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Testing and Design

Tenth Volume

Glenn C. Grimes, editor

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Overview

Introduction

The ASTM Tenth Conference on Composite Materials: Testing and Design is held so experts in the field of composite materials and structures from government, industry, and academia can present, discuss, and publish the current research and development on composites and the state-of-the-art engineering applications to structures. Important composite materials technical issues like test methodology, material properties and failure criteria, advanced materials research and development, structural analysis and test verification, quality assurance, interlaminar fracture, and damage and repair are discussed.

The general subject matter and purpose of the Tenth Conference was similar to that of the First Conference that was held 21 years ago and chaired by S. Yurenka Elliott, even though the progress in composites technology since has been great. J. Whitney, who chaired the Seventh Conference, discussed this progress. In the First and Second Conferences chaired by H. T. Corten, considerable emphasis was placed on test methodology. It should also be noted that design and fracture were covered in the first two Conferences. Fatigue, creep, and moisture effects received much attention in the Third Conference chaired by C. A. Berg, F. J. McGarry, and S. Y. Elliott. Fracture and impact response was supplemented by environmental effects in the Fourth Conference chaired by J. G. Davis, Jr., whereas, the Fifth Conference chaired by S. W. Tsai covered a wide range of effects including fatigue, time-dependent behavior, and nondestructive evaluation (NDE). The Sixth Conference, chaired by I. M. Daniel, discussed toughness and damage tolerance, failure mechanics, delaminations, and strength. The Seventh Conference, chaired by J. Whitney, included the technologies of structures, failure mechanics, strength, delamination, and analysis and characterization. The Eighth Conference, chaired by J. D. Whitcomb, covered analysis, impact and compression testing, materials characterization, failure mechanisms, nondestructive evaluation, and filament wound and woven composites. Structural considerations and analysis, delamination initiation and growth, damage mechanisms and test procedures, and general interest design analysis topics were presented in the Ninth Conference chaired by S. Garbo.

A list of the previous nine conferences on this subject, along with their ASTM STP number and publication year, are shown below.

Previous ASTM Conferences on Composite Materials: Testing and Design

First Conference	ASTM STP 460 (1969)
Second Conference	ASTM STP 497 (1972)
Third Conference	ASTM STP 546 (1974)
Fourth Conference	ASTM STP 617 (1976)
Fifth Conference	ASTM STP 674 (1979)
Sixth Conference	ASTM STP 789 (1981)
Seventh Conference	ASTM STP 893 (1984)
Eighth Conference	ASTM STP 972 (1986)
Ninth Conference	ASTM STP 1059 (1988)

In the early conferences, all test methods for composites were in a state of flux and development, whereas, in the later conferences, including this one (tenth), the papers concentrated on new types of test methods such as Mode I interlaminar fracture toughness and the continuing problems of compression testing. In addition, testing was done using standardized test methods to obtain mechanical properties for evaluation and characterization purposes. Fracture type, failure mode identification, ultimate strength measurement, and ply/laminate failure criterion development were continued throughout all the conferences, but process control and nondestructive evaluation as part of the bigger quality assurance picture have been covered in several of the last six conferences. Analysis and design were covered in the early conferences and in several recent ones. Damage tolerance and resistance were covered in three of the last six conferences.

These conferences have given the composites technical community an ongoing detailed report of the progression of the testing and design technology of composites and its applications.

Summary

The keynote technical paper by Dr. J. Whitney on the status of selected testing technologies is followed by eight technical sessions. These sessions are summarized in the following paragraphs.

Session I on "Compression Test Methodology Analysis and Development" discusses the analysis of basic phenomena including the influence of fiber waviness on compressive behavior, structural applications of post-impact compressive fatigue of stitched composites, and the extension of basic test methodology to the development of a very high strain rate dynamic compression testing procedure. These papers illustrate that considerable progress has been made on issues related to the behavior of composites subject to compressive loading and represent worthy contributions to the advancement of the state of the art of compression testing of composites and simple structural elements.

The development and analysis of new and innovative test methodologies for composite materials are presented in *Session II* on "General Test Methodology Analysis and Development." The test methodologies discussed are thermomechanical fatigue and biaxial compression testing and the effect of tab orientation on test specimen response. These general test methodologies represent the state of the art in testing for the mechanical response of composite materials.

"Material Mechanical Properties and Failure Criteria" is the subject of the papers presented in *Session III*. These two technologies come together in developing allowables for specific structural design applications. In one paper, design properties for database use are generated on an intermediate modulus-high strain graphite/thermoplastic composite material. A discussion of the problems encountered in testing hot-wet graphite/polyimide laminates and appropriate technical solutions are presented in another paper. These presentations are followed by the presentation of a new failure criterion for composite laminate strength prediction. This criterion can be used with design data and appropriate analytical methods in the structural synthesis process.

In *Session IV*, "Advanced Materials Analysis and Test," the papers are concerned with the performance of fiber-reinforced metal, intermetallic, or ceramic matrix composites subject to static and fatigue mechanical loading at room and elevated temperatures. The mechanical response of silicon carbide fiber-reinforced titanium at elevated temperature is predicted and measured in the first paper, while a silicon carbide fiber-reinforced intermetallic matrix composite subject to elevated temperature fatigue testing is presented in the second paper. A deformation and failure prediction method using shear lag analysis is developed and experimentally verified for brittle matrix composites in the third paper, and a macromechanics numerical analysis on a tensile loaded unidirectional composite with a central notch is presented in the last paper for metal matrix composites. These papers show that progress in testing and analysis has been made in recent years on such advanced composite materials, but they also show the need for further research.

Making a transition from the properties of materials to their structural design application in such a manner that the structure will be safe and yet exhibit the reliability, maintainability, and supportability (RM&S) that are necessary for certification is a major task. A small segment of this broad task is covered in *Session V* on "Analysis, Test, and Certification of Structure." In the first paper, the analysis and testing of integral composite sub-elements subject to out-of-plane loadings are discussed. The design, analysis, and test of a horizontal stabilizer that is a composite-faced sandwich shell structure is presented in the second paper. In the third paper, an all-composite stub blade joint for a high-altitude, long-endurance aircraft is designed that incorporates removable composite wing structures with large spans and high aspect ratios. In the last paper, a thick quartz/polyimide V-shaped sub-element is tested in a variable load-temperature environment to measure the structural response and degradation over time. These papers illustrate some of the problems and solutions inherent in structural design and test verification of composite structure.

Session VI on "Quality Assurance and Process Control" covers the effects of processing variables, the status of automated process control, the effects of defects, and improvements in nondestructive inspection (NDI). In the first paper, co-cured sandwich panel quality variation with process changes is evaluated with destructive test procedures. The current state of the art in automated process control is presented in the second paper. This paper shows how transducers monitor the dielectric, acoustic, and fluorescent signals that are interfaced with temperature and pressure profiles during cure to determine their effect on part quality. In the third paper on the analysis of defects in composite materials, the interaction of design/analysis tools with ultrasonic nondestructive engineering data are combined to predict the performance of actual parts. Image enhancement of the ultrasonic inspection techniques allows the analyst to improve dramatically the detectability of defects. Quality assurance and process control are at the heart of acceptable quality parts and test data.

"Interlaminar Fracture Analysis and Test" are the subject of *Session VII*. Edge effects and interlaminar shear and tensile stresses and deformations are studied along with interlaminar fracture toughness and the use of adhesive film interlayers to suppress delamination in this session. Delamination from matrix cracks in multidirectional laminates and the prediction of delamination in curved unidirectional laminates are covered in the first two papers, respectively. Subsequent papers discuss fracture toughness of composite materials and the efficient use of film adhesives to suppress delamination initiation in multidirectional laminates. The technology to calculate and measure interlaminar stresses and fracture toughness properties, as well as the ability to design delamination suppression into parts, is what the composite structures design community wants and needs.

Session VIII on "Damage, Flaws, and Repairs" describes the issues that anyone designing, building, and testing composite structures must address. In the first paper, the damage tolerance of three-dimensional braided carbon/thermoplastic composites is presented. Fracture of notched laminates under loading along with its related damage tolerance are discussed in the second paper. Damage evaluation in composites using thermographic stress analysis is presented in the third paper, and the subject of composite repairs is discussed in the last paper. Increasing damage tolerance, detecting and monitoring damage, and the repair of damage are critical issues in the design application of composite materials to structures.

The Keynote technical paper plus 28 additional technical papers presented in the eight technical sessions describe the current state of the art in advanced composite materials research and test method development as well as design engineering application of composite materials to structure. Over the last 21 years, the 10 ASTM conferences have charted the technical progress made in these areas and the resulting ASTM STP publications have become industry standard reference documents.

Glenn C. Grimes

Lockheed Advanced Development Company
(Skunk Works)
Sunland, CA; symposium chairman and editor

Keynote Address

KEYNOTE ADDRESS

James M. Whitney [1]

Reflections on the Development of Test Methods for Advanced Composites

REFERENCE: Whitney, J. M., **"Reflections on the Development of Test Methods for Advanced Composites,"** *Composite Materials: Testing and Design (Tenth Volume), ASTM STP 1120,* Glenn C. Grimes, Ed., American Society for Testing and Materials, Philadelphia, 1992, pp. 7–16.

ABSTRACT: The importance of analyzing failure modes in conjunction with the development of test methods is discussed. Illustrations are chosen from four classic areas of interest: flex testing of unidirectional composites exposed to moisture, the short beam shear test, the edge delamination test, and two configurations of the Illinois Institute of Technology Research Institute (IITRI) compression test method. In each of these tests, the failure mode is an important consideration in accepting and interpreting the resulting data.

KEYWORDS: failure modes, test methods, composite materials, short beam shear, edge delamination test, compression testing, compressive failure

The need to evaluate composite material test methods has increased in recent years as a result of the complex nature of data required for design considerations. In the early development of test methods for advanced composites, there was a tendency to use techniques originally developed for metals technology. However, the heterogeneous, anisotropic nature of fiber-reinforced composites required that any test method borrowed from metallic technology be carefully scrutinized before being applied directly to the characterization of composite materials. A number of papers in the technical literature addressed test methods from a theoretical standpoint.

Analysis has played an important role in the development of test methods. The work by Pagano and Halpin [*1*] on the end constraint problem associated with off-axis tension testing of unidirectional composites was instrumental in restricting the ASTM Test for Tensile Properties of Fiber-Resin Composites (D 3039) to orthotropic materials. The analysis by Rosen [*2*] on the tension testing of $[\pm 45°]_S$ led to the development of ASTM Practice for In-plane Shear Stress-Strain Response of Unidirectional Reinforced Plastics (D 3518). Analytical work performed in conjunction with laminated beams [*3*] led to the revision of ASTM Tests for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials (D 790) to accommodate advanced composite materials. Other examples can be cited in which analysis played an important role in the development or revision or both of ASTM standards for composite materials.

[1] Formerly, acting chief, Mechanics and Surface Interactions Branch of the Materials Laboratory, Wright Research and Development Center, Wright-Patterson Air Force Base, OH 45433-6533; now, professor of graduate materials engineering, University of Dayton, 300 College Park, Dayton, OH 45469-0240.

Although the importance of analysis in the development of experimental techniques is well recognized, attention in the present paper is concentrated in the area of failure modes associated with certain test methods. In particular, the failure mode assumed in conjunction with a given data reduction scheme may not be attained in practice. Ignoring this fact can lead to erroneous data in conjunction with material properties or material behavior.

Flex Testing of Unidirectional Composites Exposed to Moisture

Flexure tests (ASTM Tests D 790) are often used in conjunction with 0° unidirectional composites. Although the test standard refers to the calculation of "flexural strength," the test results are often compared to tensile strength data. Thus, the failure process is assumed to be dominated by the tensile strength of the fiber. For unidirectional graphite/epoxy composites exposed to moisture, resin softening occurs at temperatures considerably below the dry glass transition temperature of approximately 175°C. Because 0° unidirectional tension is assumed to be a fiber-dominated property, moisture should have little effect on tensile strength. Although 0° graphite/epoxy composites showed little effect of moisture on tensile strength, flexural strength was dramatically reduced at moderately elevated temperatures because of the presence of moisture.

This behavior was not understood because of the assumed similarity between flexure strength and tensile strength of 0° unidirectional composites. It was shown, however, that the difference in strength was due to a change in failure mode from fiber dominated to matrix dominated (interlaminar fracture) [*4*]. This change in failure mode is illustrated in Fig. 1 for four-point loading of a graphite/epoxy unidirectional composite. The numbers in parentheses represent the number of samples used in obtaining each data point.

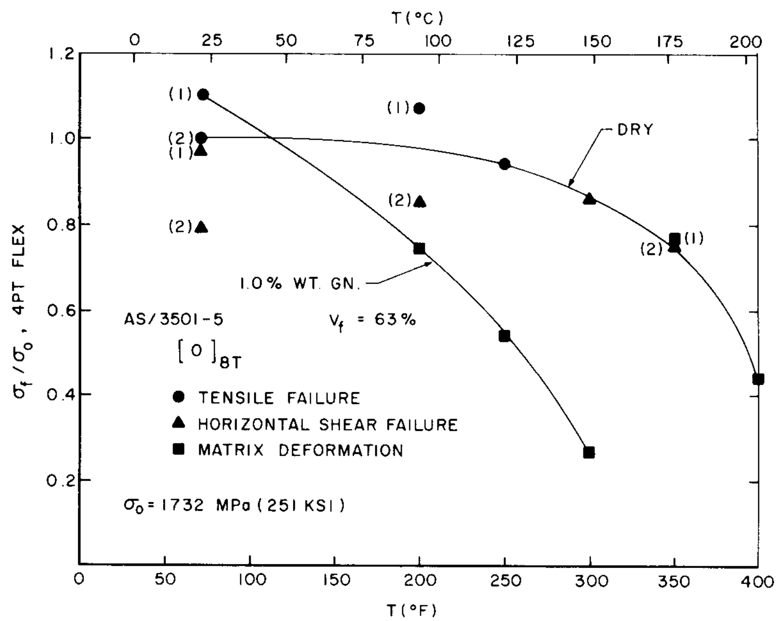

FIG. 1—*Flexure data, four-point loading of AS/3501-5 specimens* [4]. *Numbers in parentheses indicate sample size used in obtaining the corresponding data point.*

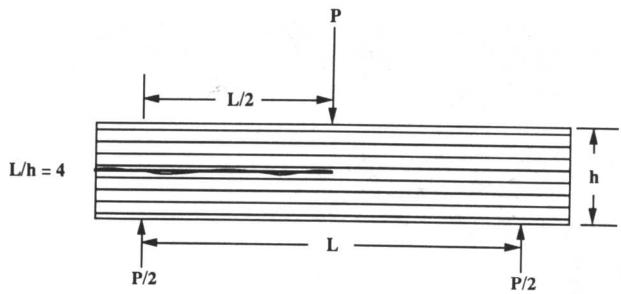

FIG. 2—*Short beam shear specimen.*

Short Beam Shear Tests

A classic example of the importance of failure mode can be observed in conjunction with the ASTM Test for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short Beam Method (D 2344). As illustrated in Fig. 2, this test method involves loading a beam under three-point bending with the span-to-depth-ratio, L/h, chosen such that an interlaminar failure is induced along the centerline rather than a tensile failure in the bottom surface of the beam. ASTM Test D 2344 used in conjunction with thin 0° unidirectional beams, which is common with graphite/epoxy, usually does not yield interlaminar failure. Such data are often reported in the literature without mentioning the failure mode, leaving the reader to believe that the desired failure mode was attained. The photomicrograph in Fig. 3 [5] shows a compressive buckling failure adjacent to the load nose for a 16-ply graphite/epoxy unidirectional short beam shear specimen.

An interlaminar failure can be produced by a thick short beam shear specimen, as illustrated in Fig. 4 [5]. The horizontal split, however, is accompanied by a vertical crack. This 50-ply specimen allows the distance between the load nose and supports to be increased for a 4:1 span-to-depth ratio compared to the thin 16-ply beam specimen. It should be noted that the

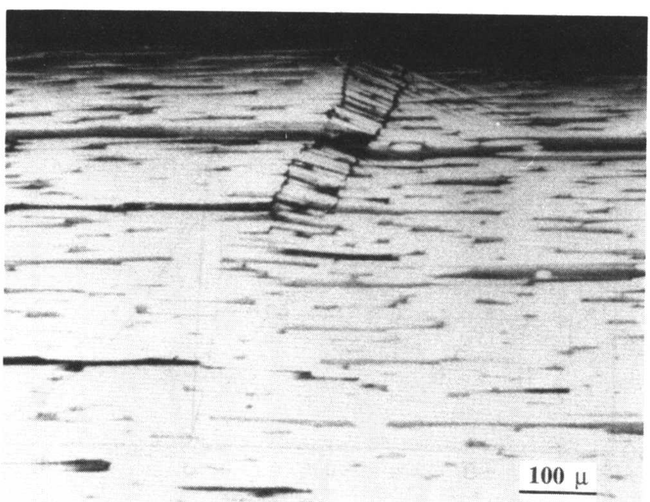

FIG. 3—*Compressive failure in 16-ply AS-1/3502 graphite/epoxy unidirectional short beam shear specimen. Load applied to the right of the damage region* [5].

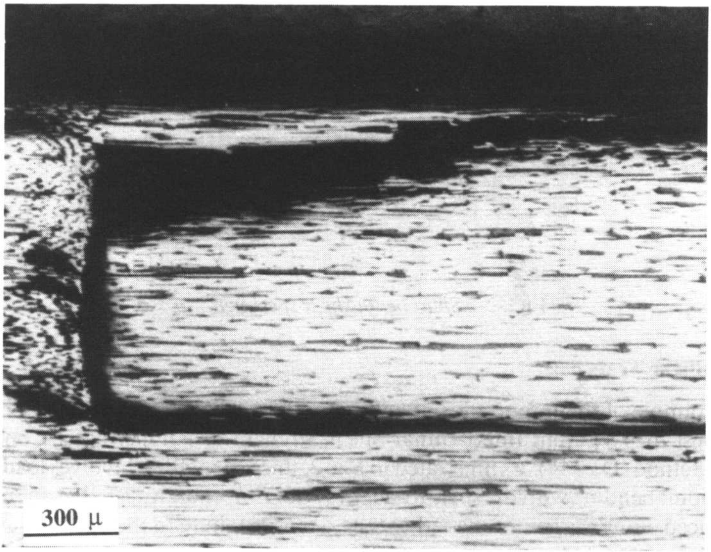

FIG. 4—*Failure mode in 50-ply AS-1/3502 graphite/epoxy unidirectional short beam shear specimen. Load applied to the left of the vertical crack* [5].

interlaminar failure of the 50-ply beam does not occur along the centerline but in the upper quarter of the beam.

Stress distributions obtained from classic theory of elasticity [6] are shown in Fig. 5 for the 50-ply short beam shear specimens. The normalized stress components, σ_ζ, σ_η, and $\tau_{\zeta\eta}$, represent the bending stress, through-the-thickness normal stress, and interlaminar shear stress,

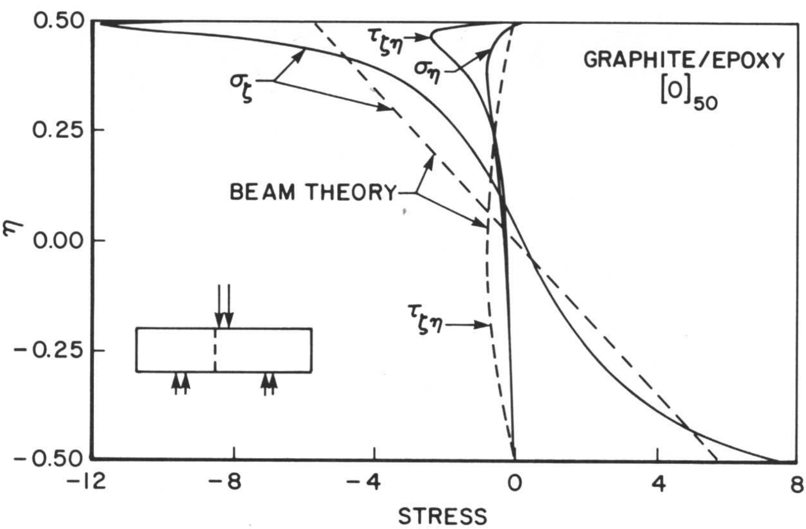

FIG. 5—*Stress distribution through-the-thickness for a 50-ply short beam shear specimen, L/h = 4* [6].