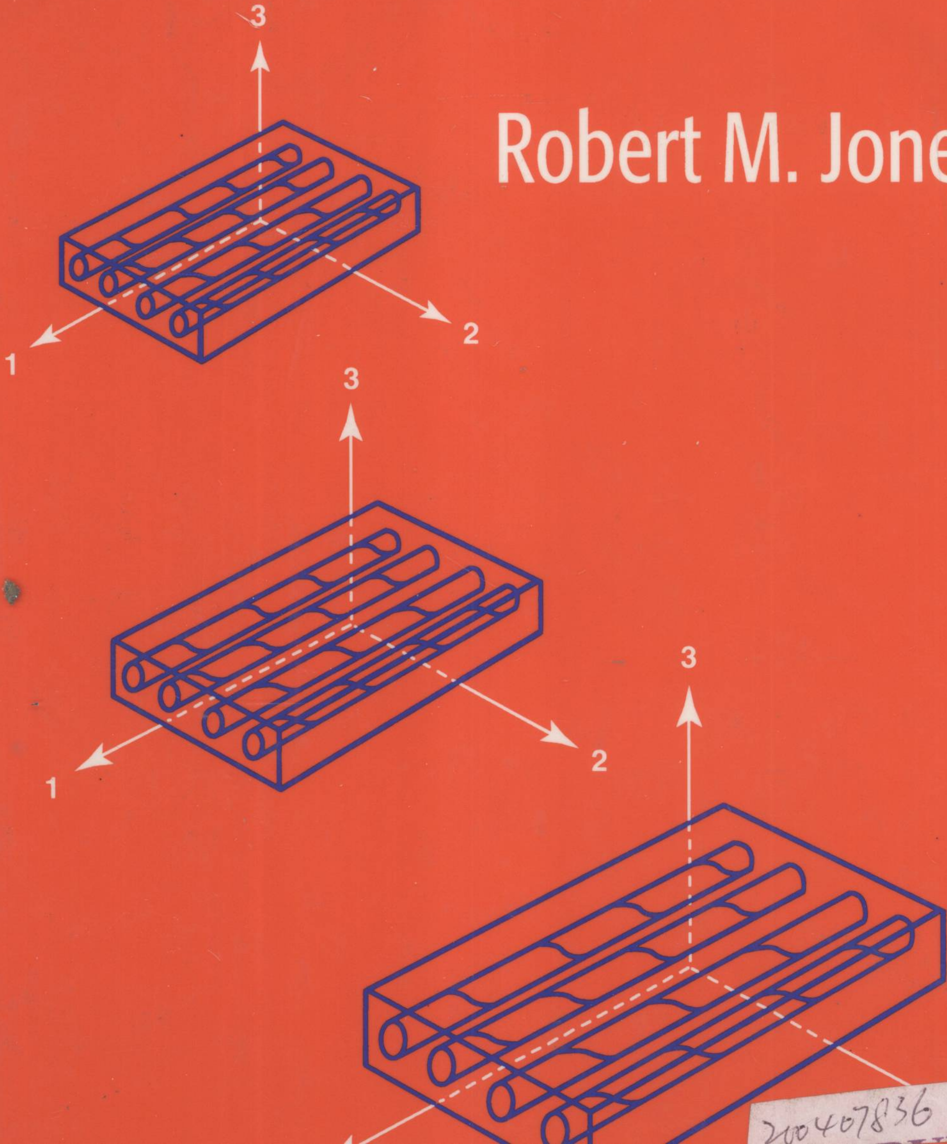
MECHANICS OF COMPOSITE MATERIALS

Second Edition

Robert M. Jones



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SECOND EDITION

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MECHANICS OF COMPOSITE MATERIALS

SECOND EDITION

PREFACE TO THE SECOND EDITION

More than two decades have passed since the first edition of this book appeared in 1975. During that time, composite materials have progressed from almost an engineering curiosity to a widely used material in aerospace applications, as well as many other applications in everyday life. Accordingly, the contents of the first edition, although in most respects timeless fundamental mechanical behavior and mechanics analyses, must be expanded and updated.

The specific revisions include more thorough explanation of many concepts, enhanced comparisons between theory and experiment, more reader-friendly figures, figures that are more visually obvious in portrayal of fibers and deformations, description of experimental measurements of properties, expanded coverage of lamina failure criteria including an evaluation of how failure criteria are obtained, and more comprehensive description of laminated plate deflection, buckling, and vibration problems. Moreover, laminate design is introduced as part of the structural design process.

The 'latest' research results are deliberately not included. That is, this book is a fundamental teaching text, not a monograph on contemporary composite materials and structures topics. Thus, topics are chosen for their importance to the basic philosophy which includes simplicity of presentation and 'absorbability' by newcomers to composite materials and structures. More advanced topics as well as the nuances of covered topics can be addressed after this book is *digested.*

I have come to expect my students to interpret or transform the sometimes highly abbreviated, and thus relatively uninformative, problem set statements at the end of each section such as 'derive Equation (3.86)' to the more formal, descriptive, and revealing form:

Given:	A composite material is to be designed.
Required:	Find the critical fiber-volume fraction necessary to ensure that the composite material strength exceeds the matrix strength, i.e., derive Equation (3.86).

Moreover, I expect students to explain on a physical basis where they start and what objectives they're trying to meet. In doing so, they should carefully explain the nature of the problem as well as its solution. I want students to gain some perspective on the problem to more fully understand the text. That is, I want them to focus on *The Why* of each problem so they will develop a feeling for the behavior of composite materials and structures. I also expect use of appropriate figures that are well discussed. Figures that have not been fully interpreted for the reader are of questionable value and certainly leave room for misinterpretation. Also, I expect students to explain and describe each step in the problem-solving process with physically based reasons and explanations. Moreover, I expect observations, comments, and conclusions about what they learned at the end of each problem. I feel such requirements are good training for survival in today's and tomorrow's more competitive world.

Completion of the problems will often require thoughtful analysis of the conditions and search for the correct solution. Thus, the problems are often not trivial or straightforward. The required mathematics are senior level except for the elasticity solutions in the micromechanics chapter where obviously the level must be higher (but the elasticity sections can be skipped in lower-level classes).

I am delighted to express my appreciation to the attendees of more than 80 short courses from 1971 through 1995 at government laboratories, companies, and open locations. They helped shape this second edition by their questions and comments, as did the more than twenty university classes I taught over the years.

I thank those who offered suggestions and corrections from their experience with the first edition. I am also delighted to express my appreciation to those who contributed to both editions: Patrick Barr (now M.D.!) for illustrations in the first edition, some of which are used in the second edition; Ann Hardell for Adobe Illustrator illustrations in the second edition; my daughter, Karen Devens, for IBM Script and GML text production; and my secretary, Norma Guynn, for miscellaneous typing.

Blacksburg, Virginia
April 1998

PREFACE TO THE FIRST EDITION

Composite materials are ideal for structural applications where high strength-to-weight and stiffness-to-weight ratios are required. Aircraft and spacecraft are typical weight-sensitive structures in which composite materials are cost-effective. When the full advantages of composite materials are utilized, both aircraft and spacecraft will be designed in a manner much different from the present.

The study of composite materials actually involves many topics, such as, for example, manufacturing processes, anisotropic elasticity, strength of anisotropic materials, and micromechanics. Truly, no one individual can claim a complete understanding of all these areas. Any practitioner will be likely to limit his attention to one or two subareas of the broad possibilities of analysis versus design, micromechanics versus macromechanics, etc.

The objective of this book is to introduce the student to the basic concepts of the mechanical behavior of composite materials. Actually, only an overview of this vast set of topics is offered. The balance of subject areas is intended to give a fundamental knowledge of the broad scope of composite materials. The mechanics of laminated fiber-reinforced composite materials are developed as a continuing example. Many important topics are ignored in order to restrict the coverage to a one-semester graduate course. However, the areas covered do provide a firm foundation for further study and research and are carefully selected to provide continuity and balance. Moreover, the subject matter is chosen to exhibit a high degree of comparison between theory and experiment in order to establish confidence in the derived theories.

The whole gamut of topics from micromechanics and macromechanics through lamination theory and examples of plate bending, buckling, and vibration problems is treated so that the physical significance of the concepts is made clear. A comprehensive introduction to composite materials and motivation for their use in current structural applications is given in Chapter 1. Stress-strain relations for a lamina are displayed with engineering material constants in Chapter 2. Strength theories are also compared with experimental results. In Chapter 3, micromechanics is introduced by both the mechanics of materials approach and the elasticity approach. Predicted moduli are compared with measured values. Lamination theory is presented in Chapter 4 with the aid of a new laminate classification scheme. Laminate stiffness predictions are compared with experimental results. Laminate strength concepts, as well as interlaminar stresses and design, are also discussed. In Chapter 5, bending, buckling, and vibration of a simply supported plate with various lamination characteristics is examined to display the effects of coupling stiffnesses in a physically meaningful problem. Miscellaneous topics such as fatigue, fracture mechanics, and transverse shear effects are addressed in Chapter 6. Appendices on matrices and tensors, maxima and minima of functions of a single variable, and typical stress-strain curves are provided.

This book was written primarily as a graduate-level textbook, but is well suited as a guide for self-study of composite materials. Accordingly, the theories presented are simple and illustrate the basic concepts, although they may not be the most accurate. Emphasis is placed on analyses compared with experimental results, rather than on the most recent analysis for the material currently 'in vogue.' Accuracy may suffer, but educational objectives are better met. Many references are included to facilitate further study. The background of the reader should include an advanced mechanics of materials course or separate courses in which three-dimensional stress-strain relations and plate theory are introduced. In addition, knowledge of anisotropic elasticity is desirable, although not essential.

Many people have been most generous in their support of this writing effort. I would like to especially thank Dr. Stephen W. Tsai, of the Air Force Materials Laboratory, for his inspiration by example over the past ten years and for his guidance throughout the past several years. I deeply appreciate Steve's efforts and those of Dr. R. Bryon Pipes of the University of Delaware and Dr. Thomas Cruse of Pratt and Whitney Aircraft, who reviewed the manuscript and made many helpful comments. Still others contributed material for the book. My thanks to Marvin Howeth of General Dynamics, Forth Worth, Texas, for many photographs; to John Pimm of LTV Aerospace Corporation for the photograph in Section 4.7; to Dr. Nicholas Pagano of the Air Force Materials Laboratory for many figures; to Dr. R. Byron Pipes of the University of Delaware for many photographs and figures in Section 4.6; and to Dr. B. Walter Rosen of Materials Sciences Corporation, Blue Bell, Pennsylvania, for the photo in Section 3.5. I also appreciate the permission of the Technomic Publishing Company, Inc., of Westport, Connecticut, to reprint throughout the text many figures which have appeared in the various Technomic books and in the *Journal of Composite Materials* over the past several years. I am very grateful for support by the Air Force Office of Scientific Research (Directorate of Aerospace Sciences) and the Office of Naval Research (Structural Mechanics Program) of my research on laminated plates and shells discussed in Chapters 5 and 6. I am also indebted to several classes at the Southern Methodist Institute of Technology and the Naval Air Development Center, Warminister, Pennsylvania, for their patience and help during the development of class notes that led to this book. Finally, I must single out Harold S. Morgan for his numerous contributions and Marty Kunkle for her manuscript typing (although I did some of the typing myself!).

R.M.J.

First Edition:

To my neglected family:
Donna, Mark, Karen, and Christopher

Second Edition:

To Christopher:
He helped many others,
but he couldn't help himself

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Chapter 1

INTRODUCTION TO COMPOSITE MATERIALS

1.1 INTRODUCTION

The objective of this chapter is to address the three basic questions of composite materials and structures in Figure 1-1: (1) What is a composite material? (2) Why are composite materials used instead of metals? and (3) How are composite materials used in structures? As part of The What, the general set of composite materials will be defined, classified, and characterized. Then, our attention will be focused on laminated fiber-reinforced composite materials for this book. Finally, to help us understand the nature of the material we are trying to model with mechanics equations, we will briefly describe manufacturing of composite materials and structures. In The Why, we will investigate the advantages of composite materials over metals from the standpoints of strength, stiffness, weight, and cost among others. Finally, in The How, we will look into examples and short case histories of important structural applications of composite materials to see even more reasons why composite materials play an ever-expanding role in today's and tomorrow's structures.

- **THE WHAT**

  WHAT IS A COMPOSITE MATERIAL?
- **THE WHY**

  WHY ARE COMPOSITE MATERIALS USED INSTEAD OF METALS?
- **THE HOW**

  HOW ARE COMPOSITE MATERIALS USED IN STRUCTURAL APPLICATIONS?

Figure 1-1 Basic Questions of Composite Materials and Structures