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Fatigue and Fracture

7th Volume

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editor

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Composite Materials: Fatigue and Fracture, Seventh Volume

Ronald B. Bucinell, Editor

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Each paper published in this volume was evaluated by two peer reviewers and the editor. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

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 the peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and their contribution of time and effort on behalf of ASTM.

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Foreword

This publication, *Composite Materials: Fatigue and Fracture, Seventh Volume,* contains papers presented at the Seventh Symposium on Composites: Fatigue and Fracture, held in St. Louis, Missouri, on 7–8 May 1997. The sponsor of the event was Committee D-30 on Composite Materials and Committee E-8 on Fatigue and Fracture.

The symposium chairman was Ronald B. Bucinell, Union College, Department of Mechanical Engineering, Schenectady, NY. He also served as editor of this publication.

Overview

The Seventh Symposium on Composites: Fatigue and Fracture was held on 7–8 May 1997 in St. Louis, Missouri. It was sponsored by ASTM Committee D-30 on Composite Materials and ASTM Committee E-8 on Fatigue and Fracture. The main purpose of the symposium was to provide a forum for presentations and discussions on the recent developments in fatigue and fracture of composites. Specifically called for were papers describing experimental and analytical research in the following areas of composite technology: failure mechanisms, nondestructive evaluation, environmental effects, prediction methodology, test method development, and impact. A total of 21 papers were presented in five sessions. The conference sessions were chaired by A. T. Nettles and M. K. Cvitkovich of NASA Langley Research Center, D. Cohen of Alient Tech Systems, J. E. Patterson of U.S. Army Missile Command, M. D. Lansing of University of Alabama at Huntsville, T. Chu of Southern Illinois University at Carbondale, and R. H. Martin of MERL. During the symposium T. K. O'Brien was awarded the Wayne Stinchcomb Memorial Award. As a result of the presentation evaluations taken during the symposium, M. K. Cvitkovich was given the award for the best presentation of a paper at the symposium.

Composite materials are found in many commercial, military, and aerospace structures. Most of these applications involve cyclic loads, foreign body impact, or thermomechanical loading. Optimizing the design of these structures requires full characterization of composite material response to the various load scenarios. Cost-effective characterization involves a combination of test methods that isolate specific phenomena of interest and models that can correlate the test method results with the actual structural behavior. The papers included in this volume address many of the important aspects of fatigue and fracture behavior of composite materials.

The papers included in this volume are classified into Fatigue and Fracture, Environmental Considerations, Impact, and Perspective sections. The papers include treatises on polymer, metal, and ceramic matrix composite materials. Included in the Fatigue and Fracture section are papers concerned with microstructural effects, damage, predictive tools, and test method development. The Environmental Considerations section focuses on the affects of temperature and other environmental factors on the long-term durability of composite structures. In the Impact section papers discuss impact response, damage formation, and the use of NDE techniques as a predictive tool. Finally, the Perspective section provides an artistic view of composite materials.

Fatigue and Fracture

O'Brien argues that the apparent G_{IIc} as typically measured is inconsistent with the original definition of shear fracture. He shows that the interlaminar shear failure actually consists of tension failures in the resin-rich layers between plies followed by the coalescence of ligaments created by these failures and not the sliding of two planes relative to one another that is assumed in the fracture mechanics theory. He presents several strain energy release rate solutions for delamination in composite laminates and structural components where failures have been experimentally documented. It is shown that failures typically occur at a location where the mode I component accounts for at least one half of the total G at failure. He argues that it is the Mode I and mixed-mode interlaminar fracture toughness data that will be most useful in predicting delamination failure in composite components in service.

Swanson presents biaxial tests to determine the stiffness and strength properties of carbon/epoxy material systems using tubular specimens. Loading includes biaxial tension, biaxial compression, mixed tension and compression, and compression under superposed pressure. The tests show a number of features that can be interpreted on both a macroscopic and a micromechanics level. He argues that relating the laminate failure values to the properties of the fiber and matrix requires a more detailed examination at the micromechanics level. He observes that ultimate fiber direction tensile strain values apparently depend on the details of the interaction of matrix cracking and fiber-matrix interphase strength, and thus in situ fiber strength in a laminate differs from that in a tow test.

Bucinell presents a stochastic model that predicts the growth of delamination in graphite/epoxy laminates subjected to cyclic loading. The advantage of this model is shown to be that both the mean and variance associated with the growth of delamination are predicted. He argues that understanding and predicting the variability associated with the delamination growth process is essential to the estimation of the reliability of composite structures. The empirical nature of the model has been minimized through the introduction of fracture mechanics parameters. The application of the model is demonstrated through an experimental evaluation that illustrates the ability of the model to predict both the mean and variance of the delamination growth process in composite laminates subjected to cyclic loading.

Ward and Hillberry present the development of an approach to fatigue crack propagation in titanium matrix composites that includes the effects on interfacial wear on the fiber-bridging behavior. They use a Coulomb friction-based fiber-bridging model, in which the effect of fiber surface roughness on the clamping stress between the fiber and matrix is included. They incorporate a previously developed wear model as a means to determine the reduction of the fiber surface roughness amplitude during fatigue cycling. They show that as the roughness decreases, its contribution to the clamping stress also decreases, resulting in a lower interfacial shear stress. The predictions of the developed model are shown to correlate well with experimental results for different loading conditions, especially those at the relatively high crack growth rates.

Joyce and Moon present their investigation of the effect of fiber waviness, which develops during the processing and manufacturing of fiber-reinforced composite structures, on compressive failure. They present data from a series of compression tests examining the effects of varying levels of in-plane fiber waviness. These tests use a novel combined shear/end loading compression test fixture to ameliorate problems typically associated with pure end-loading and pure shear loading. The fixture is shown to perform adequately when testing wavy specimens, but experienced repeated tab failures in the nonwavy specimens.

Cvitkovich, O'Brien, and Minguet present their investigation of the fatigue damage mechanisms and the influence of skin stacking sequence in carbon epoxy composite bonded skin/stringer constructions. A simple four-point-bending test fixture originally designed for previously performed monotonic tests was presented to evaluate the fatigue debonding mechanisms between the skin and the bonded frame. Microscopic investigations of the specimen edges were used to document the onset of matrix cracking and delamination, and subsequent fatigue delamination growth. The fatigue delamination growth experiments are presented and are found to include matrix cracking and delamination onset as a function of fatigue cycles as well as delamination length as a function of the number of cycles.

John, Jira, and Larsen present their results of an extensive characterization of the fatigue crack growth behavior of a model titanium alloy composite (TMC). The model TMC system used was $[0]_8$ SCS-6/Ti-6AL-4V. Presented are the results from tests conducted under tension fatigue loading at room temperature with a stress ratio of 0.1. The authors also discuss the ability of the shear lag model to predict the crack growth in these composites under a wide range of stress levels.

Peck presents her investigation of the transverse tension fatigue characteristics of IM6/3501 composite materials. To test the 90-degree laminae, she uses a three-point bend test. She argues that this potentially minimizes handling and gripping issues associated with tension tests. She presents the results of 50 specimens of nine different size configurations. She also presents the results of three-point flex fatigue testing on the smallest configuration for 59 specimens at various levels using an R ratio of 0.1 and a frequency of 20 Hz.

Environmental Considerations

Case, Iyengar, and Reifsnider present a life prediction method for ceramic matrix composites. Their model is based upon damage mechanics concepts included in the framework of the critical element model. One unique feature of the model is its ability to include general variations of temperature and applied loads as functions of time. They present a detailed description of the application of the model to elevated temperature fatigue. In addition, a validation example is presented that includes the combined effects of rupture and fatigue.

Johnston and Gates present their experimental investigation of the behavior of an open hole tension (OHT) graphite/bismaleimide composite specimen loaded in tension-tension fatigue under isothermal, fixed-frequency conditions. A range of stress levels and temperature levels were chosen to assess performance. The results of this work are shown to help explain the roles of aging and fatigue damage in the performance of OHT specimens of this material as well as providing insights to the individual and synergistic contributions of each of these processes.

Buchanan, John, and Goecke present their results of an experimental investigation of load-controlled isothermal low-cycle fatigue behavior of a titanium matrix (TMC). The TMC used in this investigation was composed of Ti-6Al-2Sn-4Zr-2Mo matrix (wire) reinforced with silicon-carbide (Trimarc-1™) fibers. The longitudinal fatigue data presented show good correlation with other TMC systems at both positive and negative stress ratios. The authors successfully use the Walker equation to correlate the longitudinal S-N data for stress ratios $R = -1.3$ and 0.1, and for predictions at $R = 0.5$ and 0.7. They show that the maximum fiber stress versus cycles to failure for several unidirectional TMC systems at similar test conditions consolidate to a narrow band, indicating that the life is fiber-dominated. The S-N behavior of the TMC, subjected to transverse fatigue loading, is successfully predicted using the matrix S-N data and a net-section model.

Liao, Schultheisz, Hunston, and Brinson study pultruded glass-fiber-reinforced vinyl ester composite coupons subjected to four-point-bend environmental fatigue to investigate long-term durability for infrastructure applications. Specimens were tested dry and while immersed in water and in solutions of water containing mass fractions of 5 and 10% NaCl salt. Some specimens were also preconditioned by soaking in the water or salt solution for 5 to 6 months without loading; the preconditioned are shown to fractionally decrease 5 to 13% in flexural strength compared to dry specimens. The authors find that for specimens cyclically loaded at or above 45% of the average flexural strength of dry coupons, no change in the fatigue life was observed for the specimens tested while immersed in the fluids as compared to specimens tested dry. The authors argue that the long-term environmental fatigue behavior is not controlled by the quantity of water absorbed; rather, it is governed by a combination of both load and fluid environment. However, they point out that a difference in fatigue life in the different fluid environments was not demonstrated.

Zaffaroni, Cappelletti, Rigamonti, Fambri, and Pegoretti discuss the accelerated hot-wet aging of glass-reinforced epoxy resin at 45 and 70°C at the same level of relative humidity

(RH = 84%). The authors compare the mechanical and physical properties of dry and differently saturated composites. The authors find that the higher the conditioning temperature the higher the equilibrium moisture content. The glass transition temperature is found to decrease for both the two moisture-saturated cases. The authors also found that the moisture absorption reduces the static properties while not modifying the endurance in fatigue tests.

Impact

Nettles presents the results of the low-velocity instrumented dropweight tests performed on carbon/epoxy laminates. The composite plates used in this study are 8-ply $[+45/0/-45/90]_s$ laminates supported in a clamped-clamped/free-free configuration with varying amounts of in-plane load applied. The author shows that for a given impact energy level, more damage is induced into the specimen as the external in-plane load is increased. The majority of damage observed is shown to consist of back face splitting of the matrix parallel to the fibers in that ply, associated with delaminations emanating from these splits. A simple free-edge delamination model is presented to explain the type and extent of the major delaminations caused by the preload/impact combinations.

Patterson presents a test program that was conducted to characterize the impact response of graphite/epoxy structures. The design of the test article utilized for this program was directed toward a generic thin-walled structure applicable for use as a rocket motorcase or launch tube. Low-energy impacts were imparted to empty cylinders and to cylinders whose casewalls were strengthened to simulate launch tube and rocket motorcase configurations. The author discussed the differences between the test configurations with regard to visual damage, impact load, absorbed energy, and casewall deflection.

Liu and Dang discuss their evaluation of the response of composite laminates under low-velocity impact using instrumented impact tests and computer simulations. The computational scheme developed by the authors included composite laminates with various thicknesses, fiber angles, and impact velocities. These results show that the peak contact force and maximum deflection are strongly affected by the thickness of composite laminates, while the fiber angles investigated seemed to play a less significant role.

Lansing, Walker, and Russell present the results of an experimental study in which two computer-sensing techniques are used to monitor filament-wound pressure vessels during pressurization. Acoustic emission was used to register the sound generated by microscopic damage propagation. Video image correlation is a noncontact computer vision technique that simultaneously measures full-field in-plane surface displacements and strains, both linear and angular, with subpixel accuracy. Neural networks were used to predict the burst pressures of impacted pressure vessels based upon data obtained at less than approximately one third of the expected burst pressure for an undamaged specimen.

Perspective

Reilly discusses the use of composite materials in sculpture and masonry murals. His discussion includes the effects of fracture by impact, thermal fatigue and fracture, multiaxial loading failure, new composite materials for art, and the monitoring of damage growth. He also shows how fracture of art can be caused by centuries of stress fatigue, pollution, seismic activity, and dynamic impact due to theft or bad custodial care.

Summary

In summary, the editor wishes to thank the authors, session chairmen, reviewers, and Dr. John Masters for working diligently to ensure that the papers included in the symposium and in this STP were of high quality. Also, thanks are extended to the ASTM staff for their efforts and perserverance in bringing the publication of this STP to fruition.

Ronald B. Bucinell

Union College
Department of Mechanical Engineering,
Schenectady, NY;
Symposium Chairman

Contents

Fatigue and Fracture

T. Kevin O'Brien[1]

Composite Interlaminar Shear Fracture Toughness, G_{IIc}: Shear Measurement or Sheer Myth?

REFERENCE: O'Brien, T. K., **"Composite Interlaminar Shear Fracture Toughness, G_{IIc}: Shear Measurement or Sheer Myth?"** *Composite Materials: Fatigue and Fracture, Seventh Volume, ASTM STP 1330,* R. B. Bucinell, Ed., American Society for Testing and Materials, 1998, pp. 3–18.

ABSTRACT: The concept of G_{IIc} as a measure of the interlaminar shear fracture toughness of a composite material is critically examined. In particular, it is argued that the apparent G_{IIc} as typically measured is inconsistent with the original definition of shear fracture. It is shown that interlaminar shear failure actually consists of tension failures in the resin-rich layers between plies followed by the coalescence of ligaments created by these failures and not the sliding of two planes relative to one another that is assumed in fracture mechanics theory. Several strain energy release rate solutions are reviewed for delamination in composite laminates and structural components where failures have been experimentally documented. Failures typically occur at a location where the Mode I component accounts for at least one half of the total G at failure. Hence, it is the Mode I and mixed-mode interlaminar fracture toughness data that will be most useful in predicting delamination failure in composite components in service. Although apparent G_{IIc} measurements may prove useful for completeness of generating mixed-mode criteria, the accuracy of these measurements may have very little influence on the prediction of mixed-mode failures in most structural components.

KEYWORDS: fractures toughness, shear, interlaminar fracture toughness, composites

One of the most common failure modes for composite structures is delamination. The remote loadings applied to composite components typically get resolved into interlaminar tension and shear stresses at discontinuities that create mixed-mode I and II delaminations. Over the past 10 to 20 years, it has become accepted practice to characterize the onset and growth of these mixed-mode delaminations using fracture mechanics. The strain energy release rate, G, and the Mode I component due to interlaminar tension, G_I, and Mode II component due to interlaminar shear, G_{II}, are calculated using the virtual crack closure technique [*1*]. In order to predict delamination onset or growth, these calculated G components are compared to interlaminar fracture toughness properties measured over a range from pure Mode I loading to pure Mode II loading.

Examples of mixed-mode delamination criteria for carbon fiber-reinforced composites with either a brittle epoxy (AS4/3501-6) or a toughened epoxy matrix (IM7/E7T1-2) are shown in Figs. 1*a* and 1*b*, respectively [*2,3*]. The critical G for delamination is plotted as a function of the Mode II percentage compared to the total G. Hence, at $G_{II}/G = 0$, the loading at the delamination front is a pure opening Mode I, whereas at $G_{II}/G = 1$, the loading at the

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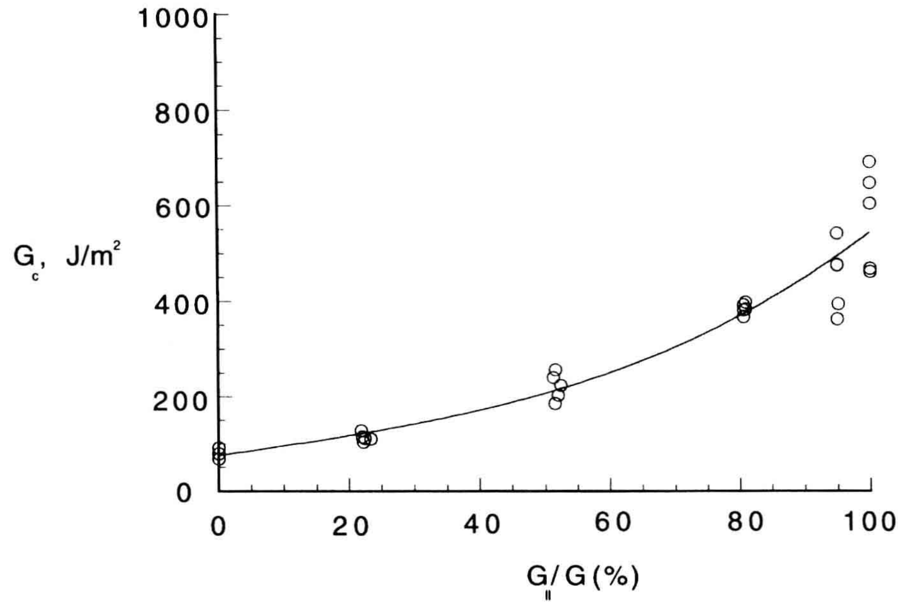

FIG. 1*a*—*Mixed-mode delamination criterion for AS4/3501-6.*

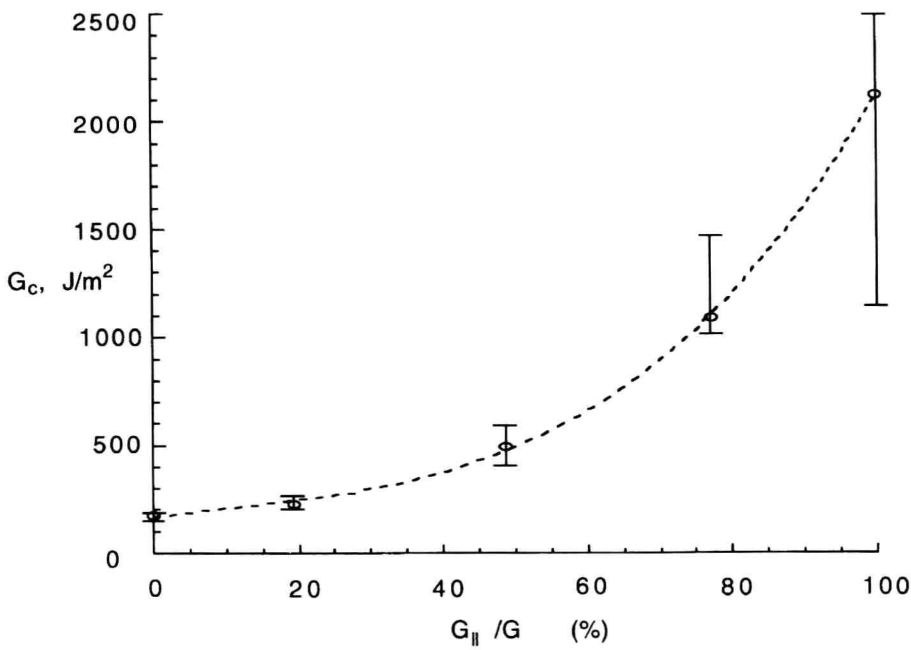

FIG. 1*b*—*Mixed-mode delamination criterion for IM7/E7T1-2.*

delamination front is a pure shear Mode II. As Fig. 1 indicates, the apparent Mode II toughness for a graphite epoxy material is typically much greater than the Mode I toughness and has significantly more variability or scatter. In this paper, some of the reasons for the differences in magnitude and scatter between G_{Ic} and G_{IIc} will be examined. The significance of these differences on the prediction of mixed-mode delamination in composite structural configurations will be discussed.

Background

In the 1950s, Irwin proposed a general theory of fracture [*4,5*], based on the method of Westergaard [*6*], that postulated the existence of three unique fracture modes that could occur at the tip of a crack (Fig. 2). These fracture modes included: (1) an opening Mode I, where the crack faces underwent opening displacements relative to one another as the crack grew, (2) an in-plane sliding shear Mode II, where the crack faces slid over one another in the direction of the crack growth, and (3) an out-of-plane scissoring (or tearing) Mode III where the crack faces slid relative to one another in a direction normal to the direction of crack growth. The elasticity solution for stress intensity factors associated with these three postulated fracture modes (K_I, K_{II}, K_{III}) were derived yielding a mathematically complete and consistent theory for fracture of materials and structures. Strain energy release rates may be related to these stress intensity factors squared through coefficients consisting solely of material properties. Solutions for cracked bodies with specific configurations and loadings were developed and applied to structural problems [*7*]. However, most of these problems consisted

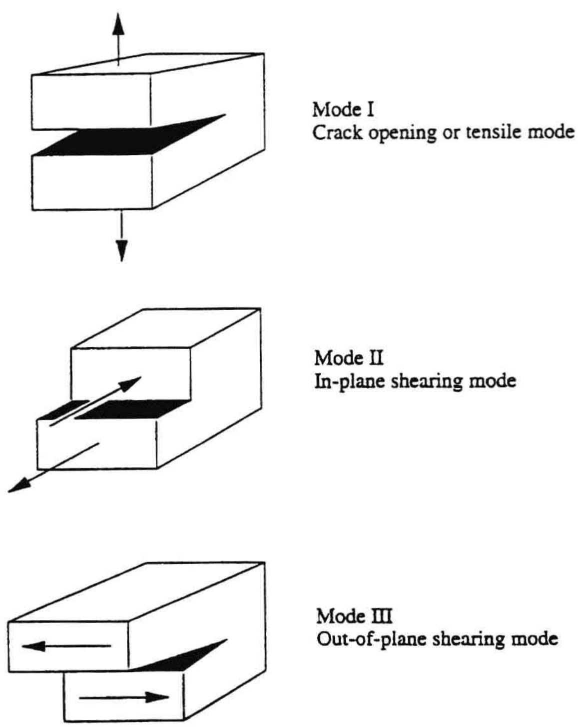

FIG. 2—*Fracture modes.*

of cracks in homogeneous materials (typically structural metallic materials) where cracks that may originally have all three fracture modes when loaded would typically turn immediately as the crack grew to assume a pure opening Mode I orientation. Hence, the resistance of these materials to fracture could be adequately described in terms of the opening mode fracture toughness, K_{Ic}, alone.

With the advent of adhesively bonded structures and laminated composite materials in the 1960s and 1970s, the problem of debonding of adhesive bonds, and delamination in composite materials, created a class of problems where cracks were constrained to grow in bond lines, or resin-rich regions between composite plies, such that macroscopically the cracks could not assume a pure opening Mode I orientation. Therefore, for this class of materials, the mixed-mode fracture problem that was resolved mathematically in the 1950s posed a challenge in terms of fracture toughness characterization.

The opening Mode I characterization proved relatively straight-forward with the advent of the double cantilever beam (DCB) test configuration, although complexities involving the influences of bondline and insert thicknesses, precracking techniques, and fiber bridging in composites delayed the standardization of this test method until the 1990s [*8*,*9*]. Development of test methods for characterizing the interlaminar shear fracture toughness, however, has proven to be a difficult task, both in terms of achieving an adequate configuration to yield a pure shear loading at the crack tip and in the interpretation of the test results [*10*]. It is the latter issue that will be the focus of this paper. As Shakespeare might have said, at issue is whether G_{IIc} is to be, or not to be, considered a generic property of the composite material. Since most of the data generated to date have been for the sliding shear Mode II fracture, the discussion will be limited to the measurement and interpretation of G_{IIc}.

Mode II Fracture Toughness Measurement Results

In the 1980s several test methods were proposed for measuring G_{IIc}. However, to date none of these have been standardized. The most popular methods are the end-notched flexure (ENF) and end-loaded split beam (ELS) shown in Fig. 3. The ENF test involves a simple three-point bend loading, but it results in an unstable delamination growth unless the initial crack is very long [*11*] or the test is controlled with a special shear displacement gage [*12*]. The ELS test involves a more complicated clamped boundary condition but results in a stable delamination growth [*13*]. Both of these test configurations have been analyzed and have been demonstrated to yield a pure sliding shear fracture Mode II at the delamination front [*13*,*14*].

Several interlaboratory "round robin" test programs have been conducted using both of these test methods [*3*,*10*]. However, interpretation of the test results has proven to be difficult to resolve. This difficulty may be illustrated by examining some typical results found in the literature [*2*,*3*,*15–34*]. For this review, papers where chosen that compared the influence of precracking versus testing from the embedded insert on G_{IIc} values measured on the same specimen. In addition, papers were chosen that reported the ratio of precracked, or insert, G_{IIc} values to G_{Ic} values measured only from the insert to avoid the complication due to fiber bridging. These data are summarized in Table 1.

Mode II Precracking Effects

One difficulty in measuring the interlaminar shear fracture toughness is the apparent inconsistency between G_{IIc} values measured by growing the crack from a thin midplane insert versus G_{IIc} values measured by growing the crack from an initial shear precrack. For G_{Ic} values measured using the DCB test, a single generic toughness value may be obtained as