Experimental Characterization of Advanced Composite Materials

Third Edition

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Dedications

D.F.A.: To my wife and very best friend, Roberta,

mother of our four children, Dave, Dan, Doug, and Jayne

L.A.C.: To the memory of Dr. Alf de Ruvo,

coadvisor of my Ph.D. dissertation and long-time friend.

R.B.P.: To the memory of Professor Roy McCullough

for his three decades of warm and supportive friendship.

Preface

The experimental characterization of composite materials has been an elusive topic, because it has been a continually evolving one. As new types of composites have been developed and new applications found, new testing challenges have continually evolved. For example, in the 1960s the primary structural composite material available to compete with metals consisted of carbon fiber in a brittle epoxy matrix, a material of relatively low toughness. Thus, toughness as a property was de-emphasized by the composite materials community. However, by the beginning of the 1980s, many new matrix materials, e.g., toughened epoxies and high-temperature thermoplastics, were being incorporated to produce toughened composites. Obviously, the need quickly arose to develop test methods for ranking the relative toughness of composite materials. But there are multiple definitions of toughness, damage tolerance, and the effect of defects. Soon many test methods not previously applied to composites were being proposed, including Mode I, II, and mixed-mode fracture mechanics, beam and plate impact, compression after plate impact, and open-hole tension and compression.

This evolution of test methods to meet new demands has continued over the years as additional aspects have risen in importance; e.g., influences of temperature, moisture, solvents, and other factors affecting durability. Improvements in fiber–matrix interfacial bonding, the introduction of organic fibers such as aramid, polyethylene, liquid crystal polymer, and natural forms such as hemp and jute, and ultrahigh modulus inorganic fibers, particularly carbon, also have occurred. Likewise, new classes of matrix materials such as bismalimides, polyimides, and many others have necessitated still more test methods, or revisions of existing ones.

As we now enter the 21st century, applications of all types of composite materials to commercial products are being emphasized. In anticipation of this development, the 1990s were a period of consolidation of test methods, and attempts to better understand those methods being used. Thus, the present text comes at an opportune time, i.e., when the evolution of test methods is in a relatively stable period and definitive recommendations can be made. The goal of this text is to present primarily only those mechanical test methods that have achieved some consensus as being the best presently available, recognizing that "best" is often subjective.

The primary audience for this text will be university, junior college, and technical school undergraduate students, and beginning university graduate students, taking a course in experimental mechanics of composite materials.

However, this text also addresses a much larger audience. Quite frequently, engineers and technicians in industry and government laboratories are assigned composite material testing responsibilities, but have little or no prior experience. These individuals are associated with a wide range of organizations, including corporate research, federal laboratories, university research, material suppliers, contract design organizations, and custom fabrication shops. They need to choose among competing test methods, to perform or supervise the performance of mechanical testing, and then interpret the experimental data obtained. In this sense this text complements American Society for Testing and Materials (ASTM) and other standards. This text is sufficiently straightforward and concise in its presentation to appeal to this group if individuals who need a quick start.

Another potential audience includes those who attend composite material characterization short courses and tutorials. The present text, because of its concise wording and numerous figures and tables, will serve both as a set of course notes and a permanent reference source of topics covered.

The 14 chapters of the text are organized to meet the class laboratory schedule needs of a one-semester or one-quarter course. Specific topics (chapters) can be deleted as required to fit the actual time available. The text is intended to be self-contained, with no reference texts required.

The first four chapters provide an introduction to the special terminology and conventions that have evolved related to composite materials (Chapter 1), a summary of the unique analysis methods and data reduction formulas required (Chapter 2), sufficient laminate processing information to permit the reader to fabricate his or her own composites for testing (Chapter 3), and details of specimen preparation and testing equipment required (Chapter 4).

Chapters 5 through 10 each cover a specific aspect of lamina testing, including tension, compression, shear, flexure, off-axis tension, and thermoelastic response. Extensions of these principles to laminate mechanical and thermoelastic response are covered in Chapters 11 and 12, respectively. The composite durability issues referred to previously are detailed in Chapter 13 (effects of defects) and Chapter 14 (fracture mechanics). Of particular note among the appendices is Appendix C, which contains a sample laboratory report. This is intended to serve as a guide for the reader in the preparation of an acceptable form of data analysis and presentation.

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Acknowledgments

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Dr. Adams received his B.S. in mechanical engineering from the University of Illinois (1957), his M.S. in mechanical engineering from the University of Southern California (1960), and his Ph.D. in theoretical and applied mechanics from the University of Illinois (1963).

His industry experience was with Northrop Aircraft Corporation, Hawthorne, CA (3 years), the Aeronutronic Division of Ford Motor Company, Newport Beach, CA (4 years), and the Rand Corporation, Santa Monica, CA (5 years). He joined the University of Wyoming in 1972.

Dr. Adams has been involved full time in composite materials analysis, testing, and design for 40 years. He headed a very active interdisciplinary composite materials research group at the University of Wyoming for many years, which was involved in a broad range of government and industry programs. Dr. Adams continues to serve on a number of national committees and review boards, and is a member of the editorial boards of four prominent composite materials journals. He is very active in the test methods committees of American Society for Testing and Materials (ASTM) and MIL-HDBK-17. He regularly presents seminars and short courses both in the U.S. and elsewhere, and has published extensively in the journal literature.

Leif A. Carlsson, Ph.D., received his advanced degrees from Uppsala University and Chalmers University of Technology in Sweden. After completion of his formal education, he spent a postdoctoral year at Rensselaer Polytechnic Institute in Troy, New York. He then returned to Sweden and served as head of the composites section at the Aeronautical Research Institute of Sweden (FFA). When he returned to the U.S., he assumed a visiting position at the Center for Composite Materials at the University of Delaware, after which he joined the faculty of mechanical engineering at Florida Atlantic University. Dr. Carlsson has published extensively in the areas of mechanics and fracture mechanics of composite materials and sandwich structures.

R. Byron Pipes, N.A.E., Goodyear Professor of Polymer Engineering (Effective December 1, 2001) served as president, Rensselaer Polytechnic Institute from 1993 to 1998. As Distinguished Visiting Scholar at the College of William and

Mary, he pursued research at the National Aeronautics and Space Administration (NASA) Langley Research Center in the field of carbon nanotechnology during 1999 to 2001. He was provost and vice president for academic affairs at the University of Delaware from 1991 to 1993 and served as dean of the College of Engineering and director of the Center for Composite Materials during 1977 to 1991 at the same institution. Dr. Pipes was elected to the National Academy of Engineering in 1987 and the Royal Swedish Academy of Engineering Sciences in 1993. He was appointed Robert L. Spencer Professor of Engineering in 1986 in recognition of his outstanding scholarship in the field of polymer composite materials ranging over the subject areas of advanced manufacturing science, durability, design, and characterization. He is the author of more than 100 archival publications, including four books, and has served on the editorial boards of four journals in his field. Dr. Pipes has been recognized for his leadership in creating partnerships for university research with the private sector, government, and academia. He served as one of the first six directors of National Engineering Research Centers of the National Science Foundation (NSF). Dr. Pipes received his doctoral degree in mechanical engineering from the University of Texas and the M.S.E. from Princeton University. He is the recipient of the Gustus L. Larson Award of Pi Tau Sigma and the Chaire Francqui, Distinguished Faculty Scholar Award in Belgium. He holds fellow rank in ASC, American Society of Mechanical Engineers (ASME), and SAMPE. Dr. Pipes has served on a number of National Research Council panels as both member and chair, and served two terms on the National Materials Advisory Board.

Table of Contents