COMPOSITE MATERIALS

FATIGUE AND FRACTURE

FIFTH VOLUME

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EDITOR

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The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution to time and effort on behalf of ASTM.

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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.

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.
6. *Impact*—John Masters, Lockheed Engineering and Sciences Company.
7. *Damage in Structural Configurations*—Kevin O'Brien, U.S. Army.
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

Contents

Delamination Characterization

P. Sriram,[1] *Y. Khourchid,*[1] *S. J. Hooper,*[1] *and R. H. Martin*[2]

Experimental Development of a Mixed-Mode Fatigue Delamination Criterion

REFERENCE: Sriram, P., Khourchid, Y., Hooper, S. J., and Martin, R. H.,"**Experimental Development of a Mixed-Mode Fatigue Delamination Criterion,**" *Composite Materials: Fatigue and Fracture—Fifth Volume, ASTM STP 1230,* R. H. Martin, Ed., American Society for Testing and Materials, Philadelphia, 1995, pp. 3–18.

ABSTRACT: Interlaminar fracture (delamination) is the dominant failure mechanism in most advanced composite materials. The resistance of a material system to delamination failure is generally quantified in terms of the interlaminar fracture toughness, G_c. The recently developed mixed-mode bending (MMB) test is unique in that it facilitates measurement of the fracture toughness G_c under any combination of mixed-mode loading from pure Mode I to pure Mode II. This makes it a very attractive technique for developing interlaminar fracture failure criteria. This paper reports on an application of the MMB test to fatigue loading for the generation of G versus N curves and identification of applicable mixed-mode fatigue failure laws. Fatigue results from unidirectional IM7/5260 carbon/bismaleimide and IM7/8320 carbon/thermoplastic specimens are presented for mode mixes varying from pure Mode I to pure Mode II. Static test results are also presented for both materials. The static and fatigue results indicate different mixed-mode failure laws for the two materials. Further, the effect of fatigue is shown to be both material and mode-mix dependent. All tests were conducted using displacement-controlled loading under room temperature dry conditions.

KEYWORDS: composite materials, laminated composites, delamination, fatigue testing, interlaminar fracture toughness, mixed-mode strain energy release rate

Nomenclature

a	Delamination length, m
b	Specimen width, m
c	Position of applied load on lever, m
E_{11}	Lamina longitudinal modulus, GPa
E_{22}	Lamina transverse modulus, GPa
G	Strain energy release rate, J/m^2
G_c	Interlaminar fracture toughness, J/m^2
G_{c0}	Interlaminar fracture toughness under static loading, J/m^2
G_T	Total strain energy release rate, J/m^2
G_{Tc}	Combined mixed-mode interlaminar fracture toughness, J/m^2
G_{13}	Lamina transverse shear modulus, GPa
G_I	Mode I strain energy release rate, J/m^2
G_{Ic}	Pure Mode I interlaminar fracture toughness, J/m^2
G_{II}	Mode II strain energy release rate, J/m^2
G_{IIc}	Pure Mode II interlaminar fracture toughness, J/m^2

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- h Specimen half-thickness, m
- L Specimen half-span, m
- N Number of fatigue cycles
- P Maximum applied load, N
- P_I Mode I load, N
- P_{II} Mode II load, N
- s Material property exponent
- λ Elastic foundation parameter, 1/m

Introduction

Laminated composite materials of high-strength fibers in polymeric matrices are found in increasing use in many aerospace applications. The multiphase nature of these materials naturally leads to several distinct failure modes. Typically, the longitudinal strength, which is fiber-dominated, tends to be much higher than the matrix-dominated transverse strength. Thus, interlaminar fracture or delamination is often the earliest failure in most advanced composite materials. Published literature strongly suggests that strength-based predictions of delamination are inadequate in the presence of mathematical singularities, and a fracture mechanics approach is more appropriate. Using such an approach, the resistance of a material system to delamination is quantified in terms of its interlaminar fracture toughness, G_c. The use of a fracture mechanics-based approach requires that attention be paid to the individual fracture modes while evaluating G_c. Since a good fraction of applications involves significant Mode I and Mode II loading with negligible Mode III contribution, we will limit our attention to such mode mixes. Further, for composite materials, toughness is highly mode dependent and thus there is a need to develop appropriate fracture laws for failures under mixed-mode loading.

Several test configurations have been proposed in the past for studying delamination fracture behavior under various kinds of loading as summarized in a recent review [*1*]. The general technique is to load a specimen with a built-in delamination in a prescribed manner until the delamination grows. Specific methods include the double cantilever beam (DCB) test for Mode I [2], the end notched flexure (ENF) test for Mode II [*3*], and several choices for mixed mode (I-II) including the Arcan [*4*], cracked lap shear (CLS) [*5*], and edge delamination (ED) tests [*6,7*]. The DCB test can be used to measure the critical strain energy release rate under pure Mode I loading, i.e.,G_{Ic}. In a similar fashion, the end notched flexure (ENF) configuration can be used to evaluate the corresponding pure Mode II value, G_{IIc}. One of the problems with this approach was that different specimens were used to determine G_c for various mixed mode ratios, leading to a consistency issue. For example, it has been shown that even the pure Mode I toughness, G_{Ic}, depends on the ply orientation at the interface, with different values for 0/0 and 90/90 interfaces [*8*]. Furthermore, the specimens for the mixed-mode tests above were not always of the same layup, introducing additional complications. The mixed-mode bending (MMB) test recently developed by Reeder and Crews [*9*] is unique in that it facilitates measurement of the fracture toughness, G_c, under any combination of mixed mode loading from pure Mode I to pure Mode II, by simple variations in the loading of the test fixture. As a further advantage, the MMB specimen is similar in construction to both the DCB and ENF specimens, allowing for a high degree of consistency in the toughness measurements. This makes it an attractive test technique for experimentally developing mixed-mode interlaminar fracture failure criteria.

A realistic appraisal of the potential for delamination growth should include the effects of cyclic loading since such fatigue effects are usually quite dominant. This paper reports on an application of the MMB test to fatigue loading for the generation of G versus N curves. In combination with DCB and ENF test data, this allows the development of applicable fracture laws under both static and fatigue conditions. Results from IM7/5260 carbon/bismaleimide and IM7/8320 carbon/thermoplastic specimens are presented for various G_I/G_{II} ratios. The tests were conducted under displacement control under ambient (23°C) dry conditions. The R ratio and loading rate were fixed at 0.1 and 5 Hz, respectively. Preliminary results were presented earlier in Ref *10* for static loading and fatigue at $G_I/G_{II} \approx 0.25$. Further test results are presented in this paper to show that such fatigue effects on the fracture toughness (and hence fracture law) are not uniform but material and fracture mode-mix dependent.

The widespread acceptance of composites technology, while pointing to the maturity of the field, also underlines the requirement for standard design and testing techniques. One of the current major issues in composite structures is the understanding and prediction of damage modes and failure mechanisms. A thorough knowledge of the failure mechanisms will significantly enhance the ability to design efficient and durable structures. The test method and data presented in this paper are intended to address this issue. It should be noted that the test data presented here have to be combined with a suitable delamination front stress analysis to estimate the delamination onset load of composite structures.

The MMB Fixture

The MMB fixture used for these tests closely follows the modified design proposed by Reeder and Crews [*12*]. The original design induced some nonlinear effects due to the geometry of the system, and these have been minimized in the modified design. The fixture resembles a three-point bend apparatus, except for two key items: there is an additional provision to load one end of the beam through hinge tabs in a manner similar to DCB testing, and the central load is not applied directly onto the specimen. The load is instead applied through an F-shaped loading lever, as shown in Fig. 1. The lower prong of the F forms the standard central load point of the three-point bend load, while the upper prong is attached to the upper hinge at one end of the specimen. The load lever is sufficiently stiff to be considered rigid in comparison with the specimen. The lever itself is coupled to the test machine crosshead through a saddle and stirrup mechanism described in Ref *12*. Standard ball bearings are incorporated into this mechanism so that the applied load can be considered to be vertical, even under fairly large deformations in the specimen. The original MMB fixture lacked the stirrup mechanism, leading to nonlinear effects related to the rotation of the lever. The use of the stirrup mechanism minimizes this problem. The specimen is supported at the nonhinged end and the central load point through bearing-mounted rollers.

The G_I/G_{II} mode ratio is controlled by varying the load point location along the lever, i.e., by varying the distance '*c*' of Fig. 1. Pure Mode II loading is achieved by shifting the load point to be directly above the specimen midspan. In this configuration, the assembly resembles the ENF test setup. To produce pure Mode I loading, the entire loading arm arrangement is removed and the specimen is loaded directly by pulling up on the hinge in DCB fashion. Two LVDTs were mounted at the ends of the loading arm to monitor its transitional and rotational displacements. These displacements can be used to correct for nonlinearity errors; however, in the modified fixture, these corrections can be ignored and hence these displacements were used only to monitor operation of the fixture.

Specimen Preparation and Test Procedure

All specimens were split 0° unidirectional laminates fitted with extruded steel hinges. Two material systems, IM7/8320 carbon/thermoplastic and IM7/5260 carbon/bismaleimide, were used in this study. The specimens were laid up as plates and sectioned into test coupons nominally 127 mm (5 in.) long, 25.4 mm (1 in.) wide, and 3.3 mm (0.13 in.) thick. A single layer

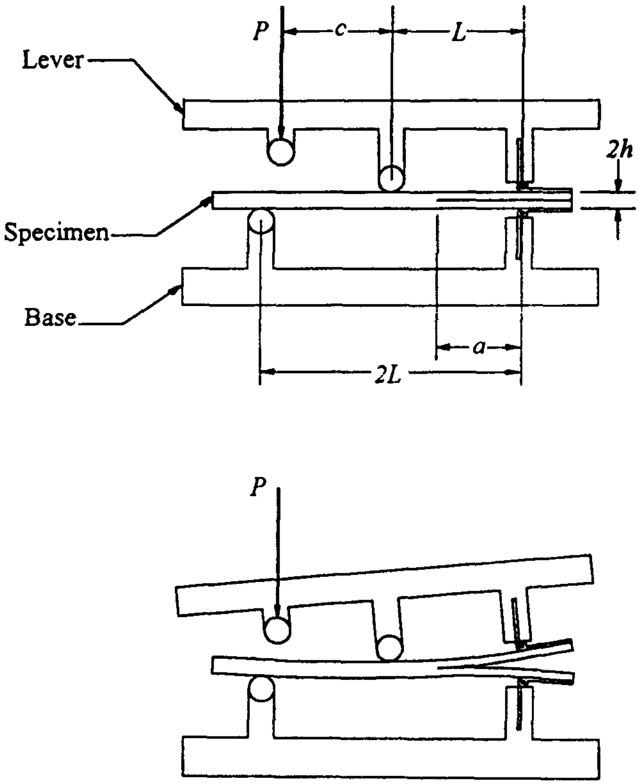

FIG. 1—*Schematic of modified MMB test fixture.*

of 0.0127 mm (0.0005 in.) TFE-fluorocarbon, which was not sprayed with a release agent, was employed to generate a starter crack in the IM7/5260 specimens. The starter crack in the IM7/8320 was created using a single layer of 0.0127-mm (0.0005-in.) Kapton which was sprayed with a release agent. The insert lengths varied from 23 mm (0.9 in.) to 28 mm (1.1 in.). Hinge tabs were bonded to one end of the specimen to provide the Mode I loading. These tabs were cut from 22-mm (0.825-in.)-wide steel piano-hinge stock. The hinges and bonding area of each specimen were abraded with a sand blaster and thoroughly degreased using methyl ethyl ketone. Since hinge alignment is critical to eliminate tearing or Mode III loading, a special alignment jig was used during bonding. The bonding agent was epoxy film adhesive (American Cyanamid FM 123) with a cure cycle of 1 h at 250°F. The choice of adhesive was governed largely by the need to provide sufficient bond strength while preventing aging of the specimen.

All tests were conducted on at 245-kN (55-kip) MTS servohydraulic frame equipped with hydraulic grips. A 2.25-kN (550-lb) or 890-N (200-lb) load cell was used for load sensing since the test loads were only of this magnitude. The tests were controlled by a PC interfaced to the test stand through a wave form generator (MTS microprofiler). The same PC was used for data acquisition through appropriate utilization of A to D converter boards and BASIC software. The tests were conducted using the load frame in stroke control. A microscope equipped with a fiber-optic ring light was used to track the crack. The specimen edges were coated with a water-based typewriter correction fluid to enhance visibility of the crack tip as needed. A minimum of three replicates were used for each test condition.

Static Testing

Static tests were carried out using DCB, ENF, and MMB configurations to obtain a mix of mode ratios. The DCB and ENF test methods are well documented in literature and will not be detailed here. They were used to determine the pure Mode I and Mode II values, G_{Ic} and G_{IIc}. The MMB tests were conducted using the test setup described previously to provide G_I/G_{II} ratios of about 0.25, 1.0, and 4.0 (the uncertainty in this is explained in the next section). The static tests were motivated by two reasons: first, to provide a load deflection curve from which the stroke requirements for fatigue loading could be deduced, and second, to suggest an applicable mixed-mode fracture law. The test was configured by adjusting the fixture to provide the desired mode-mix ratio. The specimen was then placed in the fixture and loaded at a constant displacement rate of 0.5 mm/min. A grid of lines spaced 1 mm apart was imprinted on the side of the specimen so as to allow tracking of the crack growth. Delamination growth initiation was detected using the microscope. Load and deflection data were recorded for every millimetre of crack growth thereafter till the crack grew 20 mm. The onset of crack growth was also inferred from the deviation from linearity evident in load-deflection data. In practice, the deviation from linearity criterion was convenient to use and also provided the most consistent results. This was especially so in the case of low G_I/G_{II} ratio tests because the crack growth under those conditions tended to be unstable and too sudden to be tracked reliably by visual means.

Fatigue Testing

The MMB fatigue test procedure was based on the protocol suggested by ASTM Task Group D30.06.04 (formerly D30.02.02) in connection with the interlaboratory round robin interlaminar fatigue testing program. The test machine was operated under displacement control at a loading frequency of 5 Hz. An R (ratio of minimum to maximum displacement) value of 0.1 was used. As in the static tests, G_I/G_{II} ratios of about 0.25, 1.0, and 4.0 were used. The peak displacement to be used for the first specimen was estimated based on the static load-deflection response curve; for subsequent specimen, this peak level was adjusted to bring the observed cycles to failure close to the target value. During cyclic loading, the peak load for the first load cycle was recorded as the reference value. Peak loads during subsequent load cycles were recorded periodically along with the cycle count.

Three methods were used as indicators of onset of delamination growth. The first was observation of visible crack growth through the microscope. The second method consisted of comparing the peak load during any cycle to the reference peak load. Under this criterion, delamination onset was assumed to occur when the peak load decreased by 1% from the reference value. The third method was the same as the second except a peak load drop of 5% was sought. Tests were continued until all three growth criteria were satisfied. If delamination growth was not detected after about 500 000 cycles, the test was terminated and the specimen labeled a run out. In some cases, testing was continued past 500 000 cycles until delamination was detected and the corresponding data was used.

Data Reduction

The fatigue data reduction method will be outlined first since the static data reduction scheme was a simple subset of this procedure. Based on the peak load during the first cycle and any subsequent peak load, a plot of peak load reduction (or underpeak) versus number of load cycles was generated for each specimen. A typical example is shown in Fig. 2. A fairly high level of noise is evidenced by the scatter in this raw data. It should be noted that the peak load versus cycles data itself was quite reliable, and the problem was limited to the load drop data.