

PRINCIPLES OF COMPOSITE MATERIAL MECHANICS

SECOND EDITION

Ronald F. Gibson



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PRINCIPLES OF COMPOSITE MATERIAL MECHANICS

SECOND EDITION

Dedication

*To my wonderful family, Maryanne, Tracy, Tola, Sophie, and Aidan,
and the memory of my parents,
Jim and Lora Gibson*

About the Author

Ronald F. Gibson is a professor of mechanical engineering and director of the Advanced Composites Research Laboratory at Wayne State University. Dr. Gibson received his B.S. degree in mechanical engineering from the University of Florida, his M.S. in mechanical engineering from the University of Tennessee, and his Ph.D. in mechanics from the University of Minnesota. He has held full-time faculty positions at Iowa State University, the University of Idaho, and Wayne State University, and visiting faculty positions at Stanford University, the University of Florida, and Michigan State University. He has been a development engineer for Union Carbide Corporation and a summer faculty fellow at the NASA Langley Research Center.

Dr. Gibson is an active member of numerous professional societies, including the American Society of Mechanical Engineers, the American Society for Composites, the American Society for Testing and Materials, the Society for Experimental Mechanics, and the Society for the Advancement of Material and Process Engineering. He has served the American Society for Composites as its president, vice-president, and membership secretary. He has been the recipient of the Hetenyi Award for Best Research Paper of the Year from the Society for Experimental Mechanics, the College of Engineering Outstanding Faculty Award from the University of Idaho, the Distinguished Faculty Fellowship Award, the Devlieg Professorship, and the Outstanding Graduate Faculty Mentor Award from Wayne State University. He is an elected Fellow of the American Society of Mechanical Engineers and the American Society for Composites. The results of his research have been published in numerous scholarly articles and presented at a variety of national and international meetings.

Preface to First Edition

Composite materials is truly an interdisciplinary subject, and the number of students taking courses in this area is steadily increasing. Books on the subject tend to emphasize either the mechanics or the materials science aspects of composites. *Principles of Composite Material Mechanics* is mechanics oriented. Composite materials technology is new enough for many working engineers to have had no training in this area, so a textbook in composite material mechanics should be useful not only for the education of new engineers, but also for the continuing education of practicing engineers and for reference. The high level of interest in composite materials, the interdisciplinary nature of the subject, the need to re-educate practicing engineers, and the need for a new composite mechanics textbook at the introductory level all led to my decision to write this book.

Chapters 1 through 7 form the basis of a one-semester senior/graduate-level course in mechanical engineering, which I have taught for the last 15 years. Chapters 8 through 10, along with selected papers from technical journals and student research projects/presentations, form the basis of a second one-semester course, which is taken only by graduate students, and which I have taught for the last four years. The book could also be the basis for a two-quarter sequence by omitting some topics. Prerequisites for the course are knowledge of mechanics of materials, introduction to materials engineering, and ordinary differential equations, and previous exposure to linear algebra is highly desirable. For some of the graduate-level material, earlier courses in advanced mechanics of materials, elasticity, and partial differential equations are recommended, but not required.

Some of the basic elements of composite mechanics covered in this book have not changed since the first books on the subject were published in the 1960s and 1970s, and, where possible, I have tried to use the accepted terminology and nomenclature. For example, the coverage of stress-strain relationships and transformation of properties for anisotropic materials in Chapter 2 and the classical lamination theory in Chapter 7 is consistent with that of previous textbooks such as the *Primer on Composite Materials* by Ashton, Halpin, and Petit, and *Mechanics of Composite Materials* by Jones. However, rather than beginning the study of laminates by jumping directly into classical lamination theory, I have concluded that a better pedagogical approach is to introduce first basic laminate concepts by

using the simpler theory of laminated beams in pure flexure. Also, I believe that the concept of an effective modulus of an equivalent homogeneous material, which had previously been covered only in advanced books such as *Mechanics of Composite Materials* by Christensen, is essential for the proper development of heterogeneous composite micromechanics. Thus, effective modulus concepts are emphasized from their introduction in Chapter 2 to their use in the analysis of viscoelastic and dynamic behavior in Chapter 8.

Although many basic concepts have been presented in earlier textbooks, numerous new developments in composite mechanics over the last two decades have made it increasingly necessary to supplement these books with my own notes. Thus, I have added coverage of such important topics as hygrothermal effects in Chapter 5, discontinuous fiber composites in Chapter 6, viscoelastic behavior and dynamic behavior in Chapter 8, fracture in Chapter 9, and mechanical testing in Chapter 10. The coverage of experimental mechanics of composites has been expanded to include summaries of the most important ASTM standard test methods, many of which did not exist when the early mechanics of composites books were published. A variety of example problems and homework problems, a number of them related to practical composite structures, are also included.

The contents of this book represent the cumulative effects of more than 25 years of interactions with colleagues and students, and I would be remiss if I did not mention at least some of them. My fascination with composites began in 1965 with my first engineering position in what is now part of Oak Ridge National Laboratory in Tennessee, where I was involved in the design and development of high-speed rotating equipment. At that time I realized that the advantages of using composites in rotating equipment are numerous, as is the case in many other applications. My experiences working with Dean Waters and other colleagues in the mechanical development group in Oak Ridge have had a strong influence on my later career decision to emphasize composites research and education. My doctoral research on vibration damping characteristics of composites with Robert Plunkett at the University of Minnesota further cemented my desire to continue working in the composites area and ultimately led to my career in university teaching and research.

After beginning my academic career at Iowa State University in 1975, I began a long and productive association with C.T. Sun, and later had the pleasure of spending a one-year leave working with C.T. and his colleagues Robert Sierakowski and Shive Chaturvedi at the University of Florida. I owe much of my understanding of composite mechanics to interactions with them. The notes leading to this book were developed by teaching composite mechanics courses at Iowa State University, the University of

Idaho, the University of Florida, Michigan State University, and Wayne State University, and I am indebted to the students who took my classes and helped me to “debug” these notes over the years. Most recently, my students at Wayne State University have been particularly effective at finding the inevitable errors in my notes. Interaction with my graduate students over the years has contributed immeasurably to my understanding of composite mechanics, and the work of several of those students has been referred to in this book. I am particularly indebted to Stalin Suarez, Lyle Deobald, Raju Mantena, and Jimmy Hwang, all former graduate students at the University of Idaho.

Serious work on this book actually began during a sabbatical leave at Michigan State University in 1987, and I am indebted to Larry Drzal and his colleagues for our many stimulating discussions during that year. Particularly important was the interaction with Cornelius Horgan, with whom I team-taught a course on advanced mechanics of composites. Most recently, my collaboration with John Sullivan and his colleagues of the Ford Scientific Research Laboratory has proved to be very rewarding, and I am indebted to John for his careful review of the manuscript and helpful comments. I am grateful to Carl Johnson, also of the Ford Scientific Research Laboratory, for his encouragement and support and for providing several of the figures in Chapter 1. The strong support of Wayne State University, which made it possible to establish the Advanced Composites Research Laboratory there in 1989, is gratefully acknowledged. The support and encouragement of my department chairman, Ken Kline, has been particularly important. Generous support for my composites research from numerous funding agencies over the years has also helped to make this book possible. Grants from the Air Force Office of Scientific Research, the National Science Foundation, the Army Research Office, the Boeing Company, and the Ford Motor Company have been particularly important.

McGraw-Hill and I would like to thank the following reviewers for their many helpful comments and suggestions: Charles W. Bert, University of Oklahoma; Olivier A. Bauchau, Rensselaer Polytechnic Institute; Shive Chaturvedi, Ohio State University; Vincent Choo, New Mexico State University; John M. Kennedy, Clemson University; Vikram K. Kinra, Texas A & M University; C.T. Sun, University of Florida; and Steven W. Yurgartis, Clarkson University.

Finally, my wife and best friend, Maryanne, has been my strongest supporter as I labored on this project, and there is no way that I could have done it without her love, encouragement, patience, and understanding.

Ronald F. Gibson ★

Preface

There have been many developments in mechanics of composite materials since the first edition of this book was published. Accordingly, the second edition has new sections on recent applications of composite mechanics to nanocomposites, composite grid structures, and composite sandwich structures. To strengthen the emphasis on the basic principles of mechanics, I have added a review of the basic mechanics of materials equations in the Introduction, and appendices covering the derivations of stress equilibrium equations and strain–displacement relations from elasticity theory. Coverage of micromechanics in Chapter 3 has been revised to include more detailed discussions of elasticity and finite element models. Chapter 4 on strength analysis has been updated to include results from the World Wide Failure Exercise. Chapter 8 has been improved by adding a phenomenological approach to understanding linear viscoelastic behavior of composites. Chapter 9 on fracture has been updated to include coverage of the finite element implementation of the virtual crack closure technique. Chapter 10 on testing of composites and their constituents has been extensively updated to include coverage of both new and revised ASTM standard test methods. Finally, more example problems and homework problems have been added to most chapters, and new references have been cited throughout.

As with the first edition, I am indebted to many colleagues, graduate students, and sponsors. I am grateful to Wayne State University for providing a nurturing environment for my teaching and research, and for granting me sabbatical leaves, which were essential to the completion of this project. My graduate students have been particularly helpful in identifying the inevitable errors in the first edition, and their thesis research findings have enabled me to add important new dimensions in the second edition. And as with the first edition, my wife and best friend, Maryanne, has continued to be my strongest supporter, and I will be forever grateful for her love, encouragement, patience, and understanding.

Ronald E. Gibson

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