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Conference Reports

Summary of ASTM Symposium on Test Methods and Design Allowables for Fibrous Composites

A specialist symposium sponsored by ASTM Committee D-30 on High-Modulus Fibers and Their Composites was held in Dearborn, Mich., on 2-3 Oct. 1979. The objective of this symposium was to provide a forum for the discussion of new/special test methods and analysis, as well as test methods and procedures for selecting and setting design allowables in general, plus design allowables for special applications. Twenty-two papers of the 26 presented have been accepted for inclusion in the ASTM STP 734, scheduled for publication in summer 1981.

The papers in this symposium have been grouped into four major areas. The first area deals with new/special test methods. The second deals with special test methods and analysis. The third area covers procedures for establishing design allowables in general. The fourth area deals with design allowables and procedures for special applications. A summary of these topics follows below.

New/Special Test Methods

Research continues for improved test method to measure transverse and shear properties. A single-ply test method (short and very wide specimen, one ply thick) is described by R. Foye to measure the transverse strength of fiber composites. The main advantage of this test method is that moisture conditioning is accomplished expeditiously since the single ply is thin and thus only a short time is needed to reach saturation equilibrium. Use of this method however requires care and usually a finite element analysis to minimize possible tensile buckling.

A four-point load ring test method has been investigated by L. Greszczuk to measure the shear modulus of unidirectional composites. The test method is useful for determining shear moduli of cylindrical-type shell structures subjected to elevated and cryogenic temperatures. The equations required to extract the shear modulus from deflection measurements are based on the bending and torsion of the ring but do not include the through-the-thickness shear deformation. Use of the test for metals and for several composite systems yielded results which were in good agreement with available data from different test methods.

Three different test methods were evaluated by R. Clark and H. Lisagor for measuring compression properties of fiber composites. These methods included the Illinois Institute of Technology Research Institute (IITRI), the face-supported, and the end-loaded test piece. All of these methods were used to investigate the effects of specimen size, specimen end support, load introduction, and ply configuration. The results showed that the IITRI test method provided the most consistent stress-strain data to fracture for unidirectional and quasi-isotropic angleplied laminates while the face-supported test method was more suitable for $[\pm 45]_s$ angle-plied laminates. The results also showed that the IITRI compression test method is sensitive to specimen alignment and buckling when thin specimens are used and to specimen width when thicker specimens are used. The face-supported compression test is sensitive to delaminations and local instabilities.

Low velocity impact damage, due to tool dropping for example, is receiving considerable attention. A test method to determine the low velocity impact resistance of fiber composite structures is described by A. Sharma. The method consists of sandwich specimens with faces from three different angleplied laminates. Preload and impact energy combinations to cause catastrophic failure as well as residual strength after impact damage can be determined in both tension and compression. Results presented are for ($[\pm 45/0_4]_s$, $[\pm 45/90/0]_s$, $[90/\pm 45/0]_s$) from graphite fiber/epoxy matrix angle-plied laminates. The experimental data were used to determine a lower bound failure threshold for each of the laminate configurations studied in both tension and compression. The results show that both failure threshold and residual strength depend on laminate configuration and fiber/matrix.

Special Test Methods and Analysis

Fracture toughness testing for short-fiber-reinforced thermoplastics was investigated by J. Mandell and coauthors. Linear elastic fracture mechanics testing concepts were used. The results showed that the cracks propagated in a "fiber avoidance" path. The fracture toughness parameter depended on location and direction of the crack relative to the fiber direction and fiber length but not on the fracture toughness of the resin. This would imply that the fracture toughness may be related to fiber strength and therefore is not an independent parameter.

Comparison of predicted and measured off-axis and angle-plied fracture stresses in both tension and compression continues to receive attention. A major reason for the continuing interest is the difficulty associated with compression testing of thin specimens. R. Kim found that dog-bone-type specimens with side supports can be used to measure compressive strength. These same specimens without the side supports can also be used to measure tensile strength. Data presented in the paper show that these specimens fail in the test gage region. The data also are in good agreement with predictions using a tensor polynomial failure criterion. In addition, the predicted failure modes are consistent with fracture surface characteristics.

The fracture characteristics of quasi-isotropic graphite/epoxy panels with cracks and subjected to biaxial tensile loads were investigated by I. Daniel. The effect of crack length on fracture was also investigated. The strain intensity field in the crack tip vicinity was measured using strain gages, birefringent coatings, and moire grids. The results showed that the strain field near the crack tip becomes nonlinear at relatively low loads compared to failure loads. However, the crack opening displacement and the crack shearing (forward sliding) remain linear until the crack starts propagating. The biaxial stress field reduced the fracture load by about 21% compared to uniaxial load for all crack sizes considered. The experimental data for failure stress near the crack tip correlated with predicted values using a tensor polynomial failure criterion for the ply and a progressive degradation model for the laminate.

A comparative study was performed by C. Harakovich and his colleague using finite element analysis to assess the stress distribution in commonly used in-plane shear specimens. The specimens studied were slotted, cross beam, double V-notch, and the rail shear. The results showed that the cross beam, the rigid rail shear, and the rigid double V-notch specimen provide regions of uniform pure shear in the test section. Elastic supports and load introduction fixtures affect the stress distribution in the rail shear specimen. Stress concentrations are present in all four shear specimens. Slotted specimens are not recommended. Thermal stresses affect the stress distribution in the rigid rail shear specimen.

The four-point bending sandwich beam test method continues to receive attention. J. Shuart evaluated this method to assess its use for determining the compressive properties of graphite/polyamide composites at a wide range of temperatures, 117 to 589 K (-250 to 600°F). The evaluation included experimental and three-dimensional finite element analysis studies. The results showed that the four-point bending sandwich beam test method can be used to determine the compressive properties of graphite/polyimide composites in a wide range of temperatures. A uniform compression stress field exists in the top cover between the two load points. Fracture may initiate by cover debonding or at stress concentrations under the load points. The honeycomb core material, the laminate configuration and temperature affect the failure stress.

In a parallel analytical study using finite difference, H. Salamon found that the interlaminar stresses for a $[\pm 45]_s$ angle-plied laminate are confined to boundary regions near the free edges and extend about 1.3 times the face thickness. The in-plane stresses converge to the laminate theory solutions in the interior of the face. The analytical results also showed that the face/core interface stresses have negligible influence on the in-plane stresses in the faces. Therefore, both studies (Shuart's and Salamon's) indicate that the sandwich beam is a viable test method for measuring unidirectional composite and angleplied laminate properties.

Design Allowables

Developing generic test methods and procedures to establish design allowables in general is a difficult task since most of the effort is special-case directed. However, several investigators are tackling this difficult task and have had various degrees of success. Procedures for developing composite material static and fatigue design allowables were described by M. Rich. The design allowables are established at the ply level and account for a wide range of hygrothermal conditions. For different conditions, the corresponding allowables are established by interpolation and checked by selective testing. It is useful to represent the static design allowables for environmental effects as percentages of the average room temperature, dry condition data. Fatigue design allowables for environmental effects are represented by percentages of a constant life diagram of room temperature, wet static tensile strength. The tension-compression and compression-compression range effects are shown in the constant life fatigue diagram. Statistical evaluation of experimental data indicates normal distribution; therefore, relatively small sample sizes can be used to establish reliable design allowables. Investigators testing for composite design allowables in fatigue should be aware that proven test methods for metals are not directly applicable to composites. They should also be aware that the most economical level for establishing design allowables for composites is the ply level with selective testing at the laminate level. Additionally, compression fatigue appears to degrade composite integrity rapidly and is aggravated by hygrothermal environments.

Test procedures for obtaining design allowables for composite bolted joints are described by D. Wilson and coauthors. Specifically, they investigated the static strength bolted joints in Celion graphite-fiber/PMR-15 polyimide composites. Temperature effect (21 to 315°C), strain rate (0.002 and 1.00 s^{-1}), and creep were investigated. The results showed that laminate configuration, temperature, strain rate, and time at load affect the joint strength as well as the failure modes. All these factors lead to the unavoidable conclusion that composite joints need special design considerations in order to assure the cost-effective usage of composites in structures.

Cost-effective procedures for establishing design allowables for stiffness-controlled designs are described by J. Suarez. The procedure consists of conducting a small testing program of key property characterization and simulated component testing. The key properties are obtained using simple test methods. The simulated component is designed using these key properties. The simulated component is subjected to anticipated service life loading conditions to establish the margins between the simple test and the component structural behavior. The key properties from the simple tests and the margins established for the simulated component testing constitute the design allowables base for the types of structures represented by the simulated components. This approach for establishing design allowables has the advantage in reflecting fabrication and geometric scaling-up effects.

Research in statistical approaches to establish design allowables for composites static and fatigue strengths continues. L. Ten examined four distributions and the goodness of fit for six samples of composite static strength data. The distributions considered included the normal, log normal, two-parameter Weibull, and three-parameter Weibull. The goodness of fit was determined using the chi-square and Kolmogorov-Smirnov tests and the correlation coefficient from linear regression analysis. Results showed that all four distributions and the two goodness-of-fit tests can be used to establish A and B design allowables with approximately the same level of confidence.

G. Sendeckyj described a new procedure for fitting fatigue strength models. The procedure consists of a deterministic equation to define the shape of the *S-N* curve and a probabilistic description of the fatigue data scatter. The procedure is general; it will fit any fatigue model and will work with a minimum set of fatigue data. The procedure has two added advantages: (1) it may be used with only four not-censored fatigue data points for the wearout model, and (2) it can handle runouts and tab failures through progressive censoring.

The use of intraply hybrids to obtain balanced design properties to meet diverse and competing design requirements is receiving increased attention. Test methods for generating data to establish design allowables are described by C. Chamis and coauthors. The test methods are based on the use of thin laminates (about eight plies thick) and only one laminate to determine all the properties. Results presented are for tensile properties, intralaminar properties, flexural, short-beam-shear, and IZOD impact. Though not included in the paper, face-supported compression tests can be used to determine compression properties from the same thin laminates. Simple equations can be used in conjunction with normalization to assess the translation efficiency from constituent composites to the intraply hybrid. The translation efficiency serves also as an indirect means to assess the fabrication quality and the composite action of the intraply hybrid as well as any synergistic effects.

A major concern over the last few years has been the severity of compression fatigue on fiber composites and suitable test methods for establishing design allowables. The results of an extensive experimental investigation of compression-compression fatigue are reported by G. Grimes. Several laminate configurations and hygrothermal conditions were used in the investigations. A new face-supported test method was developed for compression-compression fatigue. The results showed that unidirectional longitudinal [0] specimens have compression fatigue runouts about 60% of their static strength (1.25×10^6 cycles) for room-temperature-dry (RTD) and room-temperature-wet (RTW). Unidirectional transverse [90] specimens have RTD compression fatigue runouts about 50% and RTW about 45% of their respective static strengths. The $[\pm 45]_s$ angle-plied laminates have runouts of about 50% and the $[(\pm 45)_5/0_{16}/90_4]_s$ angle-plied laminates about 80%. One encouraging implication from this investigation is that a viable compression fatigue test method may have been developed. Also, the so-called compression fatigue severe degradation may be more a shortcoming of the test method used rather than composite material weakness.

Design Allowables for Special Applications

Buckling of cylindrical shell components under combined loads generally presents difficulties in generating experimental data to verify theoretical predictions. C. Harakovich and coauthors subjected composite cylindrical shells to combined axial compression and torsional loads. They obtained good comparisons between experimental results and theoretical predictions using an available computer program based on Flugge's cylindrical shell buckling theory. The test data generated was obtained from cylindrical shells made from boron/epoxy and graphite/epoxy composites with symmetric and unsymmetric laminate configurations. The experimental data are presented in normalized interaction diagrams. These diagrams can be used to establish design allowables in conjunction with a reliable buckling theory. A conservative approach to this combined loading is a linear interaction curve connecting the "pure" axial compression buckling load with the "pure" torsional buckling load. The effect of possible initial imperfections on the axial buckling load may require proper attention if it is known that they are present.

The integrity of internal pressure vessels is usually established by proof pressure testing. T. Hahn describes a convenient procedure which can be used to determine the proof pressure to assure the design life of Kevlar 49/epoxy composite pressure vessels. The method is developed by assuming that the lifetime distribution is exponential. Also the characteristic lifetime of the pressure vessel is related exponentially to the applied pressure. Use of the method is illustrated by two typical examples.

The fatigue strength of composite bolted joints was investigated by R. Ramkremar using an experimental analytical program. Various portions of the applied load were transferred through the bolt to the composite which was made from quasi-isotropic AS/3501 graphite/epoxy. The specimens were tested at room temperature dry and 1.2% moisture conditions. Joint fatigue strength plotted versus local bearing stress provides a basis for establishing design allowables. The local bearing stress may be determined using two dimensional finite element analysis.

Environmental effects on composite fracture behavior are reported by T. Porter. The environmental conditions included room temperature dry, room temperature wet, and wet at 150°C (300°F). The laminates investigated included an "almost" quasi-isotropic laminate, a pressure-vessel–type laminate, and an engine fan blade interply hybrid. The defects included through holes and slits, half penetration holes and slits, and internal delaminations. The results showed that the environmental conditions degrade the strength of specimens without defects while these effects are minimal in composites with defects. Also preloading showed similar trends. A useful observation from these data is that composite structural components free of defects designed for environmental degradation effects would lead into conservative designs when defects are present or induced.

Creep rupture tests conducted by S. Hoa on sheet molding compound showed that the data scatter is reduced when these tests are conducted in liquid environments compared to those in air.

It appears that test methods and procedures for establishing design allowables will be developed and adopted through an evolutionary process. From the data available to date and apparent trends the following comments are reasonable and instructive.

1. Design data and allowables should be generated and set at the ply level using thin unidirectional laminates with suitable validation at the laminate level.
2. Available sets of design data and design allowables should be used only as a guide and in preliminary designs. Selective testing will still be required for the case under consideration.
3. Compression testing is difficult especially for compression-compression fatigue. The major difficulty centers on what is "true" material compression property and what is a shortcoming of the test specimen or method used. This difficulty will be resolved as more researchers obtain hands-on experience with compression testing and designers obtain field data feedback. The face-supported test appears to be the most attractive to date.
4. Fracture toughness testing at the laminate level should be done only to validate predicted response based on ply level properties.
5. Statistical methods for quantifying the goodness of fit of strength data provide a definitive approach for establishing A and B design allowables. Those which are based on deterministic models with probabilistic descriptions of key parameters and/or data scatter have the added advantage of requiring smaller sample size to obtain the same level of confidence.
6. Design allowables for bolted or adhesive joints should be examined and set, again, at the ply level accounting for the associated or participating failure modes. At this level, the joint can be designed to be cost-effective and also preserve the cost-effective use of the composite.
7. Analysis methods, and especially finite element analysis, provide a direct means of assessing whether the test results are those that were anticipated or, if not, what do these results represent. All tests are physical events representing load induced composite response. And considerable insight to composite behavior can be gained by proper analysis. One way to ascertain that the test method used provides the desired results is to establish benchmark type cases which have been validated by thorough analysis for these test methods.

The collective discussion of the papers in these proceedings and the summary provide considerable and timely information for test methods and for composite analysis of these methods, as well as tests and procedures for establishing design allowables. The collective test data in the proceedings provide a valuable source which can be used for preliminary design of composite structures including impact, fatigue, environmental effects, and joints. The collective data also provide a reasonable, reliable base for comparing the merits of new test methods and/or new composite systems relative to those already in use.

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Abstracts of ASTM Symposia

During the week of 9-14, Nov. 1980, ASTM held two symposia on composites at Bal Harbour, Fla. One symposium, "Composites for Extreme Environments," was sponsored by Committee D-30 on High-Modulus Fibers and Their Composites and chaired by Dr. N. R. Adsit. The other symposium, sponsored by Committees E-7 on Nondestructive Testing and E-9 on Fatigue, was titled "Damage in Composite Materials: Basic Mechanics, Accumulation, Tolerance, and Characterization," and cochaired by Dr. K. L. Reifsnider, Dr. L. Mordfin, and Dr. J. T. Fong. ASTM is planning to issue Special Technical Publications to summarize the papers presented. The technical abstracts of the symposia papers are included below.

Symposium on Composites for Extreme Environments

Thermophysical Properties Data on Graphite/Polyimide Composite Materials, M. D. Campbell and D. D. Burleigh

Measurements of the thermal properties of HTS/NR 150B2 and HTS/PMR 15 laminates were made over the temperature range 116 to 588 K. Properties investigated included thermal conductivity, thermal expansion, specific heat and emittance. Layups of [0] and $[0,45,90,135[_S$ were measured in two directions for both materials.

Both materials produced somewhat poorer quality laminates than generally achievable with lower temperature resins such as epoxies. This is typical of these systems at this time. It was expected that, for a given layup and direction, thermal properties would be comparable for the two materials. In general, this was the case with some differences attributable to laminate quality rather than differences in basic materials properties. However, higher expansion coefficients for the HTS/PMR 15 specimens in the resin-dominated directions indicate a higher coefficient for PMR 15 than NR 150B2. Erratic variations in thermal expansion results from the same specimen were observed at times. Although these were tentatively attributed to laminate quality, additional work is necessary to fully understand this behavior.

V378A Polyimide Resin—A New Composite Matrix for the 1980's, L. McKague

During 1979 General Dynamics conducted an extensive screening program to evaluate new graphite composite materials. One material has met the predetermined screening criteria for harsh aircraft environments (recurrent service to 177°C (350°F) following prolonged exposure to 75% mean relative humidity). This material is V378A, a modified bis maleimid resin developed by U.S. Polymeric. The screening criteria included processing requirements as well as environmental and mechanical requirements. These criteria and the V378A results are reviewed and compared with results for Narmco 5208 resin, a widely used epoxy resin. The comparison shows that V378A resin represents an important advancement in composite properties and processibility with which to begin the decade of the 1980's.

Thermomechanical Characterization of Graphite/Polyimide Composites, S. K. Douglass

Replacement of a structural metal with a high-performance composite may be limited by mechanical and physical property retention of the fibers and matrix resin at high temperatures. The stiffness, strength and shear properties of three polyimide resins (NR 150-B2, PMR 15 and CPI 2237) combined with three different moduli graphite fibers (C6000, F5A and GY 70) have been determined in the temperature range from 20 to 370°C (68 to 700°F). Results from flexural tests on the various unidirectional composites show the stiffness to be matrix dependent with temperature. No loss in modulus occurs up to 315°C (600°F) for the PMR 15 and CPI 2237 based composites ($T_g \simeq 710$°F) or to (500°F) for the NR 150-B2 based material ($T_g \simeq 660$°F), with any of the three fibers. In contrast both flexure and shear strengths show fiber dependent behavior with increasing temperature. The higher modulus fibers (F5A, GY 70), when combined with any of the resins, undergo little change up to 343°C (650°F). The strengths of all the lower modulus graphite composites (C6000), however, degrade appreciably, by as much as 50% over the same temperature range. Thermal-oxidative stability of the various graphite fibers, and its effect on interfacial strength degradation, are considered likely causes for the fiber-dominated strength behavior. The inherently low fracture and interlaminar shear strengths measured for all the polyimide resins containing the highest modulus fibers (F5A, GY 70) are attributed to typically extensive processing-induced porosity. Strength versus temperature trends generally reflect void content values of the composites which were obtained from both metallographic sectioning and chemical digestion techniques. The accumulated mechanical property data and their correlation to microstructural features for a family of graphite/polyimide composites, some heretofore unknown, provide a basis for selection of a high temperature, structural, weight-saving material.

Elastic Properties and Fracture Behavior of Graphite/Polyimide Composites at Extreme Temperatures, D. P. Garber, D. H. Morris, and R. A. Everett, Jr.

The influence of elevated and cryogenic temperatures on the elastic moduli and fracture strengths of several Celion 6000/PMR-15 laminates was measured. Tests were run at −157°C, 21°C (room temperature), and 316°C. Both unnotched and notched laminates were tested. Several failure criteria, developed to predict the uniaxial fracture strength of epoxy laminates, were used to predict the fracture strength of polyimide laminates.

Lamina elastic moduli were measured at each temperature by testing unnotched $[0]_8$, $[90]_8$, and $[\pm 45]_{2S}$ laminates. The measured values were used with classical laminate theory to predict the elastic constants in $[0/45/90/-45]_S$, $[0/45/90/-45]_{2S}$, $[45/0/-45/0]_S$, and $[45/90/-45/90]_S$ laminates. With few exceptions, the predictions agreed with the moduli measured experimentally. As for the ultimate tensile strength, whereas the 8-ply and 16-ply quasi-isotropic laminates were about equally strong at elevated temperature, their respective strengths diverged at the lower temperatures. The 8-ply laminates lost strength as the temperature decreased, whereas the 16-ply laminates became stronger. The differences were explained by considering curing stresses and free-edge interlaminar stresses.

The notched laminates had layups of $[\pm 45]_{2S}$, $[0/45/90/-45]_S$, and $[45/0/-45/0]_S$. Widths ranged from 1.9 cm to 10.2 cm, and hole-diameter-to-width ratios ranged from 0.016 to 0.25. The measured moduli, the ultimate strengths, and the point stress or average stress criterion of Nuismer and Whitney were combined to calculate the characteristic lengths associated with each criterion. Characteristic lengths were compared to determine the effect of temperature. For the $[0/45/90/-45]_S$ laminates, the characteristic lengths were the same at room temperature and elevated temperature. But they differed at cryogenic temperature. In $[\pm 45]_{2S}$ laminates, small holes increased the strength at all temperatures, and the criteria were judged unsuitable for predicting notch effects in such laminates.

Filament-Wound Composite Thermal and Insulator Structures for Cryogenic Dewars and Instruments, E. E. Morris

The low thermal conductivity and high strength of S-glass/epoxy filament wound composite material in many forms has been extensively characterized from 394 to 4 K.

Studies showing adequate fatigue strength capabilities in conjunction with low resin outgassing properties of S fiberglass with SCI REZ 080 and 081 epoxy resins *has* resulted in use of filament wound tension straps, struts, and conical shells as thermal isolators in several high performance cryogenic systems. Results of these studies will be presented, along with mechanical and thermophysical properties of the composite laminates.

In addition, the thermal isolator structures and their use in the following systems will be discussed: cryogenic hydrogen and oxygen Dewars for Space Shuttle, cryogenic helium tank supports for the Infra-Red Astronomy Satellite, and spacecraft cryogenic refrigerators.

For example, twelve S-glass filament wound/epoxy matrix straps are used to support the pressure vessel of the power reactant storage assembly (PRSA) tanks for the Space Shuttle Orbiter. The tanks provide storage of oxygen and hydrogen used to generate the orbiter's electrical power and make up oxygen for the crew compartment. Each tank is a Dewar consisting of two concentric spheres. The inner sphere, or pressure vessel, contains the stored fluid at cryogenic temperatures and supercritical pressures. The outer sphere allows maintenance of a high vacuum between the two spheres for thermal insulation. The filament-wound composite straps, supporting the pressure vessel from the outer shell, are located within the vacuum space between the two spheres. These straps are able to minimize heat conduction from outside the tank into the stored cryogen because of the inherent low conductivity of the glass/epoxy composite and the low cross-sectional area required to support the loaded pressure vessel. All the composite straps are preloaded to as high as 8800 N (2000 lbf) to prevent compression loading during space shuttle launch vibration and $\pm 5g$ constant acceleration loads. Total static supported weight is about 405 kg (900 lb) for the oxygen tank and 80 kg (180 lb) for the hydrogen tank.

Space Environmental Effects on Graphite/Epoxy Composites, C. L. Leung

In the space environment, the following factors combine to cause composite degradation—low pressure, temperature extremes, ultraviolet radiation, and ionizing and particulate radiation. The separate and combined effects of these variables were simulated in laboratory studies.

Using T300/934 graphite/epoxy composites, which form the composite skin of the Space Shuttle cargo bay doors, the following composite properties were investigated as a function of increasing γ-radiation exposure dosages: directional moisture absorption/desorption kinetics, matrix glass transition temperatures, interlaminar shear strength, and fatigue life. Irradiation conditions were these: open atmospheric and in vacuum, ambient and high temperatures (50°C).

In open atmospheric irradiation, a weight increase was observed for the samples, increasing as the total absorbed dosages increased. Directional diffusion coefficients were higher for the exposed samples than for the unexposed control samples. For the samples exposed to the highest total radiation dosage, interlaminar shear strength and fatigue life were decreased.

Effects of high temperature irradiation are still under investigation, and the results will be presented at the meeting. Degradation mechanisms due to radiation will also be discussed.

Effects of Extreme Aircraft Storage and Flight Environments on Graphite/Epoxy, P. Shyprykevich and W. Wolter

The ability of graphite/epoxy composites to absorb moisture from the environment and the consequent degradation of resin dependent strength properties is well understood under conditions of constant temperature and humidity. However, if the environment consists of high humidity exposure with intermittent high temperature excursions, anomalous diffusion behavior occurs accompanied by further reductions in strength. This paper reports the results obtained from a test program in which graphite/epoxy specimens were exposed to a tropical environment representative of extreme aircraft runway storage and 121°C (260°F) temperature excursions of long duration representative of a supersonic flight.

The tests were conducted in a specially developed apparatus which mechanically loaded specimens in chains of five specimens each while exposing the specimens to prescribed daily environmental conditions. Two 15-month real-time simulation test series were run one without load and one with flight loads. After various intervals of exposure, weight data was gathered using accompanying travelers and residual static tests were performed at room temperature and 121°C (260°F). The test results for the extreme environment are compared to test results obtained for specimens exposed to the same flight profile but temperate runway storage. The results indicate that the moisture gains of the extreme environment specimens are much greater than what is thought possible to be held by the resin and that the reduction in static compressive strength is greater than what can be expected just due to moisture content.

It is postulated that repeated thermal cycling, especially if it exceeds glass transition temperature, causes additional degradation of the material. An analytical transport model based on Fickian diffusion and hygrothermal history dependent material properties is developed to account for changes in diffusion and absorbtivity characteristics. The model provides reasonable correlation with test observations.

In addition, accelerated tests were performed to find economic alternatives to real-time exposure tests. In these tests, the specimens were either preconditioned to a specific moisture level with this level maintained during fatigue testing or the fatigue testing was concurrent with environmental conditioning. The results of the accelerated testing indicate that it is difficult to duplicate the extreme environment real-time tests because of the dynamic conditions created by thermal cycling.

Environmental Exposure of Carbon/Epoxy Composite Material Systems, R. C. Givler

Research reported herein focuses upon the effect of potentially adverse environmental conditions on composite material systems. Interest in the cyclic thermal residual stresses of hybrid composite material systems has prompted this investigation to determine the effect upon mechanical properties. Hybrid glass-carbon/epoxy laminates were thermally cycled between −54 and 177°C (−65 and +350°F) to investigate residual composite property response to compressive and flexural loadings. Also, it will be of interest to determine the effect of this thermal fatigue loading on material degradation in the form of cracks or interlaminar disbonds. The proposed laminate configuration was a 32-ply glass/epoxy (120 weave/3501-6), carbon/epoxy (AS/3501-6) system with the following stacking sequence:

$$[0_{GL5}/0/45/-45/0/45/90/-45/0/45/-45/0]_s$$

The surface plies of glass would serve in application as an inert layer between the carbon core and a bonded aluminum substrate.

Samples of the proposed laminate were exposed to 1, 10, 100, and 1000 cycles to yield an extended spectrum of thermal fatigue with one-half cycle (cure cycle) serving as control. It was felt that one complete thermal cycle of approximately 37 min was sufficiently long enough to insure against thermal shock of the laminate. The thermal cycling unit itself was completely automated utilizing a well-suited control system and the basis of the system was to transport the samples from an elevated temperature (177°C or 350°F) chamber to a second chamber maintained at −54°C (−65°F). The lower end of the temperature cycle was achieved by exposing the specimens to a gaseous, liquid nitrogen environment. Subsequent to the desired number of cycles, the laminates were statically loaded in compression to failure via the IITRI compression method. The flexural responses of the cycled laminates were recorded by loading the laminate in three-point bending. Flexural testing was completed at an elevated temperature of 177°C (350°F).

It was found that thermal cycling of the

$$[0_{GL5}/0/45/-45/0/45/90/-45/0/45/-45/0]_s$$

laminate produced cracks in the 90° and adjacent ±45° lamina. Laminate analysis verified that indeed the thermal stresses induced by thermal cycling exceeded the intrinsic strength of the 90° lamina. An average of eight cracks per 25 mm (1 in.) were observed in the uncycled (control) samples due to curing alone. This result should be referenced to crack densities of 65 cracks per 25 mm (1 in.) reported in samples subjected to 1000 cycles. It was expected that the interface between the glass and carbon plies might be a site for delamination due to the gross mismatch of corresponding coefficients of thermal expansion. This, however, was not the case as no glass/epoxy, carbon/epoxy disbonds were observed subsequent to thermal cycling.

Compressive strength, measured at 21°C (70°F), revealed no significant change after 1000 thermal cycles; thus it appears thermal cycling has no effect upon uniaxial compressive strengths for the laminate investigated.

Flexural strength, measured at 177°C (350°F), increased 29% after 1000 thermal cycles and a conservative argument would state that flexural strength experienced no degradation due to thermal cycling.

Dynamic Tests of Graphite/Epoxy Composites in Hygrothermal Environments, L. W. Rehfield, R. P. Briley, and S. Putter

Epoxy resins used as matrix materials in structural composites experience degradation of mechanical properties due to moisture absorption and elevated temperature environments. Considerable effort has been devoted to documenting the extent of the degradation for simple layup configurations and states of stress, for several popular material systems and for static and fatigue loadings. The present work, by contrast, is concerned with dynamic behavior. The objective is to establish a data base to facilitate the use of graphite/epoxy composites in hostile, hygrothermal environments.

This objective has been accomplished by performing flexural vibration tests on graphite/epoxy beams. Dynamic behavior in the dry, room temperature state is contrasted with three elevated temperature, moisture saturated states. The properties determined are fundamental natural frequency and damping. The former can be directly related to an effective dynamic modulus in flexure. These properties reflect the consequences of plasticization of the epoxy matrix material.

The specimens were manufactured by McDonnell-Douglas Astronautics Co., 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 twelve plies thick and symmetric.

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—cannot be used. Damping contributions resulting from air and instrumentation wiring had to be evaluated in supplementary tests in order to correct the experimental data obtained in the hot, moist environments.

The experimental results, after correction for the parasitic damping contributions, are consistent with known behavioral trends. One surprise emerged, however. The glass transition temperature is between 82 and 93°C for the specimens. This is lower than values normally used in the aerospace industry.

Influence of Quality Control Variables on Failure of Graphite/Epoxy Under Extreme Moisture Conditions, L. L. Clements and P. R. Lee

Usage of composite materials in commercial aircraft primary structure is hindered by the absence of convincingly reliable techniques for predicting composite durability under actual service conditions. Development of such techniques is complicated by the fact that significant changes in composite durability can occur not only at extreme temperatures but also at moderate temperatures due to extreme moisture exposure. This problem is being addressed at NASA-Ames Research Center in a program investigating the mechanisms of deformation, strength degradation, and failure of graphite/epoxy composites. The portion of that work to be reported here was designed first of all to determine the influence of extreme moisture exposure at moderate temperatures upon the mechanical properties and failure of $(0°)_8$ Thornel 300/NARMCO 5208 graphite/epoxy specimens. Earlier work done at Ames and elsewhere on this problem, however, has produced either conflicting or surprising moisture effect data. Thus, also included in this study was an assessment of the influence of various quality control variables—specifically, material (preimpregnated) quality, cure conditions, and pre-existing flaws—upon the effect of moisture on properties.

Since earlier Ames work had indicated that the total absence of moisture has a deleterious effect upon longitudinal strength, the moisture extremes of the current study included both fully saturated and completely dry conditions. Specimens were equilibrated at the desired uniform moisture content, and then were tested in an environmental chamber at the appropriate temperature and humidity. Specimens were tested to tensile failure at constant elongation rate, and both axial and transverse stress-strain properties were determined. The failure surfaces were examined using the scanning electron microscope in an attempt to relate the appearance of the failed surfaces to the mechanical properties as a function of moisture exposure.

The presentation will cover the results of the moisture effect study including the results of the scanning electron microscopy studies. Perhaps the most significant finding, however, is that while the extremes of moisture exposure were found to distinctly influence failure properties of the material, the magnitude and, in some cases, even the direction of the influence was altered by specimen quality as related to pre-existing flaws. Other factors such as cure conditions and material quality had a much lesser influence. This finding is particularly important to environmental studies in that the flaws need not be obvious or easily detectable to completely alter the influence of moisture on properties. For example, specimens cut with a Carborundum® cutoff wheel were examined for defects visually and by X-ray radiography. Nevertheless, when specimens with no detectable flaws were tested, the properties as a function of moisture exposure were found to statistically coincide with those obtained from specimens having visible flaws. However, when the edges of saw-cut specimens were finished by wet grinding, their mechanical properties were vastly different from those of the other two sets of specimens—moisture effects were altered, mean strength was increased by as much as 20%, data scatter was greatly reduced, and so forth. These results have two important implications. First, specimen preparation technique is extremely important to such studies. The technique of finish grinding recommended in ASTM Test for Tensile Properties of Fiber-Resin Composites (D 3039) is not overly stringent. Second, flaw sensitivity should be an integral part of any moisture effects study aimed at predictions for actual service exposure. Since flaws cannot always be avoided, their influence must be determined and understood.

Symposium on Damage in Composite Materials: Basic Mechanics, Accumulation, Tolerance, and Characterization

Damage Documentation in Composites by Stereo Radiography, G. P. Sendeckyj, G. E. Maddux, and E. Porter

With the increased application of composite materials in aerospace structures, the need for detailed understanding of the failure modes and associated damage accumulation process in composites has become apparent. Since the necessary information can be obtained only through the use of nondestructive inspection (NDI) methods, a large number of NDI methods have been tried. Unfortunately, the complexity and small scale of the damage (consisting of matrix cracks, delaminations, and fiber fractures) have taxed the resolution capabilities of conventional NDI methods. Out of the many new techniques being applied in studies of damage growth in composite materials, penetrant enhanced X-ray radiography has proved to be the most successful. While conventional penetrant enhanced X-ray radiography has the required resolution to find individual matrix cracks, delaminations and fiber fractures, it does not have the spatial resolution to provide depthwise location of the damage. To overcome this difficulty, we have adopted an old medical X-ray technique. In this technique, called stereo X-ray radiography, a pair of X-ray images from different viewing angles are made of the damage. When viewed through a stereo viewer, a three-dimension image of the damage is obtained providing the necessary depth resolution. We have used this technique to successfully document the spatial distribution of damage in composites. The paper will present an overview of the stereo X-ray radiography and the results of a study of damage accumulation in notched quasi-isotropic graphite/epoxy laminates.

Fractographic Studies of Graphite/Epoxy Fatigue Specimens, G. E. Morris

Techniques have been developed for determining fracture directions and locating fracture origins for graphite/epoxy laminates that fail by overload. These techniques have used the scanning electron microscope (SEM) to identify failed epoxy component topographic features (hackles) that characterize overload failures of graphite/epoxy composites. This hackle interpretation technique is now being successfully used to trace hackles back to fracture origin locations on the fracture surfaces of tensile-failed graphite/epoxy test pieces and structures.

Recently, these SEM studies have been expanded to include fatigue tested cross-plied graphite/epoxy specimens. Patterns of arrest marks (striations) have been associated with tension-compression fatigue crack propagation for some graphite/epoxy test specimens. The striation features are distinctly different in appearance from hackles and therefore present a promising, topographic feature to differentiate tension-compression fractures from overload fractures in graphite/epoxy composites. Visual, nondestructive testing, and scanning electron microscopic techniques that were used to identify the striation topographic features are described. Progress to date is presented on attempts to correlate observed striation patterns with fatigue damage growth in graphite/epoxy test specimens.

The results of preliminary attempts to produce crack growth curves for tension-compression failed specimens are presented. Finally, photographic documentation of fatigue striation morphology variations resulting from different stress ratios are presented.

Investigation of Cumulative Damage Development in Graphite/Epoxy Laminates, J. E. Masters and K. L. Reifsnider

The objective of this paper is to present experimental and analytical results of a study of damage development in two quasi-isotropic graphite/epoxy laminates subjected to quasi-static tension and tension-tension fatigue. We used unnotched AS/3501-5 laminates and stacking sequences of $[0/90/+45/-45]_s$ and $[0/+45/-45/90]_s$. Damage development in the form of transverse cracking in all off-axis lamina, longitudinal cracking and delamination was monitored throughout the tests. Results of the study include detailed description of the chronology of events leading to failure of the two specimen types. Evidence is also presented in support of a damage model based on the concept of a characteristic damage state. This model indicates that, with increased loading, transverse cracks develop in all off-axis lamina until a uniform crack spacing is attained. Once this saturation crack spacing is achieved, no new transverse cracks appear until final fracture. The spacing of the cracks is determined by the constraint of the plies on either side of the cracked ply and by the properties of all the plies. This characteristic damage, which determines the state of stress from which the final fracture develops, is independent of load history and is characteristic of the laminate alone. Experimental results are presented in the context of this philosophy.

Effects of Moisture, Residual Thermal Curing Stresses, and Mechanical Load on Damage Development in Quasi-Isotropic Laminates,
R. D. Kriz and W. W. Stinchcomb

This investigation examines the effect of moisture, residual thermal curing stresses and mechanical load on damage development in quasi-isotropic laminates. In particular, the investigation is concerned with demonstrating how the maximum moisture absorbed in $[0/\pm45/90]_s$ and $[0/90/\pm45]_s$ laminates, fabricated from T300/5208 graphite/epoxy, significantly alters the dry initial stress state and the chronology of damage development along the laminate edge during static tension and tension-tension cyclic loading.

Classical laminate theory and a finite element model (FEM) are used to predict stress states prior to the first formation of damage. Emphasis is placed on using reasonable and consistent values for wet, dry, and out-of-plane (ν_{23}, G_{23}) elastic properties since these properties are required to predict the damage-free stress state at the laminate edge. Crack patterns characteristic of the laminate in a wet or dry condition are also predicted using a shear lag model. Development of edge damage during mechanical loading was recorded using an established replicating technique which transfers an image of edge damage onto a thin acetate sheet. Replicas taken during the test can be immediately viewed on a standard microfiche card reader which allows the investigator to interpret the edge damage and interact with the test.

Moisture significantly alters the dry edge stress state in the $[0/\pm45/90]_s$ laminate such that the sequence of damage events are altered. Due to swelling and a reduction of elastic properties, moisture alters the edge stress state such that delaminations in the 90° plies occur at a lower laminate load and transverse 90° ply cracks occur at a higher laminate load than in dry laminates. Using the replica technique the first occurrence of a transverse crack in a wet 90° ply was observed within the laminate load interval of 192 to 210 N/m (1100 to 1200 lbf/in.) and for the dry case an 87 to 105 N/m (500 to 600 lbf/in.) laminate load was observed. The laminate load required to cause delaminations was observed to decrease from 315 to 350 N/m (1800 to 2000 lbf/in.) for the dry case to 192 to 210 N/m (1100 to 1200 lbf/in.) for the wet case. As a result of moisture absorption, transverse cracks and delaminations were observed to occur simultaneously at 192 to 210 N/m (1100 to 1200 lbf/in.)

Stacking sequence can also significantly affect the laminate loads required to cause transverse cracking in wet or dry 90° plies. The difference between laminate loads required to initiate transverse cracks in $[0/\pm45/90]_s$ and $[0/90/\pm45]_s$ laminates was found to be larger for the wet conditioned specimens. A model was developed which predicted these differences. The model demonstrates that differences in the laminate loads required to initiate damage are accounted for by the predictable changes in the FEM calculated values of σ_x and σ_z in the 90° ply as the result of changes in stacking sequence.

Although moisture content affects the load at which damage initiates in graphite epoxy laminates, the complete damage state which develops from static and cyclic loads prior to fracture is a characteristic of the laminate stacking sequence and is not a function of loading history (monotonic or cyclic loads) and environmental conditioning (wet or dry). For the laminates and conditions examined in this investigation, the experimental data show that the tensile strength of monotonically loaded specimens and the residual tensile strength of cyclically loaded, fully damaged, specimens are dependent on stacking sequence and are independent of the hygro-mechanical history of specimens with the same stacking sequence. The results suggest that strength of a composite laminate is not influenced by the details of individual damage events but rather is dependent on the collective form of the various damage details as described by the concept of a damage state which is a laminate property and how the damage state affects the strength state of a laminate.

Mechanisms of Fatigue Damage in Boron/Aluminum Composites,
W. S. Johnson and G. J. Dvorak

In recent years, fatigue damage and failure of metal-matrix fibrous composites have been extensively studied. Most investigations were experimental, concerned with determination of *S-N* data, that is, number of cycles to failure at a specific level of constant-amplitude loading. This type of testing indicated only the number of cycles that a composite laminate could sustain for a given applied load level; it did not indicate the amount of degradation of the physical response of the composite due to internal fatigue damage nor give much insight into the complex fatigue damage mechanisms that exist in these materials.

The objective of this paper is to examine the fatigue damage mechanisms of continuous fiber-reinforced metal matrix composites through a series of fatigue tests on various laminates of annealed boron/6061 aluminum. The mechanical stress-strain response of each specimen was recorded at various intervals during the cyclic life in order to determine the changes in various mechanical properties caused by fatigue. Each specimen was inspected with a C-scan ultrasonic nondestructive testing technique to screen those specimens with detectable defects so that only the better quality laminate specimens would be evaluated. After failure the specimens would be evaluated. After failure the specimens were studied microscopically to define and document the fatigue damage.

The results suggest the existence of three distinct types of response of metal-matrix composite laminates to cyclic loading, as follows. First, at relative low load levels the unloading elastic modulus does not change, indicating that the matrix is not damaged.

The load level below which no detectable damage occurs has been found to be approximately equal to the shakedown limit for laminates with 0° outer plies. The shakedown limit is the maximum laminate stress for which the matrix will undergo only elastic deformation after an initial period of cyclic strain hardening. An analytical model for estimating the shakedown limit is presented.

Second, at moderate and high load levels, the unloading elastic modulus decreases, indicating damage development. The decrease in elastic modulus can be attributed to the growth of long fatigue cracks in the matrix, parallel to the fibers in the off-axis plies. At certain load levels the internal damage in a laminate containing 0° plies can stabilize, and the specimen then survives more than 2×10^6 cycles of load. The stabilized damage level is referred to as a saturation damage state. It is shown to depend on the laminate constituents, layup, and loading history. A simple model is presented which quantitatively describes the saturation damage state mechanisms. For laminates with 90° outer plies, the rate of damage accumulation has been found to be more rapid and commence at lower stress levels than for an identical laminate with 0° outer plies. The third type of response is final failure of the specimen. This is caused by a sudden fiber failure, and is localized to the immediate vicinity of the fracture surface. The conditions under which the 0° fibers fracture result from a combination of the fatigue damage accumulated in the matrix and the overall laminate load.

Stiffness-Reduction Mechanisms in Composite Laminates, A. Highsmith and K. L. Reifsnider

It is now widely recognized that stiffness changes during the service loading of composite laminates can be significantly large, especially as those changes affect deflections, dimensional changes, vibration characteristics, and load or stress distributions. While most laboratories now report stiffness changes, very little systematic philosophy has been developed to account for and explain such stiffness changes. In particular, models which predict stiffness changes based on the mechanisms which cause those changes are very difficult to find. In most cases they appear to be unavailable. This paper presents a systematic study of off-axis lamina cracking and describes several models of the behavior which deal with the influence of cracking on stiffness change at several levels of sophistication and accuracy.

Three principal generic sources of stiffness change can be identified, in various degrees, in fibrous composite materials. The source which occurs quite early in the life of a specimen or component is matrix cracking, the subject of this paper. Delamination and fiber fracture, the other two sources, will be dealt with in subsequent papers. For laminated composite materials the matrix cracking occurs preferentially in the laminate plies that are "off-axis," that is, those which have fibers oriented at some angle to the principal load direction. The stiffness changes due to this type of cracking are a function of the materials involved, the ply orientations, the stacking sequence and the applied loads or load history. Moreover, since stiffness is a tensor, it is important to notice that stiffness changes will, in general, be different in different directions and changes in a longitudinal stiffness are independent of those in a shear stiffness, or Poissons' ratio, for example.

The complexity of this situation requires systematic study, and motivates the search for a model, or models, which can describe the behavior and predict unfamiliar response. The present paper reports the results of an experimental program and an analytical modeling exercise which indicates that much of the observed matrix cracking can be predicted and the effects on stiffness calculated with various degrees of accuracy depending upon the sophistication of the model used. The analysis spans the range between three-dimensional finite difference representations to one-dimensional treatments. The limitations of each approach are described and the correlation with experimental data delineated. A preliminary discussion of the manner in which matrix cracking leads to other types of damage is included.

The Dependence of Transverse Cracking and Delamination on Ply Thickness in Graphite/Epoxy Laminates, F. W. Crossman and A. S. D. Wang

Two major types of damage that are frequently observed in polymer fiber composites involve matrix-dominated cracks. The first type of damage consists of multiple transverse cracks which occur primarily in plies whose fibers are oriented transverse to the applied load. The second type of damage is in the form on interply delamination usually found near the free-edge of the laminate. The initiation of these cracks and their growth cause great concern because they may, in some cases, lead to catastrophic laminate failure. In most other cases they induce long-term laminate property-degradation. Both are detrimental to the structural reliability and durability of the laminates.

Delamination cracking has been associated with out-of-plane normal and shear stresses which exist near the free edges of composite laminates. Finite element modeling has been employed to determine the gradient of these free edge stresses due to mechanical, thermal and hygroscopic loading. In many cases the location of the observed delamination is successfully predicted where the peak out-of-plane normal stress is calculated to exceed the transverse tensile strength of the composite. However, in other cases, especially those involving hygrothermal loading, delamination is not observed in locations near the free edge where the calculated normal stress is several times the transverse strength of the material.

Other studies conducted in the United States and in Great Britain have shown that the strain at which the onset of transverse cracking and delamination cracking is observed is dependent upon the thickness of the individual laminae. This thickness or size effect on fracture initiation cannot be predicted from stress analysis alone. Two approaches have been taken to account for these results—Weibull statistics and fracture mechanics.

This paper describes a series of experiments conducted on $[+25/-25/90_n]_s$, where $n = 1/2,1,2,3,4$, and $[+25_2/-25_2/90_2]_s$ T300/934 graphite/epoxy laminates which were examined by DIB enhanced X-radiography following progressively larger increments of tensile loading. The applied strain required to initiate transverse cracking was found to be dependent on the thickness of the 90° layer. The onset of delamination occurred before or after transverse cracking, depending on the laminate construction. Higher densities of transverse cracks were associated with regions containing delaminations. In some laminate constructions, the location of specimen separation during final fracture was associated with the growth and coalescence of edge delaminations from both sides of the specimen.

The onset and sequence of transverse cracking and delamination documented by the X-radiographs correlates closely with predictions based on the application of linear elastic fracture mechanics and finite element calculations of the strain energy release rate for both fracture processes.

Characterization of Delamination Onset and Growth in a Composite Laminate, T. K. O'Brien

The onset and growth of delaminations in unnotched laminates is described quantitatively. Graphite/epoxy $[\pm 30/\pm 30/90/90]_s$ laminates, designed to delaminate at the edge under tensile loads, were tested and analyzed. Delamination growth and stiffness loss were monitored nondestructively. Laminate stiffness decreased linearly with delamination size. The strain energy release rate G, associated with delamination growth, was determined from experimental data and analysis. A critical G was determined and then was used to predict the onset of delaminations in $[+45_n/-45_n/0_n/90_n]_s$ ($n = 1,2,3$) laminates. A delamination resistance curve (R-curve) was developed to characterize the observed stable delamination growth under quasi-static loading. A power law correlation between G and delamination growth rates in fatigue was established.

Characterizing Delamination Growth in Graphite/Epoxy, D. J. Wilkins, J. R. Eisenmann, and R. A. Camin

As part of an overall effort to develop durability and damage tolerance methods for graphite/epoxy composites, test specimens have been developed to measure the fundamental static fracture and growth behavior of delaminations. Two basic designs, one for the tensile opening mode (Mode I) and one for the forward shear mode (Mode II), are described.

The specimens have been utilized to characterize the behavior of two types of interfaces: the interface between two 0° plies, and the interface between a 0° ply and a 90° ply. These two interfaces represent limiting cases for "nesting" of fibers between plies.

Specimen design, test procedures, and results to date for static fracture, constant amplitude fatigue, and spectrum fatigue will be reported.

Compression Fatigue Behavior of Composites in the Presence of Interlaminar Delaminations, R. L. Ramkumar

The complex behavior of fiber-reinforced composites is a result of their inherent heterogeneity that presents many planes of weakness where local failures initiate and grow until structural failure occurs. The interface between adjacent layers in a laminate presents one such plane of weakness where an interlaminar delamination can initiate and grow. There are many processing, handling and operating conditions under which an interlaminar delamination can occur. In most of these cases the delamination is generally present within the laminate invisible to the naked eye on inspection. A low velocity impact of a blunt body on a laminated structure, for example, causes such a damage at low impact energy levels. If the structural component containing the delamination were to be an upper wing skin of an aircraft and is subjected to compressive loads during service, the residual strength and the service life of the component could be severely affected. An experimental program, reported in this paper, studied the effect of compression fatigue loads on laminated coupons containing interlaminar delaminations.

The test program examined three stacking sequences of a 64-ply, quasi-isotropic T300/5208 graphite/epoxy laminate. Test coupons obtained from the fabricated panels were tested under static compression and compression fatigue loads. Some coupons were fabricated with no flaws in them, some had imbedded delaminations across the entire width, and the remaining specimens had circular delaminations buried within the layup near the surface ply. Delaminations were introduced in one of two locations during fabrication through the use of nonadherent Teflon® material. Unflawed specimens provided baseline data used in estimating strength loss due to the presence of delaminations. Specimens with delaminations across the entire width exhibited a one-dimensional growth of the flaw within the interfacial region on compression loading. Buried circular delaminations, on the other hand, exhibited a two-dimensional growth of the flaw when compressive loads were applied. Also, the growth of the flaw was catastrophic in static compression and stable until failure under constant amplitude compression fatigue loads.

During testing the specimens were unsupported laterally to permit the large transverse deflections of the delaminated region. To preclude the possibility of gross specimen buckling between tabs thick laminates were used. The growth of the imbedded flaws was monitored during testing to relate the flaw growth rate to the amplitude of the loading. A radiographic technique employing a microfocus X-ray source, a dye penetrant (DIB) and Polaroid film was used to monitor the growth of the delamination during compression fatigue. The S-N and residual strength data were obtained and analyzed in conjunction with the flaw growth records to assess the relative criticality of the different flaw and loading situations.

Effect of Stacking Sequence of Delamination Propagation in Composite Laminates, M. M. Ratwani and H. P. Kan

Fatigue of composites has attracted considerable interest in recent years. Works of various investigators have shown that there is significant life reduction for both tension-compression and compression-compression fatigue loading when compared to tension-tension loading. These results have shown that compression fatigue loading is an important design parameter and should be investigated. Composites exhibit progressive delaminations under fatigue loads. The extent of delamination depends on the applied loads, fiber orientation, stacking sequence, and so forth.

In the present studies, delamination propagation under constant amplitude tension-compression and compression-compression loading and compression dominated blocked spectrum loading has been investigated.

Sixteen ply laminates with four different stacking sequences were selected for static and fatigue tests. All laminates have the same percentage of 0, 90 and ±45 degree plies. The stacking sequences selected were these:

1. Laminate 1, $(0/\pm 45/90/0_2/\pm 45)_s$
2. Laminate 2, $(90/\pm 45/0_3/\pm 45)_s$
3. Laminate 3, $(90/0/\pm 45/0_2/\pm 45)_s$
4. Laminate 4, $(\pm 45/0/90/0_2/\pm 45)_s$

Constant amplitude fatigue tests were performed at R (minimum to maximum stress ratio) $= -1.0$ and $-\infty$. The specimens of the laminates were periodically taken out of the testing machine and subjected to nondestructive inspection, X-ray radiography with diiodobutane was used for nondestructive inspection. The direction of damage propagation and extent of damage was determined three to four times in the lifetime of specimens tested.

The results of nondestructive inspection indicate the direction of delamination propagation to depend on the stacking sequence in the composite laminate. The delaminations may propagate predominantly along the loading direction or in a direction at some angle to the loading direction, depending on the stacking sequence. The results of nondestructive inspection on specimens, tested under spectrum loading, show the damage to be significantly different from that in specimens tested under constant amplitude loading.

Interlaminar stress analysis of four laminates has been performed to correlate the direction of delamination propagation with the nature of interlaminar stresses. It is found that the direction of delamination propagation depends on whether interlaminar normal tensile stresses or shear stresses are predominant.

Damage Mechanism and Fatigue Life Prediction of Graphite/Epoxy Composites, R. Badaliance

This paper describes observation of fatigue damage mechanism in composites, formulation of a damage indicating parameter and correlation of spectrum life prediction with experimental data.

Tetrabromoethane (TBE) enhanced X-ray radiography was used to facilitate observation of fatigue damage progression in graphite/epoxy laminates. The damage progression sequence begins with matrix cracking at the fiber-matrix interface within a ply at fiber discontinuities. Ply delaminations occur in areas which have accumulated extensive matrix cracking. Delaminations and interlaminar matrix cracking interact to produce eventual fatigue failure.

While initial cracking and fiber/matrix disbonding occur very early regardless of lay-up or stacking sequence, the time required to initiate delamination is controlled by interlaminar stresses which are heavily dependent upon lay-up and stacking sequence. For the same lay-up, a stacking sequence that produces high interlaminar stresses and promotes early ply delamination will have a shorter fatigue life than a stacking sequence which produces lower interlaminar stresses.

However, TBE-enhanced X-ray radiographs have shown that matrix cracking is the dominant degradation mechanism over the greater part of the fatigue life of the graphite/epoxy composite structures.

These observations led to the development of a damage indicating parameter based on strain energy density. Constant amplitude fatigue data for different laminates and stress ratios was used initially for this development. In this approach to quantifying fatigue life degradation in composites, it is assumed that the matrix is the weak link of the system. The laminate is modeled as isotropic layers of resin containing a crack-like flaw sandwiched between semi-infinite orthotropic plates representing combined fibers and matrix. Each ply of the laminate is subjected to far-field stresses obtained through classical lamination plate theory to determine stress intensities and strain energy density factors at crack tips. Finally, a damage correlation parameter is obtained by summing the strain energy density factors for each ply in compression and/or tension and normalized with respect to ultimate compressive or tensile strengths of the laminate.

This damage correlation parameter is used in conjunction with linear fatigue damage or linear residual strength reduction models (such as Miner's Rule or modified Miner's Rule) to predict spectrum fatigue life of center hole specimens of AS/3501-6 graphite/epoxy laminates. The predicted lives of three different layups are compared with the corresponding experimental data; correlation is good.

Workshop on Nondestructive Evaluation of Composite Materials

A one-day workshop on nondestructive evaluation (NDE) of composite materials was held at the Air Force Wright Aeronautical Laboratories (AFWAL) on 31 Oct. 1980. The goals of the meeting, sponsored by the Mechanics and Surface Interactions and Nondestructive Evaluation branches of the Materials Laboratory of AFWAL, were to review existing NDE technology as it applies to the investigation of composites and to identify approaches to the inspection and evaluation problem. The workshop consisted of seven formal presentations and an open discussion. The formal presentations were:

- "Nondestructive Inspection Requirements During Full-Scale Development of Composite Components and Structures" by John Goodman, AF Aeronautical Systems Division.
- "Review of NDE Technology" by Grover Hardy, Materials Laboratory, AFWAL.
- "Nondestructive Evaluation to Investigate the Response of Composites" by W. W. Stinchcomb, E. G. Henneke, K. L. Reifsnider, and J. C. Dukes, Virginia Polytechnic Institute and State University.
- "Nondestructive Characterization of Composite Materials" by Bar-Cohen, SRL, Inc. and R. L. Crane, Materials Laboratory, AFWAL.
- "Microstructure and Damage Documentation for Composite Materials" by G. P. Sendeckyj, Flight Dynamics Laboratory, AFWAL.
- "A Review of NDE Research As It Is Applicable to Composite Materials and Structures" by R. L. Crane, Materials Laboratory, AFWAL.
- "Fatigue Damage Monitoring in Composites by Ultrasonic Mapping" by I. M. Daniel, and S. W. Schramm, IIT Research Institute and T. Liber, Travenol Laboratories.

Dr. Goodman presented the current Air Force nondestructive inspection (NDI) requirements for composite structures during full-scale development. These include the detection and mapping of manufacturing flaws in composite parts and then fatigue testing of the parts to insure that the flaws do not grow to catastrophic sizes during a specified interval. The NDI requirements were illustrated by specific examples.

Grover Hardy reviewed four NDE methods (ultrasonics, X-ray radiography, liquid penetrants, and eddy current), indicating the state of the art for each. He also described the semi-automated ultrasonic scanning system for composite structures, being developed by AFWAL, and the results of the AFWAL in-service composite structure monitoring program. Dr. Crane reviewed the Materials Laboratories effort in the application of NDE methods to the detection and mapping of physical flaws in composites. Dr. Bar-Cohen presented the results of his recent research on the application of acoustic backscattering to inspection of damaged composite laminas. He clearly demonstrated that significant backscattering occurs for orientations where the fiber axis or internal flaw is aligned perpendicular to the propagation vector. Fiber orientations and the distribution of cracks within a specific ply can be easily mapped. This technique has a lot of future potential.

Professor Stinchcomb presented the damage documentation philosophy that has been evolved at Virginia Polytechnic Institute and State University. The philosophy is that a combination of NDE methods must be used to monitor damage accumulation in composites. No single method will provide all of the desired information. Dr. Sendeckyj discussed his experiences in using ultrasonic, X-ray and holographic nondestructive inspection methods for damage documentation in composites. He indicated that, of all the NDE methods, penetrant-enhanced stereo X-ray photography provides the best description of damage in composites. Finally, S. W. Schramm presented the results of an AFWAL-sponsored program in which ultrasonic mapping was used to monitor fatigue induced damage in composites.

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Call for Papers

Compression Testing of Homogeneous Materials and Composites

A call for papers is issued for an ASTM symposium, "Compression Testing of Homogeneous Materials and Composites, slated for 10-11 March 1982 in Williamsburg, Va. The symposium is sponsored by ASTM Committee E-28 on Mechanical Testing, and a special technical publication on the symposium proceedings is anticipated by ASTM.

The chairman for this symposium is Richard Chait; vice-chairmen are Ivan Martorell and Ralph Papirno. Chait and Papirno are with the U.S. Army Materials and Mechanics Research Center in Watertown, Mass. Martorell is with Westinghouse Corp. in Dayton, Ohio. They are requesting papers on any aspect of compression testing. They especially encourage experimental and/or theoretical submissions in the following areas:

- Large deformation testing related to forging processes (example: ring compression testing).
- Ceramics, composites, layered solids, and polymer testing.
- Rapid rate and/or temperature extreme testing.
- End friction effects on stress and strain distributions in standard and nonstandard specimen configurations.
- Automated testing control, data acquisition and data analysis.
- Failure modes in compression tests.
- Improved techniques for load transmission, specimen lubrication, stress calculation, and strain measuring in standard and nonstandard tests.

Prospective authors are requested to submit a 200- to 300-word abstract and an ASTM paper offer form by 1 June 1981 to Ralph Papirno, EMD, Bldg. 39, Army Materials and Mechanics Research Center, Watertown, Mass. 02172. ASTM paper offer forms are available from Papirno or from Kathy Greene, ASTM Publications Div., 1916 Race St., Philadelphia, Pa. (215/299-5414). Acceptance notices will be mailed by 30 September 1981. Manuscripts of accepted papers will be due on or before the first day of the symposium.

Producibility and Quality Assurance of Composite Materials

A call for papers is issued for an ASTM symposium, "Producibility and Quality Assurance of Composite Materials," to be held 20-21 October 1981, in St. Louis. The symposium is sponsored by Committee D-30 on High Modulus Fibers and Their Composites. A special technical publication is anticipated by ASTM.

The objective of the symposium is to bring together the active workers in composites technology and to provide a forum for presentation and discussion of the latest developments in composites processing and quality assurance, including applications to the aerospace, automotive, and related industries. Papers that describe previously unpublished research are solicited in the following areas: quality assurance of starting materials, quality assurance methodology development, processing science of composite materials, in-process controls, in-process inspection, adaptive process controls, environmental effects on processability, quality assurance of processed parts, nondestructive evaluation, methodology for achieving reproducible/reliable composite processing, and producibility of composite materials.

A 500-word abstract and ASTM Paper Offer form should be submitted to the symposium chairman, Charles E. Browning, Air Force Wright Aeronautical Labs., AFWAL/MLBC, Wright-Patterson AFB, Ohio 45433 (513/255-2201). ASTM paper offer forms can be obtained from Browning or from Kathy Greene, ASTM Publications Div., 1916 Race St., Philadelphia, Pa. 19103 (215/299-5414). The due date for abstracts is 1 June 1981.

Composites Technology Review

The American Society for Testing and Materials (ASTM) announces the publication of a new journal called *Composites Technology Review*. The *Review* will consist of the existing sections currently published under the same name, plus a new section devoted to the publication of full-length technical articles. The editor for the new Article Section will be Dr. G. P. Sendeckyj of the Air Force Wright Aeronautical Laboratories, Dayton, Ohio (513/255-6104). T. T. Chiao will continue as the General Editor for the *Review*

The objective of the *Composites Technology Review* is to provide a credible forum for the presentation of technical information, in the form of formal articles, informal extended abstracts, research briefs, technical reviews, and news items, dealing with composite materials, their response to applied environments, and engineering and technical concerns of their application to components and structures. Information about new materials, new investigative methods, and new processing and manufacturing techniques is welcome, as are reports of related professional society and academic activities.

A call for papers to be considered for publication in the *Composites Technology Review* has been made by ASTM. Full-length formal articles should deal with the results of original research. These articles shall be subjected to peer reviews. All papers, reports, and articles should be sent to ASTM, Attn: Rosemary Horstman, 1916 Race St., Philadelphia, Pa. 19103. Further information about the *Review* can be obtained from K. L. Reifsnider, Editorial Chairman of the *Review*, Virginia Polytechnic Institute and State University, Blacksburg, Va. 24061 (703/961-5316) or from T. T. Chiao, General Editor of the *Review*, Lawrence Livermore Laboratory, L-338, P.O. Box 808, Livermore, Calif. 94550 (415/422-9271).

Program for the Sixth Conference on Composite Materials: Testing and Design

Conference Chairman: *Dr. I. M. Daniel, IIT Research Institute, Chicago, Ill.*

Session 1—Test Methods

Tuesday, 12 May 1981, 8:30-12:00
Chairman: Dr. J. M. Whitney, AFWAL/MLBM Wright-Patterson AFB, Ohio

"Through-the-Thickness Tensile Strength of Glass Reinforced Plastics," by T. H. Mao, Chinese Academy of Sciences, Peking, China; and M. J. Owen, University of Nottingham, Nottingham, U.K.

"Nondestructive Technique for Determining the Elastic Constants of Advance Composites," by Cynthia M. Rutkowski, Mark F. Nelson, and Joseph A. Wolf, Jr., General Motors Research Laboratories, Warren, Mich.

"Iosipescu Shear Properties of SMC Composite Materials," by Donald F. Adams and David E. Walrath, University of Wyoming, Laramie, Wyo.

"Finite Element Analysis of Biaxial Stress Test Specimen for Graphite/Epoxy and Glass/Fabric/Epoxy Composites," by R. H. Marloff, Westinghouse R&D Center, Pittsburgh, Pa.

"Analysis of Macroscopic Orthotropic Photoelasticity with Residual Birefringence," by Charles W. Bert, University of Oklahoma, Norman, Okla.

"Characterization of Lamina and Interlamina Damage in Graphite/Epoxy Composites by the Deply Technique," by S. M. Freeman, Lockheed-Georgia Company, Marietta, Ga.

Session 2—Material Characterization

Tuesday, 12 May 1981, 8:30–12:00
Chairman: Dr. G. P. Sendeckyj, AFWAL/FIBE, Wright-Patterson AFB, Ohio

"Thermal Behavior of Graphite/Epoxy Composites in the Subcured State," by Linda Blankenship, Dublin, Ohio.

"Damage in Composite Materials During Quasi-Static Shear Loading," by H. Aytac, J. Renard and G. Verchery, ENSTA, Palaiseau, France.

"Mechanical Characteristics of T300-6K/V378A Graphite/Polyimide," by Lee McKague, Jack Reynolds and John Fruit, General Dynamics, Fort Worth, Tex.

"High Temperature Composites for Advanced Missile and Space Transportation Systems," by D. E. Skoumal, Boeing Aerospace Company, Seattle, Wash.

"Hybrid-Fiber Reinforced SMC-Composite," by David C. Chang, General Motors Research Laboratories, Warren, Mich.

"On the In-Plane Behavior of Ribbon Reinforced Composite," by Y. T. Yeow, Allied Chemical, Morristown, N.J.

Session 3—Fracture and Failure Analysis

Tuesday 12 May 1981, 1:30–5:30
Chairman: Dr. C. C. Chamis, NASA-Lewis Research Center, Cleveland, Ohio

"A Fracture Analysis of the Micromechanics of Crack Extension in Glass Fibre and Carbon Fibre Composites in Monotonic and Cyclic Failure," by J. K. Wells, P. D. Austice, and P. W. R. Beaumont, University of Cambridge, Cambridge, U.K.

"Initiation and Accumulation of Damage in Composite Laminates," by R. L. Gallo, G. P. Sendeckyj and R. S. Sandhu, Air Force Wright Aeronautical Laboratories, Dayton, Ohio.

"Strength and Fracture Characteristics of Graphite-Glass Intraply Hybrid Composites," by N. M. Bhatia, Northrop Corp., Hawthorne, Calif.

"Experimental Investigations of Fibre Composite Reinforcement of Cracked Metallic Aircraft Structures," by M. M. Ratwani, J. D. Labor, and H. P. Kan, Northrop Corp., Hawthorne, Calif.

"Matrix Cracking in Short Fibre-Reinforced Composites," by B. L. Lee, B. F. Goodrich R&D Center, Brecksville, Ohio.

"Characterization and Failure Analysis of Steel/Tungsten Composites," by C. Kin, A. Pattnaik and R. J. Weimer, Naval Research Laboratory, Washington, D.C.

"The First-Ply Failure Surface of Laminated Composites," by N. Balasubramanian, Air Force Wright Aeronautical Laboratories, Dayton, Ohio.

Session 4—Fatigue

Tuesday, 12 May 1981, 1:30–5:30
Chairman: Prof. C. T. Sun, Purdue University, Lafayette, Ind.

"Stiffness Reduction as an Indicator of Damage in Graphite/Epoxy Composite," by E. T. Camponeschi and W. W. Stinchcomb, Virginia Polytechnic Institute and State University, Blacksburg, Va.

"Failure Characterization of a Graphite/Epoxy Laminate Through Proof Testing," by H. Thomas Hahn and D. G. Hwang, Washington University, St. Louis, Mo.

"Evaluation of Load History Effects on Material Response of a Graphite/Epoxy Composite," by J. T. Ryder, Lockheed-California Company, Burbank, Calif.

"Effects of Spectrum Variations on Fatigue Life of Composites," R. Badaliance, H. D. Dill, McDonnell Douglas Corp., St. Louis, Mo., and J. M. Potter, Air Force Wright Aeronautical Laboratories, Dayton, Ohio.

"Biaxial Strength Behavior of Glass Fabric Reinforced Polyester Resins," by M. J. Owen and D. J. Rice, University of Nottingham, Nottingham, U.K.

"Biaxial Fatigue of Fiber Reinforced Composites at Cryogenic Temperatures," by S. S. Wang, Edwin S. M. Chim and D. F. Socie, University of Illinois, Urbana, Ill.

"Interlaminar Shear Fatigue of High Strength Sheet Molding Compounds," by J. M. McKittrick, N. S. Sridharan, and B. D. Gujrati, International Harvester Co., Hinsdale, Ill.

Session 5—Fatigue and Nondestructive Evaluation

Wednesday, 13 May 1981, 8:30–12:00
Chairman: Dr. J. B. Whiteside, Grumman Aerospace Corp., Bethpage, N.Y.

"Stiffness Changes Caused by Tensile Fatigue Damage in Fibrous Composites," by Ramesh Talreja, Technical University of Denmark, Lyngby, Denmark.

"Fatigue Response of Composite Laminates with Internal Flaws," by M. N. Gibbins and W. W. Stinchcomb, Virginia Polytechnic Institute and State University, Blacksburg, Va.

"Influence of Damage Growth on Mechanical Response of Composite Laminates," by K. N. Lauraitis and D. E. Pettit, Lockheed-California Company, Burbank, Calif.

"Relationship Between Ultrasonic Indications and Mechanical Properties of Graphite-Aluminum Composites," by L. W. Davis, L. Raymond and T. Romano, NETCO, Long Beach, Calif.

"Nondestructive Evaluation of Damage in FP/Aluminum Composite," by David A. Ulman and Edmund G. Hennecke, II, Virginia Polytechnic Institute and State University, Blacksburg, Va.

"Nondestructive Evaluation of Composite Materials with Backscattering Measurements," by Y. Bar-Cohen, Systems Research Lab., Dayton, Ohio, and R. L. Crane, Air Force Wright Aeronautical Laboratories, Dayton, Ohio.

Session 6—Time-Dependent and Dynamic Response

Wednesday, 13 May 1981, 8:30–12:00
Chairman: Prof. Y. T. Weitsman, Texas A and M University, College Station, Tex.

"Predicting Viscoelastic Response and Delayed Failures in General Laminated Composites," by D. A. Dillard, H. F. Brinson, and D. H. Morris, Virginia Polytechnic Institute and State University, Blacksburg, Va.

"History-Dependent Thermo-mechanical Properties of Graphite Aluminum Unidirectional Composites," by B. K. Min and F. W. Crossman, Lockheed Palo Alto Research Laboratories, Palo Alto, Calif.

"Strain Rate Characterization of Unidirectional Composites," by I. M. Daniel, IIT Research Institute, Chicago, Ill.

"Influence of Frequency and Environmental Conditions on Dynamic Behavior of Graphite/Epoxy Composite," by Shlomo Putter, David L. Buchanan and Lawrence W. Rehfield, Georgia Institute of Technology, Atlanta, Ga.

"Indentation Law Between Elastic Spheres and Composite Laminates," by S. H. Yang and C. T. Sun, Purdue University, Lafayette, Ind.

"The Effect of Different-Resin Materials on the Strength of Damaged Graphite/Epoxy Laminates," by Jerry G. Williams and Marvin D. Rhodes, NASA-Langley Research Center, Langley, Va.

Session 7—Environmental Effects, Durability, and Reliability

Wednesday, 13 May 1981, 1:30–5:00
Chairman: Dr. F. P. Gerstle, Sandia Laboratories, Albuquerque, N.M.

"Use of the Lognormal Distribution for Characterizing Composite Materials," by James M. Whitney, Air Force Wright Aeronautical Laboratories, Dayton, Ohio.

"Durability/Life of Fiber Composites in Hygrothermomechanical Environments," by C. C. Chamis and J. H. Sinclair, NASA-Lewis Research Center, Cleveland, Ohio.

"Effect of Static Immersion in Water on the Tensile Off-Axis Properties of Unidirectional Composites," by B. L. Lee, B. F. Goodrich R and D Center, Brecksville, Ohio, and R. E. Sacher, Army Materials and Mechanics Research Center, Watertown, Mass.

"Study of the Static and Fatigue Compression Properties of Graphite/Epoxy Composites with Discontinuities Under Severe Environmental Exposures," by G. C. Grimes and E. G. Dusablon, Northrop Corporation, Hawthorne, Calif.

"Fatigue and Fracture of Graphite/Epoxy Under Varying Moisture and Temperature Environments," by T. R. Porter, Boeing Co., Seattle, Wash.

"Failure Morphology of Graphite/Epoxy as Influenced by Environments and Processing," by Linda Clements and Michael J. Adamson, NASA-Ames Research Center, Moffett Field, Calif.

Session 8—Structural Testing and Design

Wednesday, 13 May 1981, 1:30–5:00
Chairman: K. E. Hofer, IIT Research Institute, Chicago, Ill.

"The Structural Behavior of Quasi-Isotropic Sandwich Panels," by Michael W. Hyer and Jane A. Hagaman, Virginia Polytechnic Institute and State University, Blacksburg, Va.

"Fabrication and Spin Tests of Thick, Laminated, S2-Glass Flywheel Discs," by R. P. Nimmer, K. A. Torossian and J. S. Hickey, General Electric Company, Schenectady, N.Y.

"Structural Test and Evaluation of Advanced Composite Hydrofoil Test Components," by Maureen Barry, Henry Chaskelis, David W. Taylor Naval Ship R and D Center, Bethesda, MD; and Longin Greszczuk, McDonnell Douglas Astronautics Co., Huntington Beach, Calif.

"Testing of Buried Fiberglass Reinforced Plastic Pipes," by N. Galili, Texas A and M University, College Station, TX; and I. Shmulevitch, Technion, Haifa, Israel.

"Initial Buckling and Postbuckling Strength of Composite Plates," by K. T. Kedward, Material Sciences Corp., El Cajon, CA; and E. E. Spier, General Dynamics, San Diego, Calif.

"Response of Graphite/Epoxy Laminates to Ballistic Penetrators and Blast Overpressures," by John G. Avery and Susan J. Bradley, Boeing Military Airplane Co., Seattle, Wash.

Calendar on Composites

22-26 June 1981
15th Biennial Conference on Carbon
University of Pennsylvania, Pa.
Contact: Prof. F. L. Vogel
University of Pennsylvania, Philadelphia, Pa. 19104
(215/243-8386)

16-18 September 1981
International Conference on Composite Structures
Paisley, Scotland
Contact: Dr. I. H. Marshall
Department of Mechanical and Production Engineering
Paisley College of Technology, Paisley Scotland
(041/887-1241, ext. 258)

13-15 October 1981
13th National SAMPE Technical Conference
Mt. Pocono, Pa.
Contact: Marge Smith
SAMPE, P.O. Box 613, Azusa, Calif. 91702 (213/334-1810)

20-21 Oct. 1981
ASTM D-30 Symposium on Producibility and Quality Assurance of Composite Materials
Chase Park Plaza, St. Louis, MO
Contact: D. A. Tobias
ASTM, 1916 Race Street, Philadelphia, PA 19103 (215-299-5546)

15-20 November 1981
102nd ASME Annual Meeting
Washington, D.C.
Contact: Prof. S. S. Wang
University of Illinois, Urbana, Ill. 61801 (217/333-1835)

12-15 Jan. 1982
37th Annual SPI Reinforced Plastics/Composites Institute Conference
Washington, D.C.
Contact: SPI
355 Lexington Avenue, New York City, NY 10017 (212-573-9400)

9-10 March 1982
ASTM D-30 Symposium on the Long-Term Behavior of Composites
Williamsburg, VA
Contact: D. A. Tobias
ASTM, 1916 Race Street, Philadelphia, PA 19103 (215-299-5546)

4-6 May 1982
27th National SAMPE Symposium and Exhibition
San Diego, CA
Contact: Marge Smith
SAMPE, P.O. Box 613, Azusa, CA 91702 (213-334-1810)

13-14 July 1982
Jointing in Fiber Reinforced Plastics
Imperial College/RAE, London, England
Contact: F. L. Matthews
Aeronautics Department, Imperial College, London, SW7-2BY, England

15-17 Dec. 1982
ASTM-ASME-ASM-SAE Symposium on Multiaxial Fatigue
San Francisco, CA
Contact: Kathy Greene
ASTM, 1916 Race Street, Philadelphia, PA 19103 (215-299-5414)

June 1983
2nd Japan U.S. Conference on Composite Materials; Mechanics, Mechanical Properties, and Fabrication