Damage Detection In Composite Materials

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Peer Review Policy

Each paper published in this volume was evaluated by three peer reviewers. 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 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, *Damage Detection in Composite Materials,* contains papers presented at the International Symposium on Damage Detection and Quality Assurance in Composite Materials, which was held in San Antonio, Texas, 13–14 Nov. 1990. The symposium was sponsored by ASTM Committee D-30 on High Modulus Fibers and Their Composites in cooperation with the American Society for Composites. John E. Masters, Lockheed Engineering and Science Company, NASA Langley Research Center, Hampton, Virginia, served as chairman of the symposium. Session chairmen were Wayne Stinchcomb, Virginia Polytechnic Institute and State University, and P. H. Johnston, NASA Langley Research Center, Hampton, Virginia.

Contents

Overview

Defining the effects of defects and damage on composite material stiffness, strength, and life has long been a subject of investigation in the composites community. Indeed, ASTM Committees D-30, E-9, E-24, and E-7 individually and jointly sponsored several symposia on the subjects in the early 1980s.

Our knowledge of composites has advanced significantly in the intervening years. Structural design and nondestructive test techniques have evolved as increased emphasis has been placed on durability and damage tolerance. The materials have likewise improved. Tough thermoplasic and thermoset resins have been developed to improve impact and delamination resistance. Ceramic and metal matrix systems have also evolved to address high-temperature applications.

The objective of this symposium was to detail the effects of these advances in material design and non-destructive evaluation (NDE) on composite material usage. Designing, building, certifying, and maintaining a composite structure requires the coordinated efforts of the material scientist, the stress analyst, and the NDE specialist. The interaction of these disciplines was the theme of the meeting.

Sixteen papers are included in these proceedings. They capture the interdisciplinary nature of this work. Advances in NDE techniques are the focus of several of the papers. They highlighted the refinements that have been made to ultrasonic and X-ray imaging techniques. These papers also introduce new, emerging technologies and unique measurement concepts. A number of papers, on the other hand, focus on developing the mechanics tools necessary to establishing the flaw criticality from the NDE measurements. Papers in this category feature mathematical models which predict mechanical response of a material containing manufacturing or service-induced damage.

The manuscripts may be organized into two broad categories based on their general content and approach. A short précis of each paper is included here to assist the readers in identifying works of particular interest.

Advanced Imaging and Measurement Techniques

The ability to locate and define damaged regions within composite material structures has greatly improved over the years as radiographic and ultrasonic techniques have become more sophisticated. Advances in these technologies were reflected in a number of papers.

Bathias and Stock et al., for example, provided examples of the latest developments in the application of X-rays to NDE of composites. The former used a medical scanner to study damage in graphite/epoxy and fiberglass/epoxy laminates subjected to impact, tension, and compression loading. Most of the internal damage was observed using X-ray tomography. Stock and his associates used X-ray tomographic microscopy, a high-resolution variant of industrial computed tomography, to investigate five metal matrix composite systems. They outlined an experimental approach for nondestructively quantifying damage evolution with this technique.

Advanced ultrasonic imaging techniques were discussed in the paper by Steiner. He used automated, multi-axis robotic systems to scan graphite/epoxy laminates and then digitized the ultrasonic information to utilize powerful computer graphics image enhancement techniques to aid in the interpretation of the results. A variety of ultrasonically detectable defects such as porosity, contaminations, delaminations and impact damage were interrogated.

While flaw identification and location are vital inspection functions, several investigators have investigated the possibility of extracting additional information from their NDE measurements to yield quantitative data on the material.

Simpson and McClung, for example, employed ultrasonic property measurements such as shear and longitudinal wave velocities and attenuation to detect fatigue damage in fiberglass/epoxy energy storage flywheels. The material's elastic constants were determined and the behavior of the ultrasonic properties was assessed as a function of the specimen's strain and fatigue history. The authors concluded that the velocities are excellent indicators of the maximum strain incurred at each point in the flywheel, and that attenuation delineates the region in which the stress is high enough to initiate microcracking.

Osiroff and Stinchcomb used dynamic mechanical analysis (DMA), a technique commonly used to characterize polymeric materials, to assess damage in laminated graphite/thermoplastic specimens. The effects of fatigue damage on the time, temperature, and frequency response of laminates subjected to different amounts of fatigue loading were determined in this study. The authors interpreted the DMA results in terms of other conventional measures of fatigue response such as the change in dynamic stiffness and residual strength. They concluded that, although much work remains to be done, the application of the technique to composites holds a great potential for applications such as characterization of interfacial behavior and damage detection and characterization.

An analogous approach was proposed by Heuillet et al. in their efforts to characterize damage in solid rocket propellant. They proposed an experimental approach which measures an energetic quantity that is sensitive to cumulative damage that develops in these particulate composites. The energy variable is defined from the measure of the irreversible energy loss which is dissipated in the dewetting process of particles from the elastomeric binder. The dissipated energy is found to be load path independent and uniquely related to the maximum deformation undergone in this material system.

The emerging fiber optical technology holds great potential for composite structures. Optical fiber transducers embedded within the composite to measure strain in the structure during a service cycle and to detect damage that might shorten service life are envisioned for large engineering structures of the future. Demirdogen et al. described an optical fiber transducer used to measure bending strains in a structure. Their paper details the development of the mathematical model for the attenuation of light as a function of the curvature and stress on the serpentine fiber transducer developed for this application.

Dunyak et al. applied a variety of NDE techniques including ultrasonic C-scans, acoustic microscopy, X-ray radiography, thermography, acousto-ultrasonics, and acoustic emissions to ceramic matrix composite materials. These NDE data were correlated with the performance of tubular specimens loaded in uniaxial tension. The authors correlate initial defects in the material to observed damage development. They also performed failure surface analysis to identify critical performance-limiting defects in chopped fiber-reinforced borosilicate glass. The work provides an information base on the application of these techniques to assist researchers in planning and selecting NDE methods for ceramic composites.

Manufacturing Defects and Service-induced Damage Mechanics Modelling

Once an imperfection has been identified and located, its criticality must, of course, be established to define the appropriate response. A number of manuscripts contained in this volume discuss mechanics models which relate flaw size and location to material mechanical response. These are the tools which will be used to define the severity of the flaw.

The sources and nature of these flaws are many and varied. For organizational simplicity, two general categories, manufacturing defects and service-related damage, have been defined. Investigations of both are represented in this volume.

Manufacturing Defects

A wide variety of materials and manufacturing defects were investigated by the authors.

Zenkert employed a fracture mechanics approach to predict the effects of four common manufacturing defects on the strength of foam core sandwich beams. Flaws modelled included foam/core debonding, debonding at the foam core mid-plane, and two core butt-joint defects. He computed fracture mechanics parameters, i.e., stress intensity factors and energy release rates, using both analytical and numerical methods for these flaws and predicted their effect on the load-bearing capability of the sandwich structures. Reductions varied by factors which ranged from 1.5 to 4.9 depending on the flaw type. The predictions agreed well with experimental results.

The effect of porosity, defined by the authors as voids in the matrix material, on fatigue strength of fiberglass/epoxy laminates was investigated in the study by Dill et al. They conducted an experimental program in which porous and nonporous fiberglass specimens were cycled in zero to maximum ($R = 0$) loading over lifetimes ranging from a few hundred to a few million cycles. The authors observed that if voids are assumed to constitute stress concentration factors which accelerate the breakdown of the matrix material, then a fatigue strength reduction factor of about 1.5 to 1.2 may be inferred from the data. These results were consistent with their finite element analysis results.

Matrix cracking and multiple level delaminations around holes in composite aircraft components due to over-torquing of fasteners was the subject of the paper by McRae et al. They developed an ultrasonic imaging technique to acquire ultrasonic data which represent a three-dimensional volume of the laminate in the region surrounding the fastener. In this technique, two data sets, one from each surface, were collected from the specimen, deconvolved with respect to the transducer impulse response, and combined to form a more complete unified ultrasonic image. This approach was necessary because delaminations near the outer surface will obscure those located deeper within the specimen.

Linking advanced nondestructive evaluation data directly to mechanics analyses. Frankle described software that permits digital NDE results to be input to finite element analysis. The code automatically assigns measured parameters such as X-ray density of ultrasonic attenuation to integration points in a three-dimensional finite element analysis. These parameters are then used to modify the material properties input to the analysis in order to characterize anomalies in a part. When fully developed, this technique can form the basis of a system for the automated and quantitative evaluation of anomalous parts.

Service-Induced Damage

Damage that developed as a result of in-service conditions, specifically impact loading and fatigue cycling, was also the subject of a number of investigations reported here.

Modelling impact damage in laminated composites was the subject of two papers. Chester and Clark review their combined analytical and experimental approach to impact damage modelling. They developed a simple two-ply model which examines each lamina interface in a laminate to predict delamination locations. Then, using inclusions to simulate the shape and extent of delaminations present in the impact-damaged zone, they conducted an experimental study to establish which microstructural features are of major importance in determining the strength of the damaged laminate.

In the second paper on this subject, Girshovich et al. reviewed the results of their ultrasonic and radiographic investigations of impact-induced damage in 48-ply-thick graphite/epoxy laminates. Laminate compression strengths after impact were then predicted using a simplified damage model which applies classical laminated plate theory to calculate the effective elastic moduli of sublaminates created within the laminate upon impact and to determine load redistribution among the sublaminates.

Henaff-Gardin et al. characterized the transverse ply cracking in cross ply laminates subjected to tension-tension fatigue loading. They developed a fatigue-cracked surface propagation law based on a fracture mechanics approach to describe the damage development. This model—which incorporates two damage parameters, average crack length, and crack density—is independent of stacking sequence.

The evaluation of damage progression in a composite material hip implant during multiaxial fatigue loading was the subject investigated by Gavens et al. They utilized compliance or stiffness measurements, surface replication, ultrasonic measurements, acoustic emission, and acousto-ultrasonics to monitor damage. The authors concluded that radiography and surface replication were most effective in their application. They noted that, due to the nature of the damage in these specimens, structural stiffness and acousto-ultrasonic methods did not provide an adequate indication of damage accumulation.

It is hoped that the papers presented in this volume will aid investigators in the composites and NDE fields. It is also hoped that additional symposia will be held as this body of knowledge continues to be developed.

The editor would like to gratefully acknowledge the many contributions provided to this volume by the authors, reviewers, and the ASTM staff.

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