design of stiffness critical composite structures; vibration and buckling behavior were to be emphasized. It was discovered that there were some background theoretical problems that required treatment before the bulk of the study could proceed. This was a stroke of good fortune! It has lead to a significant breakthrough in engineering bending theory.

Hygrothermal effects in resin matrix/graphite composites manifest themselves by amplifying the importance of matrix controlled behavior modes. Transverse shear deformations, for example, play a greater role in the response to environmental loading. This effect was the first to be considered. The objective, therefore, was to lay the foundation for a bending theory which accounts appropriately for all the physical processes germane to the prediction of hygrothermal effects in resin matrix composites. The ultimate objective is a composite lamination theory.

Accomplishments

Hygrothermal Effects on Dynamic Behavior. This work has been directed toward determining the influence of moisture absorption and elevated temperature environments on the dynamic behavior of resin matrix composites in bending. An extensive series of beam vibration experiments have been performed. Specimens of four distinct ply layups have been tested at four different temperatures. The early experiments have produced nearly 2000 distinct data values over a two year period.

The specimens were manufactured by McDonnell Douglas Astronautics Company - St. Louis from Narmco 5208/T300 unidirectional tape. Four

distinct layup configurations have been tested as beams: $[0]$, $[+45]$, $[0, +45, 90, -45, 0, +45]_s$, and $[90]$. They are each 12 plies thick and symmetric. The layup configurations are denoted A, B, C and D, respectively.

Considerable attention must be given to test conditions and testing technique. Since environmental effects are to be determined, vibration testing in a vacuum chamber at room temperature --- the usual means of determining damping --- could be used only for the reference state. All other tests have been performed in an environmental chamber at the proper temperature. Moisture saturation is achieved by immersion in a constant-temperature water bath for an extended period. Moisture absorption is monitored by periodically weighing the specimens.

The beams have been tested in cantilever fashion. In the early tests, transient excitation was used in order to insure short testing time and thereby minimize drying out effects. A tip mounted accelerometer was used to sense response. Damping was determined by the logarithmic decrement method, while fundamental natural frequency was found approximately by counting the number of response peaks in a given time interval.

The contribution of aerodynamic damping to the damping measured in tests is of considerable practical importance. The usual approach is to test specimens in a vacuum chamber, thereby eliminating aerodynamics altogether. This approach was not used because near in situ hygro-thermal environmental tests were required. For small amplitudes, aerodynamic damping is proportional to amplitude. Therefore, tests have been conducted at several amplitudes. Damping vs. amplitude plots are constructed. Extrapolation to zero amplitude yields intrinsic material damping and aerodynamic damping. This technique is quite effective

and good estimates of the aerodynamic damping contributions to the results have been obtained. Material and air damping values are the proper magnitude and agree well with values published in the literature.

The other extraneous contribution to damping in the early tests is due to parasite effects associated with the accelerometer cable. The effects may be partially attributable to aerodynamics and partially due to mechanical deformation of the cable. Regardless of the cause, a reliable estimate of this contribution is desirable. Supplementary tests to determine the cable contribution were conducted. The results suggest that the cable damping is largely independent of amplitude. Therefore, simple adjustments to the data could be made.

Later, vibration experiments were performed which utilize electromagnetic noncontacting transducers and exciters. The primary purpose of these tests is to determine the influence of exciting frequency as well as environmental conditioning. The properties determined were an effective flexural modulus and damping for frequencies from 10-1000 Hertz.

In these tests, both excitation and response are created using electromagnetic noncontacting transducers. The tests are resonance tests. The natural frequency is varied by means of three approaches: mass addition, excitation of higher modes, and variation of unsupported beam length. This permits data in the 10-1000 Hertz range to be obtained. Small amplitude excitation is used exclusively in the elevated temperature tests to reduce aerodynamic damping effects to a minimum. Reliable aerodynamic damping estimates suggest that this influence is ignorable for the test conditions adopted. Damping is determined by suspending excitation and observing the decay of the response.

A and C specimens respond in a fiber controlled mode of behavior. Both environment and frequency have little effect on their stiffness. B and D specimens, however, exhibit matrix controlled behavior. Naturally, the response of these specimens is more sensitive to both environment and frequency; apparent stiffness decreases with the severity of the conditioning. Frequency effects on damping are small in all cases. Again, A and C specimen behavior is not greatly influenced by environmental conditioning. B specimen damping is affected by moisture, but very little by temperature. The damping of saturated D specimens increases sharply from 82°C to 93°C.

Overall, the damping results indicate that frequency effects are quite small in all cases. They are a bit greater for matrix controlled modes of response exhibited by the B and D specimens at the higher frequencies. At the same temperature, damping increases with moisture saturation. For dry specimens, however, by contrast, damping decreases with temperature.

This work provides an experimental data base for graphite/epoxy composites that describes the influence of moisture absorption, elevated temperature and frequency effects on dynamic behavior. The early work was cited as a major contribution to structural dynamics in 1978.* The data has been used by engineers at Rockwell International in connection with a vibration problem with a composite panel for the space shuttle.

Dynamic Behavior of Woven Composites. Composites manufactured from woven cloth prepreg are microscopically and macroscopically different from their counterparts manufactured from unidirectional tape. Woven

* Research on vibration of composite cited in "Highlights 1978-Structural Dynamics," Astronautics and Aeronautics, Vol. 16, No. 12, December 1978, pp. 85-86-, 97.

cloth composites can be manufactured at significantly lower cost for many applications. This is due to the greater fiber volume laid down per unit of time. It is of interest, therefore, to contrast the behavior of woven and unidirectional tape composites.

This task consisted of dynamic testing corresponding beam specimens of woven cloth and unidirectional tape and documenting the observed differences. Also, exploratory hygrothermal effect studies were planned, depending upon the outcome of dry, room temperature dynamic tests.

Room temperature tests were performed in a vacuum chamber on two types of woven graphite/epoxy beam specimens. Also, similar tests were performed on [0] and [45] beam specimens of the same material system but of unidirectional tape prepreg. The testing procedure used was identical to that used in the later hygrothermal tests conducted using non-contacting transducers. It was found that woven cloth and unidirectional tape composites behave in the same manner. The similarity in damping characteristics is a significant finding. It permitted testing to be terminated without having to consider hygrothermal environments.

New Bending Theory. The scope of this work is restricted to planar bending situations. In its' present form, the theory applies to beams with thin rectangular cross sections which respond to planar bending in plane stress or to infinitely wide plates which respond in plane strain (cylindrical bending). Both isotropic and orthotropic materials are considered. Beams of orthotropic material are the simplest type of structures where composite material behavior can be studied.

Shear deformation theory for homogeneous, isotropic beams originated in a paper by S. P. Timoshenko published in 1921. Since then, there have been some refinements and extensions to plates and shells, but no

conceptual differences. Our recent reassessment of this theory has shown that there are two additional effects that are the same order as transverse shear and that have never been consistently accounted for in any previous engineering bending theory. These effects are called nonclassical bending and transverse normal strain effects.

The above observations have led to the development of an engineering bending theory that accounts for the two effects mentioned above. A complete static theory for the bending of homogeneous, isotropic beams was developed first. Predictions using this theory agree exactly with elasticity solutions for several distributed loading cases. The theory has been extended in two directions. A first approximation dynamic theory has been formulated. Also, a corresponding theory for orthotropic beams, a logical step in the direction of a lamination theory for composites, has been defined.

An evaluation of the first approximation dynamic theory for homogeneous, isotropic beams has been completed. Extremely fine agreement with the elasticity theory solution for a rectangular slab has been obtained.

Consistent progress has been made in developing and applying the new bending theory. Emphasis on the application to beams has been given to simple static bending under uniform distributed loading and flexural vibrations. Both isotropic and orthotropic beams have been considered for the following four limiting cases of boundary restraint:

- (1) fully clamped
- (2) clamped-propped
- (3) simply supported
- (4) cantilever

Comparisons with Bernoulli-Euler and Timoshenko theories have been made.

A number of observations have been made:

- (1) natural frequencies and mode shapes predicted by the new theory are close to Timoshenko theory predictions;
- (2) bending moment values for fully clamped and clamped-propped beams depart significantly from Timoshenko theory predictions;
- (3) differences in predictions between our new theory and Timoshenko theory are more pronounced for orthotropic beams;
- (4) the additional factors accounted for in the new theory appear to be more significant for static applications.

One of the significant hygrothermal effects on resin matrix composites is the reduction in resin controlled stiffness properties. A preliminary assessment of the effect of hygrothermally induced transverse shear stiffness reduction has been made for unidirectionally laid up beams (which are orthotropic). Properties corresponding to three environmental conditions were used. Our findings suggest very significant changes in behavior at the higher moisture content levels.

The extension of the ideas behind the new bending theory to plates was explored. A new bending theory for isotropic plates has been developed. Several limited applications have been considered which facilitate comparisons with Reissner's plate equations. Thus far, findings have been analogous to those for the beam theory. This work is quite interesting and encouraging and has both fundamental and applied consequences.

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2. Rehfield, L. W., "Vibration Behavior of Advanced Resin Matrix Composites in Hygrothermal Environments," DOD/NASA Mechanics of Composites Review, Dayton, Ohio, October 31 - November 2, 1978.
3. Rehfield, L. W., and Briley, R. P., "A Comparison of Environmental Effects on Dynamic Behavior of Graphite/Epoxy Composites With Aluminum Alloy," ASME Paper 78-WA/Aero-10, presented at the ASME Winter Annual Meeting, San Francisco, December 10-15, 1978. See H6.
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6. Rehfield, L. W., and Murthy, P. L. N., "Toward a New Engineering Theory of Bending," AIAA Paper 80-0683-CP, Proceedings of the AIAA/ASME/ASCE/AHS 21st Structures, Structural Dynamics and Materials Conference, Seattle, WA, May 12-14, 1980.
7. Putter, S., Buchanan, D. L., and Rehfield, L. W., "Influence of Frequency and Environmental Conditions on Dynamic Behavior of Graphite/Epoxy Composites," DOD/NASA Mechanics of Composites Review, Dayton, Ohio, October 28-30, 1980.
8. Rehfield, L. W., Briley, R. P., and Putter, S., "Dynamic Tests of Graphite/Epoxy Composites in Hygrothermal Environments," ASTM Symposium on Composites for Extreme Environments, Bal Harbour, FL, November 11, 1980.
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PHASE R2

"Behavior of Advanced Composite Isogrid Structures"

L. W. Rehfield

Introductory Remarks

The search for efficient, light-weight aerospace structural concepts is a continuing process. One promising concept is isogrid. It is a simple discrete stiffening gridwork that employs a repetitive equilateral triangular pattern of ribs. The name "isogrid" is derived from the fact that the triangular grid exhibits isotropic properties in a gross or overall sense. The stiffening concept was developed by Dr. Robert R. Meyer of McDonnell Douglas Astronautics Company - Huntington Beach in 1964 under a NASA Contract.

Continuous filament composite isogrid (CFCI) is a type of construction developed by McDonnell Douglas Astronautics Company-St. Louis. The ribs of the grid are constructed of continuous unidirectional fibers by using a weaving process. It combines synergistically the efficiency of a stiffened structure with the superior properties of a composite material system in a manner consistent with automated manufacturing technology. Pioneering evaluation of this concept in stiffness critical applications was accomplished earlier. Flat panels were manufactured by McDonnell Douglas and tested under compression at Georgia Institute of Technology.

Work on the evaluation of isogrid structures continued under the present contract. Strength and stiffness information has been gathered from elements cut from the three original, large flat panels. Considerable progress toward understanding the behavior of isogrid structures has been made.

Objectives

For the full potential of CFCI to be realized, basic data must be acquired and evaluated in conjunction with current theoretical models and analysis methods. A data base has been established and an extensive correlation study has been performed.

Both strength and stiffness controlled behavior have been studied. Three large panels, designed and manufactured by McDonnell Douglas Astronautics Company - St. Louis, were tested previously as wide columns in uniaxial compression with fixed loaded ends. A variety of element tests, including assessment of fiber content, have been performed to determine a maximum of information from the three original panels.

The objectives of the investigation described herein are to

- 1) explore fundamental behavioral processes for this new type of structure;
- 2) create an experimental data base to inspire confidence in the use of this concept;
- 3) correlate experimental data with theoretical predictions; and
- 4) identify and define problem areas where the state-of-the art in design analysis and manufacture of CFCI must be advanced.

Accomplishments

An extensive element test program, including assessment of fiber content, has been completed. Compression and bending strength and stiffness data are presented that have been determined from elements cut from the original panels. This data permitted a comprehensive study to be performed which provides good correlation of theoretical predictions with the experimentally determined buckling loads. All issues are resolved and the degree of correlation is most satisfying. In addition,

interlaminar-type short beam shear tests and ex-situ tests of skin and grid ribs have been performed.

A wide variety of element types were prepared and tested extensively in bending, buckling, compression, and tension. Assessment of fiber content using chemical procedures was also carried out. A data base of strength and stiffness information is established which permits design with a measure of confidence.

Depending mainly on the manner in which the load is applied, the mechanical tests are grouped into the following five categories:

- 1) Element compressive tests
- 2) Bending tests - small panels and beam specimens
 - a. Three-point
 - b. Four-point
- 3) Compressive buckling tests - small panel and beam specimens
- 4) Ex-situ tensile tests - rib skin specimens
- 5) Short beam shear tests

The experimental data from all the tests was analyzed for consistency. The objective is to understand the observed behavior and correlate it with theoretical predictions whenever possible. An approximate scaling law based upon elementary physical reasoning is developed for relating the stiffness controlled behavior of beams to panels. Finally, the behavior of elements and panels has been predicted utilizing appropriate existing theories and the predictions compared with experimental results.

The experimental data obtained through this extensive, systematic research are self-consistent and show good agreement with theoretical predictions. The pronounced effect of transverse shear flexibility is

evident in the bend tests and in the correlation of buckling data. A scaling law is suggested which is useful in assessing buckling behavior of compressed CFCI structures. Manufacturing inconsistencies are clearly identified as the primary reason for the scatter in test data. Improvements in manufacturing technology must receive the highest priority if this structural concept is to be used in applications.

The element test data and results of the buckling correlation study are sufficient to establish a basis for design and utilization of continuous filament advanced composite isogrid. The most significant finding is the necessity of accounting for transverse shear flexibility in bending and buckling.

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