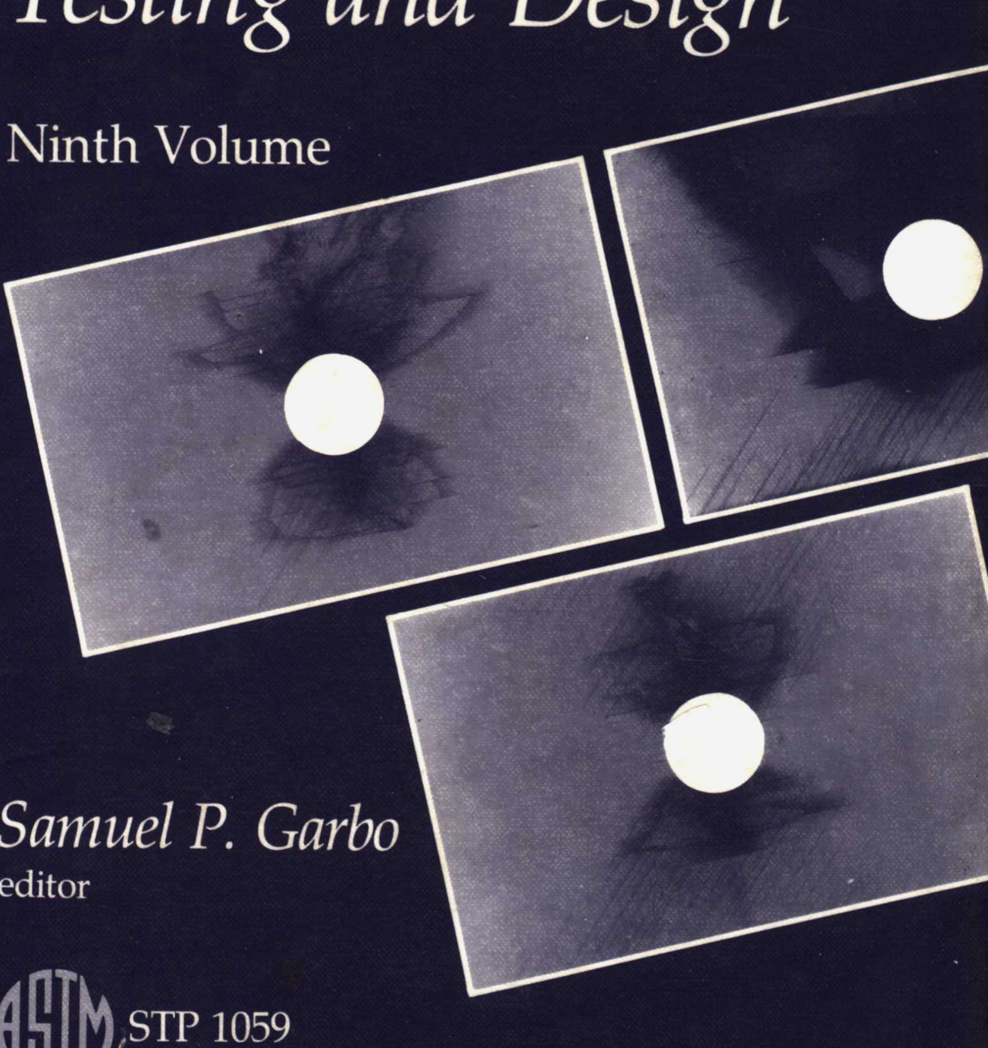
COMPOSITE MATERIALS

Testing and Design

Ninth Volume



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editor

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Composite Materials: Testing and Design (Ninth Volume)

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Foreword

This publication, *Composite Materials: Testing and Design* (*Ninth Volume*), contains papers presented at the Ninth Symposium on Composite Materials: Testing and Design, which was held on 27–29 April 1988 in Sparks, Nevada. The symposium was sponsored by ASTM Committee D-30 on High Modulus Fibers and Their Composites. Samuel P. Garbo, United Technologies Corp., presided as chairman of the symposium and also served as editor of this publication.

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Overview

The Ninth Symposium on Composite Materials: Testing and Design, upon which this publication is based, was held 27–29 April 1988 in Sparks, Nevada. The symposium was sponsored by ASTM Committee D-30 on High-Modulus Fibers and Their Composites. The focus of the symposium was on significant advances in the area of damage tolerance and durability of composite structures; however, as was true for the previous eight symposia in this series, sufficient theme freedom was permitted to allow papers on other testing and design issues. This Special Technical Publication is based upon that symposium.

Before beginning an overview of the particular papers, the Editor wishes to point out a number of background subthemes which permeated the presentations and discussions at the conference and which are found in these papers. These subthemes provide an additional context for evaluating the contributions in this volume.

One subtheme is associated with the fast-paced (historically unprecedented) development of composite material systems, material forms, and manufacturing processes which has paralleled the expanding use of high-modulus composite materials in commercial and military structural applications. The driving catalysts have been the need to increase structural efficiency markedly and the need to lower dramatically the cost per pound of manufactured composite structures. The advantage of these trends is that the composite structural designer now has virtually unlimited design options. However, there is growing concern as to whether structural designers and analysts (or certifying agencies) can cope with this still-expanding list of composite design options while maintaining historically expected levels of structural integrity and reliability.

This concern is further exacerbated by recent trends in certifying agency requirements and in commercial and military design specifications which require unprecedented and guaranteed levels of structural integrity, efficiency, reliability, maintainability, and durability. Traditional conservative elements of design have been dramatically reduced at the same time that design variables and mechanical behavior phenomena have increased or changed markedly. Thus, corollary concerns are whether traditional, hardware-program, design-development philosophies and schedules are still technically adequate, even for conventional metallic structures, and whether they represent an appropriate basis for assessing business risks when dealing with the development of new composite structures.

A second subtheme is that some of the difficiencies in hardware design, testing, and analysis and some of the structural issues of the past 20 years are still with us today. As composite applications have expanded, the need for mechanics-based studies to provide generic understanding of old, as well as new, application structural failure phenomena have expanded with it.

One implication might be that industry will simply increase experimental evaluations in what is referred to as the "building-block" design development approach. However, the reality of the composite technology revolution is that the number of design options (variables) potentially available precludes a predominately experimental approach. The development and verification of mechanics-based analytic models *must significantly expand* to provide the insight needed for properly defined and fully integrated experimental verifications.

Finally, general application discussions in this volume may provide some researchers with a perhaps disturbing awareness of how *overgeneralized* some of their originally *limited* models have become in usage. The counterpoint to this is the awareness that industries (and universities) bear a responsibility to discipline engineers to evaluate not only the mathematical manipulations of structural analysis procedures but also the mechanics-based limitations of foundation assumptions

With these subthemes in mind, the Editor has chosen to divide the papers of this publication into four subject areas: structural considerations and analysis, delamination initiation and growth analysis, damage mechanisms and test procedures, and other test and design subjects.

Structural Considerations and Analysis

The first category of papers, on structural considerations and analysis, focuses on global structural considerations related to application hardware issues. The eight papers selected cover topics ranging from overall structural qualifications or certification to the adequacy of generic material characterization data in laminate structural analysis. The main feature of this grouping of papers is that the authors are addressing composite *structural* issues, not solely composite material issues. The authors convey a common message that additional mechanistic studies are required to provide a more generic understanding of these application structural issues.

Two papers provide overviews of the current and evolving philosophies regarding the damage tolerance, durability, and qualification or certification of aircraft composite structures. Composite structure delamination-onset and fail-safety procedures are proposed using fracture mechanics, the strain energy release rate threshold criterion, and laminate analysis. Certification testing procedures are also reported which address the significant differences between metal and composite materials and propose approaches for qualification of metal and composite hybrid design concepts.

The issues of damage tolerance and durability and their implications at both the material and structural levels underlie most of the newly proposed procedures. Reported are aircraft industry requirements for increased building-block design development, experimental evaluations of structural coupons, elements, components, material configurations, environmental conditions, and loading interactions. This industry qualification trend emphasizes the large number of design options inherent in current aircraft composite structures and the lack of analytic models for accurately predicting the associated *structural* mechanical behavior. The number of design variables and structural unknowns continues to increase markedly with the growing number of new material systems, material forms, and novel fabrication procedures.

Four papers present experimental and analytic studies for evaluating the mechanical behavior of composite structural design concepts. These papers report on the extensive experimental efforts required to evaluate damage tolerance of structural hardware and the large number of design variables involved. Specific analytic models are proposed to evaluate the effects of low-velocity impact damage on the strength of laminates and stiffened composite panels and the effects of a variety of design variables on the strength of mechanically fastened composite joints.

The lamina-to-laminate analytic model for assessing the effect of impact damage is particularly appealing for industrial design usage because of its minimal input data requirements and general laminate and load condition capabilities. If verified, this model could provide industry with needed analytic insight into the effects of damage on part strength. This insight would permit development of *selective* verification test programs and reduce full-scale qualification test requirements.

While the six papers just described alert readers to new and evolving structural concerns, two other papers remind us that unresolved mechanics-based and strength prediction issues still exist. In particular, these papers question (1) the adequacy and industry acceptance of unidirectional-lamina, mechanical-property databases for use in structural analysis of fibrous composites and (2) the use of one-phase homogenous models of orthotropic lamina for strength predictions. These papers propose alternative characterization test procedures which are better suited to analysis of application laminate mechanical behavior, and a "pseudo-single-phase" strength model is also proposed which permits the fiber or resin phase to dominate, as appropriate, depending on the laminate application stress state.

Delamination Initiation and Growth Analysis

In the second category of papers, on delamination initiation and growth analysis, seven papers were selected which use fracture-mechanics-based strain energy release rates to characterize or predict delamination phenomena in composite materials or structures. The papers document studies concerning geometric or laminate-level effects on the magnitude of the strain energy release rates, the presence and extent of mixed-mode fracture, the adequacy of composite material fracture characterization test procedures, delamination initiation and the growth criterion, and the failure criterion. Results include theoretical correlations with test data obtained from various cracked lap shear, double-side-notched, double-cantilever beam, end-notched flexure, and adhesive joint specimens.

Damage Mechanisms and Test Procedures

In the third category of papers, on damage mechanisms and test procedures, six papers emphasize the continued need to assess our knowledge of basic failure characteristics and the adequacy of the test procedures used to provide generic characterization data. These studies report on experimental procedures used to evaluate the initiation and evolution of failure mechanisms in composite lamina and laminates under static and fatigue load cycles. New results are presented using vibrothermography, temperature measurement, and interrupted-ramp strain-input test techniques to evaluate time-dependent damage mechanisms, as well as to provide further insight into time-independent failure mechanisms.

Laminate and lamina test results of various material system configurations are reported which reveal significant differences in the damage mechanisms being observed in fiber-reinforced material systems that use toughened resin systems. The reported differences emphasize the need for long-term fatigue (>10 E + 5 cycles) evaluations in addition to typical static and short-term life assessments. While research continues, current and future application users are urged to perform both short-term and long-term mechanical property evaluations and to be alert for contradictory indications of property improvements, as well as time-dependent effects.

Other Test and Design Subjects

In the last category of papers, on other test and design subjects, some general interest design and analysis topics are reported. The topics include loading-rate effects, lamina-to-laminate viscoelastic predictions, the nonlinear energy failure criterion, the micromechanics of wavy fibers, torsional-test lamina characterization, and carbon-carbon interlaminar evaluations. The loading-rate and visoelastic discussions reinforce earlier papers in reporting concerns that new toughened resin systems will require more intensive evaluation of time-dependent mechanical behavior.

In summary, the Editor feels that the papers in this Special Technical Publication indicate that the original conference goals of ASTM Committee D-30 were successfully met. As a most important comment, the Editor wishes gratefully to thank the authors who contributed their research to this conference and especially those who participated in the ardors of the ASTM review process. Important thanks are also directed to the many reviewers who volunteered their time to work with ASTM staff and the Editor to review the contributed papers critically and constructively. Finally, special thanks is expressed for the tireless and often unrewarded efforts and perseverance of ASTM staff, who brought the many facets of the book production to fruition. The combined efforts of all are appreciated sincerely.

Samuel P. Garbo

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Structural Considerations and Analysis

T. Kevin O'Brien[1]

Towards a Damage Tolerance Philosophy for Composite Materials and Structures

REFERENCE: O'Brien, T. K., **"Towards a Damage Tolerance Philosophy for Composite Materials and Structures,"** *Composite Materials: Testing and Design (Ninth Volume), ASTM STP 1059*, S. P. Garbo, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 7–33.

ABSTRACT: A damage-threshold/fail-safety approach is proposed for ensuring that composite structures are both sufficiently durable for economy of operation, and adequately fail-safe or damage tolerant for flight safety. Matrix cracks are assumed to exist throughout the off-axis plies. Delamination onset is predicted using strain energy release rate thresholds. Delamination growth is accounted for in one of three ways: either analytically, using delamination growth laws in conjunction with strain energy release rate analyses incorporating delamination resistance curves; experimentally, using measured stiffness loss; or conservatively, assuming delamination onset corresponds to catastrophic delamination growth. Fail safety is assessed by accounting for the accumulation of delaminations through the thickness. A tension fatigue life prediction for composite laminates is presented as a case study to illustrate how this approach may be implemented. Suggestions are made for applying the damage-threshold/fail-safety approach to compression fatigue, tension/compression fatigue, and compression strength following low-velocity impact.

KEY WORDS: damage tolerance, threshold, fail-safe, composite materials, delamination, impact, fatigue, compression, strain energy release rate, fracture mechanics

Nomenclature

- A Coefficient in power law for delamination growth
- a Delamination size
- b Laminate half width
- c Uncracked ply thickness
- d Cracked ply thickness
- E Axial modulus of a laminate
- E_{LAM} Axial modulus before delamination
- E^* Modulus of an edge delaminated laminate
- E_{LD} Modulus of a locally delaminated cross section
- E^*_{LD} Modulus of local cross section with edge and local delaminations
- E_0 Initial modulus measured
- E_{11} Lamina modulus in the fiber direction
- E_{22} Lamina modulus transverse to the fiber direction
- G_{12} In-plane shear modulus
- G Strain energy release rate

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G_I Mode I strain energy release rate
G_{II} Mode II strain energy release rate
G_c Critical value of G at delamination onset
G_{max} Maximum G in fatigue cycle
K_ϵ Strain concentration factor
ℓ Laminate length
M Number of sublaminates formed by edge delamination
m Slope of G versus log N curve for delamination onset
n Exponent in power law for delamination growth
N Number of fatigue cycles
N_F Cycles at failure in fatigue
p Number of local delaminations through the laminate thickness
R Cyclic stress ratio in fatigue ($\sigma_{min}/\sigma_{max}$)
$2s$ Matrix crack spacing
t Thickness
t_{LAM} Laminate thickness
t_{LD} Thickness of a locally delaminated cross section
ϵ Uniaxial strain
ϵ_c Critical strain at delamination onset
ϵ_F Strain at failure
ϵ_{max} Maximum strain in fatigue cycle
σ Uniaxial stress
σ_{max} Maximum stress in fatigue cycle
σ_{min} Minimum stress in fatigue cycle
σ_{alt} Alternating stress in fatigue cycle

As composite materials are considered for primary structural applications, concern has been raised about their damage tolerance and long-term durability. The threat of barely visible, low-velocity impact damage, and its influence on compression strength, has surfaced as the most immediate concern for primary structural components such as composite wings [*1*]. Recent government programs have focused heavily on this issue in developing damage tolerance criteria that will satisfy the safety requirements of current military aircraft [*2–3*]. At the same time, research has been conducted on low-velocity impact, both in the prediction of damage accumulation during the impact [*4,5*] and in the assessment of the influence of impact damage on compression strength [*6–13*]. Several methods for improving the performance of impacted composite panels and components have been proposed. One approach is to increase the inherent toughness of the composite by using tougher resin matrices, such as toughened epoxies [*9*] and thermoplastics [*10*], or to modify the form of the material by adding tough adhesive layers during the lay-up or as interleaves in the prepreg [*12*]. In terms of wing skin design, the goal has been to increase the compression failure strain after impact above the strength of a comparable laminate with an open hole [*6,7*]. Although this goal may be achieved using clever structural design and the improvements in materials cited, other issues have yet to be adequately addressed.

Although compression strength is greatly reduced after low-velocity impact, any further reduction with subsequent fatigue cycles is minimal. Hence, impacted composite panels have very flat compression *S-N* curves [*1,6,13*]. This observation has resulted in damage tolerance criteria for composite structures that require only static loading [*2*]. However, for toughened matrix composites, where the compression strength after low-velocity impact exceeds the strength of the laminate with an open hole, a static criterion may no longer be sufficient. The compression *S-N* curve for composite laminates with an open hole is not flat, even for toughened matrix composites [*14*], because the interlaminar stresses at the hole boundary cause delaminations that form in fatigue and grow with increased number of cycles [*15*]. Furthermore, other sources of delamination (straight edges, ply drops, and matrix cracks) may exist in wing skins and other composite primary structures, such as composite rotor hubs [*16*]. Although delamination may not cause immediate failure of these composite parts, it often precipitates component repair or replacement, which inhibits fleet readiness and results in increased life cycle costs. Furthermore, delaminations from several sources may accumulate, eventually leading to catastrophic fatigue failures.

In metallic structures, damage tolerance has been demonstrated using fracture mechanics to (*a*) characterize crack growth under cyclic loading for the constituent materials, (*b*) predict the rate of crack growth in the structure under anticipated service loads, and (*c*) establish inspection intervals and nondestructive test procedures to ensure fail safety. Because composite delamination represents the most commonly observed macroscopic damage mechanism in laminated composite structures, many efforts have been undertaken to develop similar procedures for composite materials by characterizing delamination growth using fracture mechanics [*17–20*]. Although this approach is promising, there are some fundamental differences in the way fracture mechanics characterization of delamination in composites may be used to demonstrate fail safety compared with the classical damage tolerance treatment used for metals.

Previously, a damage-threshold/fail-safety approach to composite damage tolerance was proposed as an alternative to the classical approach used for metals [*21*]. The purpose of the current paper is to expand on this concept by demonstrating how a damage-threshold/fail-safety approach may be used to predict the tension fatigue life of composite laminates, and then illustrating the similarities between this application and the use of the same philosophy for predicting compression fatigue life and compression strength after low-velocity impact.

Delamination Characterization

Many papers have been published recently where the rate of delamination growth with fatigue cycles, da/dN, has been expressed as a power law relationship in terms of the strain energy release rate, G, associated with delamination growth [*17–20*]. This fracture mechanics characterization of delamination growth in composites is analagous to that of fatigue crack growth in metallic structures, where the rate of crack growth with cycles is correlated with the stress intensity factor at the crack tip. However, delamination growth in composites occurs too rapidly over a fairly small range of load, and hence G, to be incorporated into a classical damage tolerance analysis for fail safety [*18,21,22*]. Where in metals the range of fatigue crack growth may be described over as much as two orders of magnitude in G, the growth rate for a delamination in a composite is often characterized over barely one order of magnitude in G. Hence, small uncertainties in applied load may yield large (order of magnitude) uncertainties in delamination growth.

Different damage mechanisms may also interact with the delamination and increase the resistance to delamination growth. Delamination growth resistance curves may be generated to characterize the retardation in delamination growth from other mechanisms [*23–25*]. These delamination resistance curves are analogous to the R-curves generated for ductile metals that account for stable crack growth resulting from extensive plasticity at the crack tip. However, unlike crack-tip plasticity, other composite damage mechanisms, such as fiber bridging and matrix cracking, do not always retard delamination growth to the same degree. Hence, the generic value of such a characterization is questionable.

One alternative to using the classical damage tolerence approach for composites as it is used for metals would be to use a strain energy release rate threshold for no delamination growth, and design to levels below this threshold for infinite life. Metals are macroscopically homogeneous, and the initial stress singularities that create cracks at particular locations in preferred directions cannot be easily identified. Composites, however, are macroscopically heterogeneous, with stiffness discontinuities that give rise to stress singularities at known locations such as straight edges, internal ply drops, and matrix cracks. Although these singularities are not the classical $r^{-1/2}$ variety observed at crack tips, and hence cannot be characterized with a single common stress intensity factor, they can be characterized in terms of the strain energy release rate, G, associated with the eventual delamination growth.

The most common technique for characterizing delamination onset in composite materials is to run cyclic tests on composite specimens, where G for delamination growth is known, at maximum load or strain levels below that required to create a delamination monotonically. A strain energy release rate threshold curve for delamination onset may be developed by running tests at several maximum cyclic load levels and plotting the cycles to delamination onset versus the maximum cyclic G, corresponding to the maximum cyclic load or strain applied [*26–30*]. This G threshold curve may then be used to predict delamination onset in other laminates of the same material, or from other sources in the same laminate [*31*].

Damage-Threshold/Fail-Safety Approach

One concern with a no-growth threshold design criteria for infinite life has been the uncertainty inherent in predicting service loads. If service loads are greater than anticipated, then corresponding G values may exceed no-growth thresholds and result in catastrophic propagation. This concern is paramount for military aircraft and rotorcraft, where original mission profiles used to establish design loads are often exceeded once the aircraft is placed in service. However, unlike crack growth in metals, catastrophic delamination growth does not necessarily equate to structural failure. In situations where the structure experiences predominantly tensile loads, such as composite rotor hubs and blades, delaminated composites may have inherent redundant load paths that prevent failure and provide a degree of fail safety [*21*]. This degree of fail safety has led some designers to think of composite delamination as a benign failure mode. Unfortunately, delaminations may occur at several locations in a given component or structure. Delaminations will typically initiate at edges, holes, ply drops, and ultimately, matrix cracks. Hence, an iterative composite mechanics analysis that considers each of these potential sites must be performed to ensure that the structure is fail safe.

Previously, a damage-threshold/fail-safety approach for composite fatigue analysis was proposed [*21*] that involved the following steps:

1. Predict delamination onset thresholds using fracture mechanics.
2. Assume delamination threshold exceedence corresponds to complete propagation.
3. Determine the remaining load-carrying capability of the composite with delamination present using composite mechanics (i.e., check for fail safety).
4. Iterate on Steps 1 to 3 to account for multiple sources of delamination.

This type of analysis need only be applied to primary structures. However, Step 1 may be used to demonstrate the delamination durability of any composite structure by providing an assessment of component repair or replacement costs over anticipated structural service lives. Step 2 reflects a conservative way to deal with the rapid delamination growth rates observed relative to metals as discussed earlier. An alternative to Step 2 would be to predict