Overview

The Sixth Symposium on Composites: Fatigue and Fracture sponsored by Committee D30 on High Modulus Fibers and Their Composites, was held in Denver on 16–17 May 1995. The symposium featured 38 paper presentations covering metal matrix composites, fatigue and damage progression, strength and residual properties, damage tolerance and fracture analysis, mode mixity and delamination, property characterization and environmental effects, and standardization and design. The symposium sessions were chaired by W. S. Johnson of Georgia Institute of Technology, R. Martin of Materials Engineering Research Laboratory, J. Masters of Lockheed Engineering and Science, L. Carlsson of Florida Atlantic University, G. Murri and J. Reeder of NASA Langley Research Center, A. Rosenberger of Wright-Patterson Air Force Base, J. Fish of Lockheed Advanced Development Co., B. Davidson of Syracuse University, P. Lagace of Massachusetts Institute of Technology, and S. Hooper of Wichita State University.

This publication includes 29 papers organized in 6 sections.

Damage Tolerance and Fracture Analysis

Lagace and Priest investigated the damage tolerance of longitudinally notched pressurized composite cylinders and explored the limitations of a methodology developed for biaxially loaded quasi-isotropic configurations. This methodology uses coupon fracture data to predict cylinder failure. In all cases, the methodology was not able to predict the failure pressures of uniaxially loaded cylinders. Their results show that failure is controlled by local damage mechanisms and underscores the importance of understanding local behavior in developing failure prediction methodologies.

Hooke, Armanios, Dancila, Thakker, and Doorbar presented an investigation into the failure of a SCS-6/Ti-6-4 thin-walled cylindrical shell subjected to internal pressure. An experimental setup was designed to allow application of an internal pressure using a hydraulic system while maintaining zero axial load. The results indicated that the failure pressure was in good agreement with theoretical predictions from an anisotropic shell and an engineering thin-walled solutions and coupon strength data.

Saczalski, Lucht, and Saczalski reviewed advanced experimental design methods related to load capacity degradation of composite recreational structures. The results of a case study dealing with a mountain bike frame failure suggested that such structures are susceptible to design load degradation due to manufacturing variations and usage. The paper illustrated the benefits of the multivariable experimental methodology as a design tool in optimizing competitive, cost effective, and safe recreational composite structures.

Chamis, Murthy, and Minnetyan presented an overview of a computational simulation approach for progressive fracture in polymer matrix composite structures. The approach is independent of stress intensity factors and fracture toughness parameters and integrate composite mechanics with finite element. Results of structural fracture in composite plates, shells, and builtup structures are presented, and parameters/guidelines are identified for use as structural fracture criteria, inspection intervals, and retirement for cause.

Marcucelli and Fish designed a torsion specimen to evaluate the transverse shear strength of composite materials. Tests of specimens made of graphite/epoxy material with six different layups exhibited linear load-deflection behavior and failure was due to transverse shear stress. A quasi-three-dimensional finite element analysis was conducted to determine the interlaminar shear stress at failure and the test specimens failed at the predicted value.

Fatigue and Life Prediction

Hermann and Hilleberry performed constant amplitude fatigue tests on unidirectional and cross-ply SCS-6/TIMETAL 21S titanium matrix to study fiber bridging of matrix cracks. Broken fibers were observed among intact, bridging fibers in the wake of the matrix fatigue crack. A model was developed to study the mechanism of the cracked composite and predictions were compared with test measurements.

Tanaka and Tanaka present a study on the effect of stress ratio on the Mode II fatigue crack propagation in unidirectional graphite/epoxy laminates. Both end-notched and end-loaded split specimens were tested under various stress ratios, and a fracture mechanics equation was proposed for predicting crack propagation rate. The effect of stress ratio on the micromechanisms of crack propagation was discussed on the basis of microscopic fracture surface observations.

Pelegri, Kardomateas, and Malik studied delamination growth of cross-ply graphite/epoxy laminates under constant amplitude cyclic compressive loads. Expressions describing the fatigue crack growth and accounting for mode dependence are derived and numerically integrated to produce delamination length versus number of cycles. Experimental results were compared to data from a previous study using unidirectional specimens.

Krüger and König used elastic fracture mechanics criteria to predict delamination growth under tension-tension and tension-compression fatigue loading. A Paris law diagram was obtained experimentally using Modes I and II specimens and correlated with computed mixed-mode results from a three-dimensional finite element analysis.

Schaff and Davidson presented a residual strength-based wearout model for predicting the life of polymeric composite laminates subjected to two-stress level and randomly ordered load spectra. The model includes a cycle mix factor and accounts for the dispersion of strength distribution during fatigue loading. The theoretical fatigue life distributions are compared to experimental results, and excellent correlation was obtained based on the 63.2 percentile of the probability of failure distribution.

Strength and Residual Properties

Chatterjee, Yen, and Oplinger examined the stress fields in tabbed unidirectional and cross-ply specimens to improve the methods for determining the axial strength of unidirectional composites. Use of soft tabs, low taper angles and ductile, tough adhesives are recommended to reduce failure near end tabs of unidirectional coupons. Data reduction schemes for cross-ply specimens are critically examined, and test results from cross-ply and unidirectional tension and compression specimens are compared.

Sawicki and Nguyen examined the performance of biaxially loaded composite joints using an apparatus designed to apply transverse bearing loads independent of longitudinal bypass loads. Two configurations were considered to compare transverse bearing effects in relatively high and low stiffness laminates. High stiffness laminates exhibited greater sensitivity to transverse hole deformation, laminate damage, and fastener torque. The results of this investigation showed the importance of using conservative bearing strengths in developing bolted joint allowables.

Wu and Wilson investigated the residual strength of aramid reinforced aluminum laminate, ARALL-3, and glass aluminum reinforced epoxy, GLARE-2, center notched panels and used the linear elastic fracture mechanics R-curve approach for the residual strength prediction. The R-curves calculated from test of different layup, and size panels with various initial crack extensions showed that they were independent of initial crack lengths and panel width. The results showed that the R-curve approach was a suitable and simple predictive method for fiber/metal laminates.

Miller, Portanova, and Johnson evaluated experimentally the impact damage resistance and residual mechanical properties of $[0/\pm45/90]_s$ SCS-6/TIMETAL 21S composites using quasi-static indentation and drop-weight tests at two nominal energy levels. The composite strength and constant amplitude fatigue response were evaluated to assess the effects of the sustained damage. Results showed that matrix cracking, characteristic of low impact energies, was not sufficient to reduce tensile strength or fatigue life. Only when the fibers were broken, as is the case at higher impact energies, the tensile strengths and failure strains were reduced.

Mode Mixity and Delamination

Trakas and Korschot explored the relationship between the mode of fracture, ply orientation, and apparent interlaminar toughness using double cantilever, end notched flexure, and modified split cantilever beam tests. Extensive use of SEM fractography was made in an attempt to correlate measured energies to the fracture surface deformation. While Modes II and III shared common fractographic features, corresponding values of critical strain energy release rate did not correlate. The work pointed to the need to quantify subsurface deformation and crazing to account for the relatively large values of critical strain energy release in Modes II and III.

Martin and Hansen presented a novel method to achieve stable delamination growth for all mixed mode ratios in the mixed mode bending specimen by maintaining constant opening displacement rate. Such a constant rate is achieved by attaching a second displacement transducer to the hinges of the specimen and externally controlling the test machine using this transducer. Compliance calibration expressions were developed, and comparisons from double cantilever and edge notched flexure beams data were performed.

Beuth and Narayan addressed the problem of separating crack extension modes in oscillatory composite delamination models. Using a modified virtual crack closure technique they developed a method for obtaining energy release rate quantities independent of the virtual crack extension length. Predicted mode mix values are compared to energy release rate ratios using other methods proposed in the literature for the analysis of oscillatory delamination problem.

Palmer, Armanios, and Hooke developed an analytical model to predict the effect of internal delamination in unsymmetric laminates. The model accounts for shear deformation and was applied to a class of hygrothermally stable graphite/epoxy laminates. The model predicted a larger magnitude of shear and peel stresses at the free-edge compared to the delamination tip. Test data exhibited more coupling than analytically predicted which was attributed to the interfacial stresses associated with the nonplanar deformation of the Teflon film as a result of the cure cycle.

Friis, Hahn, Cooke, and Hooper proposed a finite element model for predicting the effect of fiber bridging, fiber properties, and fiber-matrix interface strength on the crack tip stresses and propagation potential of a chopped fiber composite. A technique for modeling variable fiber-matrix interface strength with contact element of variable coefficient of friction was presented. Results showed that fiber bridging reduced the crack tip stresses and resulted in stable crack propagation or crack arrest.

Environmental Effects

Crasto and Kim conducted an investigation to determine the effects of temperature and moisture on the initiation of free-edge delamination in a graphite/epoxy laminate under uniaxial compression. The onset of delamination was determined experimentally by monitoring axial and transverse strains. Absorbed moisture and elevated test temperature reduced the residual stresses. However, delamination initiated at significantly lower stresses with increasing test

temperature due to significant decrease in interlaminar transverse strength. Comparison of stress level prediction and onset of delamination interface with experiment was performed.

Rosenberger and Nicholas examined the influence of an oxidizing environment on the isothermal and thermomechanical fatigue of unidirectional SCS-6/TIMETAL 21S composites through a comparison of tests performed in air and helium. In general, an environmental influence on fatigue life was found under conditions in which matrix crack initiation and growth are dominant. Fatigue conditions in which life is dominated by fiber were not affected by test environment.

Li and O'Brien developed a shear deformation theory including hygrothermal effects for the analysis of laminates with midplane edge delamination under torsion loading. The analysis of edge crack torsion test layup indicated no hygrothermal effects on the Mode III strain energy release rate. Another class of antisymmetric layups was investigated leading to a means of determining Mode III toughness between two dissimilar layers.

Parida, Prakash, Mangalgiri, and Vijayaraju evaluated the influence of environmental and geometric parameters on the behavior of fastener joints in carbon fiber composites using single and double shear lap configurations. Laminates made from unidirectional and fabric prepregs were tested in as-received condition at room temperature and under hot/wet condition after hygrothermal aging. The degradation of bearing strength in hygrothermally aged specimens under hot/wet condition was about 25 to 30% as compared to the corresponding room temperature values.

Kallmeyer and Stephens investigated the localized creep response of a quasi-isotropic graphite/polymer matrix composite laminate subjected to bolt-bearing loads at ambient and elevated temperature in order to assess the long term durability of advanced composite joints. Monotonic tensile and static creep tests were performed on single-hole bolted joints at various temperatures and the influence of lateral constraint on the creep response was studied. The test temperature and bolt clampup torque were found to have a substantial influence on the elongation of bolt holes subjected to bearing loads.

Testing and Failure Mechanisms

Alif and Carlsson examined the stress-strain responses and damage evolution of five harness satin weave carbon/epoxy and four harness satin weave glass/epoxy composites in tension, compression, and shear. In contrast to conventional laminates where distributed damage in the form of matrix cracks is observed, the damage in both composites was confined to the region where ultimate failure occurred. Elastic properties were in good agreement with micromechanics predictions based on uniform strain, but failure stress predictions were less accurate.

Benson, Karpur, Stubbs, and Matikas correlated the results from six nondestructive evaluation techniques with the residual tensile strength of a unidirectional metal matrix composite after being isothermally fatigued. Scanning electron microscopy and metallography were used in the correlation and verification of fatigue damage. The immersion surface wave technique proved to be the most promising method for correlating damage with the residual strength for this particular composite.

Koudela, Strait, Caiazzo, and Gipple evaluated quasi-isotropic spool and unidirectional curved-beam specimens to determine the viability of using either one or both to characterize the interlaminar static and fatigue behavior of carbon/epoxy laminates. The interlaminar tensile strength of the spool specimen was larger than the curved-beam specimens, and the data scatter, attributed to fabrication process, was significantly lower for the spool specimens. The fatigue limit for both specimen was shown to be at least 40% of the average interlaminar tensile strength. Both specimens were found to be adequate for characterizing the interlaminar tensile static and fatigue behavior of carbon/epoxy laminates.

Minnetyan and Chamis investigated the use of the compact tension specimen in laminated composites using two examples. A computational simulation methodology is used and damage initiation, growth, accumulation, progressive fracture, and ultimate fracture modes were identified. The influence of laminate configuration and composite constituent properties on the compact tension specimen test characteristics were quantified.

Wu, Reddy, and Wilson conducted a design study to determine the weight savings and performance increase in stiffened wing skin panels made of aluminum lithium 2090-T83, aramid reinforced aluminum laminate, ARALL-3 and glass aluminum reinforced epoxy, GLARE-2. Six Z-stiffened compression panels representing upper and lower wing covers were fabricated from these material systems and tested to failure. The study confirmed that a 10 to 15% weight savings could be achieved. All panels tested under compression failed in a column bucking mode and the predicted critical loads, compared to those from the tests, were conservative.

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