Foreword

This publication, *Composite Materials: Fatigue and Fracture—Fifth Volume*, contains papers presented at the Fifth Symposium on Composite Materials: Fatigue and Fracture, which was held in Atlanta, Georgia, 4–6 May 1993. The symposium was sponsored by ASTM Committee D-30 on High Modulus Fibers and Their Composites. Roderick H. Martin, Materials Engineering Research Laboratory, Ltd., Hertford, England, presided as symposium chairman.
## Contents

**Overview**

*ix*

### DELAMINATION CHARACTERIZATION

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental Development of a Mixed-Mode Fatigue Delamination Criterion—</td>
<td>P. SRIRAM, Y. KHOURCHID, STEVEN J. HOOPER, AND RODERICK H. MARTIN</td>
<td>3</td>
</tr>
<tr>
<td>Mode I and Mode II Delamination Growth of Interlayer Toughened Carbon/Epoxy (T800H/3900-2) Composite System—</td>
<td>KAZURO KAGEYAMA, ISAO KIMPARA, ISAMU OHSAWA, MASAKI HOJO, AND SHIGENORI KABASHIMA</td>
<td>19</td>
</tr>
<tr>
<td>Interlaminar Fracture Toughness of Glass Fiber Laminates Additionally Reinforced with Carbon Bead—</td>
<td>JUNG-J. LEE, STEPHEN L. OGIN, AND PAUL A. SMITH</td>
<td>38</td>
</tr>
<tr>
<td>Delamination of Carbon/Epoxy Laminates Under Cyclic Mode II Loading—</td>
<td>KARL KUSSMAUL, MATHIAS V. ALBERTI, ULRICH EISELE, AND THOMAS SCHNEIDER</td>
<td>61</td>
</tr>
<tr>
<td>Mode III Delamination Using a Split Cantilever Beam—</td>
<td>FARHAD SHARIF, MARK T. KORTSCHOT, AND RODERICK H. MARTIN</td>
<td>85</td>
</tr>
<tr>
<td>Mixed Mode Interlaminar Fracture Toughness of Unidirectional Glass/Epoxy Composite—</td>
<td>XIAO-JING GONG AND MALK BENZEGGAH</td>
<td>100</td>
</tr>
<tr>
<td>Improvement of Delamination Resistance with Carbon Nonwoven Mat Interleaves—</td>
<td>EILEEN ARMSTRONG-CARROLL AND ROLAND COCHRAN</td>
<td>124</td>
</tr>
<tr>
<td>Mode I and Mode II Fracture Toughness Measured Between Differently Oriented Plies in Graphite/Epoxy Composites—</td>
<td>ITON CHOU, ISAO KIMPARA, KAZURO KAGEYAMA, AND ISAMU OHSAWA</td>
<td>132</td>
</tr>
</tbody>
</table>

### DAMAGE MODELING

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prediction of Energy Release Rate for Edge Delamination Using a Crack Tip Element Approach—</td>
<td>BARRY D. DAVIDSON</td>
<td>155</td>
</tr>
<tr>
<td>Stress and Energy Based Fracture Conditions for Fiber-Wise Splitting in Composites—</td>
<td>N. SURESH AND ALBERT S. D. WANG</td>
<td>176</td>
</tr>
</tbody>
</table>
Modeling of Accumulated Damage and Failure of Multidirectional Composite Plates Subjected to In-Plane Loads—IQBAL SHAHID AND FU-KUO CHANG 186

Shear Deformation Analysis of the Energy Release Rate of Transverse Cracking in Laminated Composites—P. SRIRAM AND ERIAN A. ARMANIOS 215

A Random-Damage Finite Element for Modeling Failure in Advanced Composite Materials—KERRY T. SLATTERY 232

MATERIAL DAMAGE CHARACTERIZATION

Stacking Sequence Effects and Delamination Growth in Graphite/Epoxy Laminates Under Compression-Dominated Fatigue Loading—JERZY P. KOMOROWSKI, DOMINIQUE LEFEBVRE, CLERMONT ROY, AND CATHERINE RANDON 249

The Effect of Graphite Fiber Properties on Microcracking Due to Thermal Cycling of Epoxy-Cyanate Matrix Laminates—BRIAN J. KNOUFF, STEPHEN S. TOMPKINS, AND N. JAYARAMAN 268

Marine Environmental Effects of Polymer Matrix Composites—FRÉDÉRIC POMIÉS, LEIF A. CARLSSON, AND JOHN W. GILLESPIE, JR. 283

Observations of the Load Redistribution in Polymeric Composite Laminates Under Tension-Tension Fatigue Loading—MARK P. CONNOLLY AND DAVID L. DAVIDSON 304

A New Test for Compression Testing of Impregnated Tows—DOUGLAS S. CAIRNS 317

IMPACT

Non-Penetrating Impact Behavior of CFRP at Low and Intermediate Velocities—DANIEL DELFOSSE, ANOUSH POURSARTIP, BRIAN R. COXON, AND ERNEST F. DOST 333

Post-Impact Fatigue Response of Stitched Composites—DARWIN G. MOON AND JOHN M. KENNEDY 351

Impact and Fatigue Resistance of a [±30°/0°] 3-D Braided Carbon Epoxy Composite—MARC A. PORTANOVA AND JERRY W. DEATON 368

Influence of Impact Parameters on the Response of Laminated Composite Plates—DAMODAR R. AMBUR, JAMES H. STARNES, JR., AND CHUNCHU B. PRASAD 389

STRUCTURAL DAMAGE CHARACTERIZATION

Damage Tolerance and Arrest Characteristics of Pressurized Graphite/Epoxy Tape Cylinders—CLAUDIA U. RANNIGER, PAUL A. LAGACE, AND MICHAEL J. GRAVES 407
Fatigue and Fracture of the 767 Graphite Torsion Spring—RICK W. BLISS, DENNIS L. WHEELER, AND RUSSELL MAGUIRE

Fracture of Glass-Epoxy Laminates Under Torsion and Combined Tension-Torsion Load—JOYANTO K. SEN AND JOHN C. FISH

Influence of Realistic Ply-Drop Geometries on Interlaminar Stresses in Tapered Laminates—ANTHONY J. VIZZINI

Delamination in Composites with Terminating Internal Plies Under Tension Fatigue Loading—MICHAEL R. WISNOM, M. I. JONES, AND WEICHENG CUI

Indexes
Overview

The Fifth Symposium on Composite Materials: Fatigue and Fracture, sponsored by ASTM Committee D30, was held in May 1993 in Atlanta, Georgia. The symposium was the fifth in a biannual series of symposia that addresses current issues in the field of damage mechanics of high modulus fibers and their composites. The special technical publication (STP) number and the editors of the previous symposia on fatigue and fracture of composites are listed below:

1st Volume: ASTM STP 907 Publication year 1986 H. Thomas Hahn, Editor
2nd Volume: ASTM STP 1012 Publication year 1989 Paul Lagace, Editor
3rd Volume: ASTM STP 1110 Publication year 1991 T. Kevin O'Brien, Editor
4th Volume: ASTM STP 1156 Publication year 1993 Wayne Stinchcomb & Noel Ashbaugh, Editors

The objective of these symposia is to increase the understanding of how composite materials and composite material structures fail and to develop analyses and test methods to predict this failure. Topics of these symposia include:

1. Micromechanics where analysis methods to determine the interfacial stresses between the fiber and the matrix are developed and evaluated and tests which determine the strength and toughness of the interface are developed.
2. Fracture mechanics for analytical and experimental characterization of pure and mixed-mode delamination and crack growth to rank materials and to design durable and damage-tolerant structural parts are covered.
3. Effects of different environments and loadings such as exposure to temperature, liquids, fatigue loads, or impact events on material properties and structural failure.
4. Characterization of new types of material forms such as interlaminar-toughened materials and stitched or braided composites or ceramic or metal matrix composites.
5. Fatigue and fracture of composites in structural configurations.

Over 30 papers were presented at the fifth symposium, addressing items from the topics listed above. The symposium had eight sessions, listed below along with the session chairmen:

1. Delamination Characterization A—Anoush Poursartip, University of British Columbia.
2. Damage Modeling—John Fish, Lockheed Advanced Development Company.
3. Damage Growth—Wayne Stinchcomb (deceased), Virginia Polytechnic Institute and State University.
4. Factors Affecting Fatigue Response—Steven Hooper, Wichita State University.
5. Damage Prediction—Erian Armanios, Georgia Institute of Technology.
8. Delamination Characterization B—Kazuro Kageyama, University of Tokyo.

For this publication, the papers have been reorganized into five sections.
Delamination Characterization

Papers in the first section cover the topic of characterizing delamination fracture of laminated composite materials in terms of their interlaminar fracture toughness. This topic continues to receive much attention as the importance of interlaminar fracture properties gains acceptance in materials ranking and in damage-tolerant design. The papers in this section discuss the specific topics of mixed mode delamination and the generation of a mixed mode failure criteria under static and fatigue loads using the mixed mode bending specimen and some newly developed specimens (Sriram et al. and Gong and Benzeggagh). Also, delamination characterization in interlaminar-toughened materials using interleafs or beads is covered (Kageyama et al., Lee et al., and Armstrong-Carroll and Cochran). Delamination in fracture specimens of nonunidirectional layups is discussed in two papers (Kussmaul et al. and Chou et al.). Also, a Mode III delamination test is presented (Sharif et al.); this paper won the best presentation award at the symposium.

Damage Modeling

The ability to model composite damage and to predict the onset of fiber matrix debonding, matrix cracking, delamination, buckling, fiber failure, or some other damage mode such as stiffness reduction is essential, and papers in this section address some of these issues. The topics covered include a closed form method to determine the individual modes of strain energy release rate for an edge delamination (Davidson), a fracture analysis approach to fiber matrix or transverse cracking (Suresh and Wang and Sriram and Armanios), and the consideration of reducing material properties in a finite element analysis to predict damage growth (Shaid and Chang and Slattery).

Material Damage Characterization

This section investigates forms of damage associated with composite materials under environmental exposure and mechanical loads. In many papers in this section, “material” damage is a result of the composite being formed into a laminate and, hence, becoming in itself a structure. It is imperative to understand damage growth at this level of a composite material “structure” before further structural configurations can be understood. Papers in this section present damage observations in laminates with different layups under tension and compression fatigue loads (Komorowski et al. and Connolly and Davidson), while another paper discusses the effects of thermal cycling as experienced in space on matrix cracking (Knouff et al.). The other topics covered in this section include the effects of marine environments on composite properties (Pomies et al.) and a test method for measuring the compression strength of an impregnated tow (Cairns).

Impact

The maximum benefits derived from utilizing laminated composite materials is severely limited by the inability to predict the performance of composites under impact conditions. This section covers topics such as the damage size in a brittle and tough matrix composite under low and intermediate impact velocities (Delfosse et al.), the post-impact response of stitched and braided composites (Moon and Kennedy and Portanova and Deaton), and the effects of thickness and clamping conditions on the response of a panel under impact (Ambur et al.)
Structural Damage Characterization

Ultimately, information from the materials tests, the modeling, and the materials property evaluation tests must be used to determine structural failure. The papers in this section describe some of the issues of failure or damage in specific structures. One paper covers the growth and arrest of cracks in pressurized composite cylinders such as pipes or aircraft fuselages (Ranniger et al.). Another describes a project investigating the fatigue failures of a graphite torsion spring used indoors on a Boeing 767 aircraft (Bliss et al.), while two other papers investigated stresses and delamination in tapered laminates (Vizzini and Wisnom et al.). The fracture of a laminate under torsion and tension-torsion loads consistent with rotor craft applications (Sen and Fish) was discussed in a further paper.

Papers Not Published

There were five presentations at the symposium whose manuscripts do not appear in this publication. One, entitled “A Characterization of Fiber-Matrix Interface Strength,” was presented by Rajiv Naik of Analytical Services and Materials in Virginia. His presentation described the use of a closed form solution to determine fiber matrix stresses and the use of an off-axis flexure test to determine fiber matrix strength under different ratios of transverse and shear stress. Another paper, entitled “Delamination Growth Under Cyclic Compression in Composite Plates,” was presented by George Kardomateas of The Georgia Institute of Technology. His presentation described fracture models describing the growth of delaminations from repeated buckling/post-buckling and unloading. A further presentation by John Bakuckas, then of the National Research Council, entitled “Modelling Fatigue Crack Growth in Cross Ply Titanium Matrix Composites,” described experimental crack growth data for two TMC composites and used a fiber-bridging model to determine the stress intensity factor at the crack tip. A fourth paper, presented by Wade Jackson of the U.S. Army, entitled “Effect of Plate Size on Impact Damage,” compared the damage area from static indentation tests and low-velocity impact tests on plates of different dimensions. The fifth paper presented but not published was entitled “Evaluation of the Long-Term Behavior of a Notched Thermoplastic Laminate,” given by W. S. Kohl, then of Virginia Polytechnic Institute. This paper used NDE techniques and DMA tests to investigate changes in the viscoelastic nature of fatigue damage in notched laminates. The paper was co-authored by the late Wayne Stinchcomb.

This STP is a result of hard work by many people, and the editor would like to acknowledge and thank these people: The ASTM staff: Dorothy Savini, Kathie Schaaf, Kathy Dernoga, Rita Hippensteel, David Jones, and Therese Pravitz; the session chairman, listed above; the reviewers, approximately 100 of them; and finally the authors for their papers and presentations.

Roderick H. Martin

Materials Engineering Research Laboratory, Ltd. (MERL), Hertford, England; symposium chairman and editor