Overview

Although this conference was billed as the third ASTM symposium with the title "Composite Materials: Fatigue and Fracture," it was actually the tenth ASTM symposium addressing these topics. The first was held in Bal Harbour, Florida, in 1973. Since then, the interest in this topic has grown along with the application of advanced composites in primary structures. Furthermore, the interest in these topics has become truly international, as evidenced by the large percentage of papers presented from outside the United States. Of the 40 papers that were presented, 13 had authors or coauthors from other countries, including England, Canada, Switzerland, Japan, France, Australia, and Korea. Furthermore, there was a general balance between papers presented by authors from universities, government, and industry. The conference was organized into nine sessions, with two parallel sessions in the morning, afternoon, and evening of the first day, and single sessions in series on the morning, afternoon, and evening of the second day. The sessions were organized under topics of Matrix Cracking and Delamination, Interlaminar Fracture, Delamination Analyses, Fatigue and Fracture (I, II & III), and Strength and Impact (I & II). One evening session on the first day was devoted to a meeting of the ASTM D30 task group on Interlaminar Fracture Toughness Measurement. The conference sessions were chaired by C. E. Harris, R. H. Martin, W. S. Johnson, and J. H. Crews, Jr. of NASA Langley Research Center, K. L. Reifsnider and W. W. Stinchcomb of Virginia Polytechnic Institute, E. A. Armanios of Georgia Institute of Technology, and A. Russell of DREP, Canada.

Matrix Cracking and Delamination

Boniface, Ogin, and Smith reviewed the growth of matrix cracks in composite laminates. They compared closed-form analyses for strain energy release rates associated with matrix cracking. These models were shown to be consistent with an alternative approach based on an approximate expression for the stress intensity factor at the tip of a growing transverse ply crack.

Ilcewicz, Dost, and McCool analyzed and tested matrix cracking in IM7/8551-7, a graphite epoxy composite reinforced with a toughened interlaminar layer. They found that the in situ strength for thin, angle-ply groups decreases with decreasing interlaminar layer thickness, but this strength is significantly higher than the lower limit exhibited for brittle matrix composites.

Lee, Allen, and Harris proposed a mathematical model utilizing the Internal State Variable (ISV) concept for predicting the upper bounds of the reduced axial and shear stiffness in cross-ply laminates with matrix cracks. Their comparison with experimental data showed the potential applicability of their model to angle-ply laminates subjected to general in-plane loading.

Davies, Cantwell, and Kausch described cooling rate effects on short and long term properties of carbon fiber PEEK composites. Both their short- and long-term results indicated that the internal stresses induced during fast cooling are more detrimental to mechanical properties than the changes in matrix structure observed at slow cooling rates.

Hooper, Subramanian, and Toubia discussed the environmental effects of jet fuel absorption on the delamination of Graphite/PEEK and Graphite/Epoxy composites. A Fickian moisture distribution was used to analyze the effect of absorbed moisture and jet fuel on the strain energy release rate associated with delaminations occurring at straight free edges. The effect of absorption of several fuels and water on the interlaminar fracture toughness was quantified.

Kan, Bhatia, and Mahler analyzed the effect of porosity on flange-web corner strength. They developed a strength of materials model to determine the interlaminar tensile stress, and used this along with experiments on curved flange-web corner elements to establish a relationship between ultrasonic signal attenuation loss due to porosity and the interlaminar tension strength of porous structures.

Interlaminar Fracture Toughness

Hashemi, Kinloch, and Williams interpreted interlaminar fracture tests on fiber composite materials. They showed that even with composites that give linear and reversible loading/unloading curves, correction terms compensating for the fact that these beams do not act as built-in cantilevers are needed when linear beam analyses are employed to deduce values of interlaminar fracture toughness.

Naik, Crews, and Shivakumar documented the effects of large deflections and loading tabs on double cantilever beam (DCB) specimens used to measure interlaminar fracture toughness. They found that large delections and T-tabs cause the loading point to move closer to the delamination tip, leading to an effective crack length that decreases with load. They developed a simple analysis method that accounts for these effects.

Poursartip and Chinatambi discussed their work on experimental determination of the Mode I strain energy release rate in cracked-lap shear (CLS) specimens. They generated a crack opening displacement (COD) profile by measuring the difference in displacement of the two faces of the CLS specimen and allowing for Poisson contraction effects. Results were presented for both thick adhesive joints and delaminations.

Kageyama reported on a stabilized end notched flexure (ENF) test utilizing a special displacement gage for direct measurement of crack shear displacements (CSD). Interlaminar shear fracture toughness and crack length were calculated from the load versus CSD diagram using an analytical relationship between crack length and CSD compliance.

Russell discussed his work on the initiation of Mode II delamination in toughened composites. He found that for tough matrix composites, load-displacement curves generated in ENF tests exhibit a significant amount of nonlinearity below the maximum load corresponding to unstable propagation in shear. The degree of this nonlinearity varied depending on the method used to start the shear delamination. He presented results for IM6/5245C, IM7/8551-7, and AS4/PEEK using either tensile or shear precracks, or starting the delamination directly from the insert. The mechanisms responsible for the nonlinearity were discussed.

Martin described his evaluation of the split cantilever beam (SCB) for Mode III delamination testing. He used a three-dimensional finite element analysis to show that a Mode II component existed at the delamination front near the free edges. This Mode II presence was verified experimentally by observation of shear hackles on the fracture surface. Furthermore, he discovered fiber bridging on the fracture surfaces resulting from the Mode III fracture in the center of the beam. He concluded that the SCB does not represent a pure Mode III delamination.

Delamination Analysis

Armanios, Sriram, and Badir developed an analysis for matrix crack tip and free edge delamination in composite laminates. This paper won the best presented paper award at the conference. They developed a shear deformation model for analyzing the local delaminations originating from transverse cracks in 90° plies. They used their model to predict delamination onset in $(25/-25/90_n)_s$ T300/934 laminates.

Salpekar and O'Brien reported on the combined effect of matrix cracking and free edge on delamination analyses. A three-dimensional finite element analysis was performed on $(0_2/90_4)_s$ cross ply and $(45/-45/90_4)_s$ orthotropic laminates with delaminations growing from 90° matrix cracks. The total G, and the Modes I, II, and III components, calculated along the delamination front, increased from a minimum value calculated in the interior to a maximum value calculated near the free edge. The Mode I component vanished after the delamination had grown a distance of one-ply thickness from the matrix crack. A closed form solution for the total G, calculated from a simple analysis utilizing laminated plated theory, agreed with the asymptotic total G values calculated near the free edge from the three-dimensional analysis.

Murri and O'Brien analyzed delaminations in tapered composite laminates with internal ply drops. A finite element analysis was performed on unidirectional tapered laminates containing internal ply drops to taper the thickness. Strain energy release rates calculated from this model were used with cyclic DCB data to predict the onset of delamination in fatigue due to the tapered geometry.

Armanios and Parmas developed a closed form analysis for the total G associated with delamination in tapered composite laminates under tensile loading. The equilibrium equations were derived using a complementary potential energy formulation on an elastic foundation for the outer belt.

Tratt discussed the effects of delaminations on the compression behavior of composite structures. He used a three-dimensional finite element analysis to predict the onset of midplane and near surface delaminations simulated by embedded Teflon inclusions in compressively loaded AS4/3501-5A carbon fabric-reinforced epoxy laminates.

Palazotto and Wilder described the characteristics of an implanted delamination within a cylindrical composite panel. They found that, for the level of delamination damage investigated, a linear bifurcation gave accurate predictions of global panel strength.

Strength and Impact

Guynn and Bradley compared experimental observations and numerical predictions for the initiation of fiber microbuckling in notched composite laminates. They found that compressive failure of open hole multidirectional thermoplastic composites begins with in-plane fiber microbuckling at the hole boundary. They emphasized that models for compression strength in the literature are conservative because they make no allowance for edge effects. They developed a "fiber on an elastic foundation" model to describe in-phase (shear mode) fiber microbuckling incorporating edge effects.

Whitcomb developed a micromechanics model for woven composite materials. His model showed the effect of several weave parameters on the composite moduli and stresses.

Camponeschi and Kerr evaluated compression testing of thick-section composite materials for use in large Navy structures. They designed a compression test fixture for testing composites greater than one inch in thickness, and tested 48, 96, and 192 ply carbon epoxy and S2-glass epoxy composites.

Madan discussed the influence of low-velocity impact on composite structures. A simple empirical model was proposed incorporating the effects of impact energy, laminate properties, and static influence coefficients. Results indicated that residual strength is a function of the damage present, independent of whether it was inflicted with different impacter masses, velocities, and energies. A semiempirical relation was developed for impact damage area in stitched laminates.

Dost, Ilcewicz, Avery, and Coxon determined the effects of stacking sequence on impact damage resistance and residual strength for quasi-isotropic laminates. They predicted residual compression strength after impact by predicting the stability of sublaminates created by delaminations and matrix cracks. Stacking sequence was varied by changing the thickness of repeating sublaminates or by modifying the sublaminate structure such that it varied through the laminate thickness. They found that ply group thickness affects both the damage resistance and residual strength of the laminate. Laminates with thicker ply groups resulted in greater damage areas following low-velocity impact, but they had increased laminate stability under compression loading for a given damage diameter compared to laminates with thin ply groups.

Poe discussed the relevance of impacter shape to damage of thick graphite epoxy laminates constructed from filament wound rocket motor case cylinders. For a given impacter mass and kinetic energy, the depth and breadth of damage increased with increasing sharpness and decreasing impacter radius. The damage extent was predicted using Hertz's law, Love's solution for hemispherical pressure applied to a semiinfinite body, and a maximum shear stress criterion. Residual tension strength was predicted using fracture mechanics by assuming a surface crack with the same length and depth as the impact damage.

Bucinell, Nuismer, and Koury described the response of filament wound composite plates to large mass impact events. A two degree of freedom lumped mass model was found to predict the effect of mass, velocity, and energy level up to the point of impacter penetration. Detailed response predictions from a distributed mass Rayleigh-Ritz energy model agreed well with experimental data.

Fatigue and Fracture

Curtis, Davies, Moore, and Slater discussed the fatigue behavior of continuous carbon fiber reinforced polyetheretherketone (PEEK). Tension and compression fatigue results were presented for a variety of layup geometries, fiber types, cooling rates, and test temperatures.

Kortschot and Beaumont reviewed their damage-based strength models for notched, cross-ply graphite epoxy laminates. Finite element analysis was used to determine the effect of splitting and delamination on the stress distribution in the zero degree ply. Their model predicted the effect of both notch size and layup on strength, without the need for empirical parameters.

Spearing, Beaumont, and Ashby described fatigue damage mechanisms in notched graphite epoxy laminates. A power law relationship between damage growth and strain energy release rate was developed in which the material constants were shown to be invariant for all the layups investigated. Damage progression was predicted in cross-ply and quasi-isotropic laminates subjected to tension fatigue. Residual strength was calculated as a function of damage dimensions using a stress based criterion with a Weibull distribution in the zero degree ply strength.

Bathias and Lai discussed the hole effect in compression fatigue of T300/5208 composite materials. In order to avoid generalized buckling of the laminated plate, they tested a modified compact specimen. They compared the ratio of the endurance limit to the static strength for various combinations of cyclic tension and compression.

Underwood, Burch, and Bandyopadhyay documented the effects of notch geometry and moisture on fracture strength of carbon/epoxy and carbon/bismaleimide laminates. They performed tension tests on carbon epoxy cross-ply panels with a center notch, of various ply orientations and thickness, to determine translaminar fracture toughness. In addition, they performed bending tests to determine bulk flexural strength. Tests were performed to investigate the effect of notch width, notch length, and ply orientation as well as the effects of moisture and temperature on fracture toughness.

Piggott and Lam reviewed fatigue failure processes in aligned carbon-epoxies. They found that during tensile fatigue, the slope of the S-N curve is increased by plasticizing the polymer and reducing the adhesion between fibers and polymers, and is decreased by reducing the internal microstresses in the composite. They also found that if fiber waviness is present, the antinodes of the wavy fibers create transverse stresses that cause fiber debonding and matrix splitting.

Bahei-El-Din and Dvorak analyzed the fracture of fibrous metal matrix composites containing discontinuities. Unidirectional boron-aluminum specimens with center notches and circular, square, and rectangular holes were tested in tension to failure. The fracture strength was unaffected by the shape of the discontinuity, and was only influenced by the size of the discontinuity. Local stresses were evaluated by a finite element analysis allowing plastic deformation only in specific regions observed in experiments. Evaluation of local stresses at loads corresponding to fracture showed that fracture is controlled by a critical ratio of the average principal stress in a representative volume of the unnotched ligament near the discontinuity to the unnotched tensile strength in the principal stress direction.

Kantzos, Telesman, and Ghosn reviewed the mechanisms of fatigue crack propagation in SiC/Ti-15-3 unidirectional composites. Specimens were tested with fibers parallel or perpendicular to the applied load. Compact tension specimens were tested at room temperature ambient conditions, and single-edge-notched specimens were tested using an in situ loading stage in a scanning electron microscope.

Majumdar and Newaz documented the thermomechanical fatigue (TMF) of metal matrix composites. Isothermal and in-phase thermomechanical fatigue was performed on Ti 15-3/SCS6 composites. Results showed that for the same stress range, the TMF results in delamination failures and lives that are orders of magnitude less than the isothermal fatigue lives, which are governed by matrix cracking perpendicular to the load direction.

Naik and Johnson discussed fatigue crack initiation and growth in notched titanium matrix composites. Four unnotched laminates of SCS_6/Ti-15-3 had tension fatigue S-N data that could be correlated by a common degradation in the zero degree fiber stress as a function of applied cycles. The double-edge-notched specimen was analyzed using finite elements and was tested to predict the onset of local fiber failure at the notch in fatigue.

Osiroff, Stinchcomb, and Reifsnider discussed their damage and performance characterization of ARALL laminates subjected to tensile cyclic load. They found that at low cyclic stress levels, the fatigue properties of fiber reinforced plies are key factors, whereas at high cyclic stress levels, the fatigue properties of the aluminum plies govern the response of the laminate.

Wilson and Wilson determined effective crack lengths by a compliance method for ARALL-2 laminates as a means for determining stress intensity factor solutions. Fatigue crack growth rate measurements were made on middle-crack tension specimens. An effective crack length was defined to be the length of a through-thickness crack with the same compliance as a crack bridged by the aramid fibers. The variations in compliance and stress intensity factors with effective crack lengths were determined.

Lee and Wilson investigated the effects of temperature on the impact behavior and residual tensile strength of an ARALL-2 laminate. Impact damage was introduced using an instrumented pendulum impact testing system. Damage area and energy absorption were found to vary considerably with temperature. Residual tension strength following impact was measured and was found to increase with increasing test temperature.

Summary

In summary, the editor wishes to thank the authors, session chairmen, and reviewers for working diligently to ensure that the papers included in the symposium, and in this STP, were

of high quality. Special thanks is also extended to the ASTM staff for their efforts and perseverance in bringing the publication of this STP to fruition.

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