



ENGINEERING
MECHANICS OF
COMPOSITE
MATERIALS

Thu Vien DHKTCN-TN



KNV.15002218

second edition

Isaac M. Daniel Ori Ishai

ENGINEERING MECHANICS OF COMPOSITE MATERIALS

SECOND EDITION

Isaac M. Daniel

*Departments of Civil and Mechanical Engineering
Northwestern University, Evanston, IL*

Ori Ishai

*Faculty of Mechanical Engineering
Technion-Israel Institute of Technology, Haifa, Israel*

New York ■ Oxford
OXFORD UNIVERSITY PRESS
2006

Oxford University Press, Inc., publishes works that further Oxford University's objective of excellence in research, scholarship, and education.

Oxford New York
Auckland Cape Town Dar es Salaam Hong Kong Karachi
Kuala Lumpur Madrid Melbourne Mexico City Nairobi
New Delhi Shanghai Taipei Toronto

With offices in
Argentina Austria Brazil Chile Czech Republic France Greece
Guatemala Hungary Italy Japan Poland Portugal Singapore
South Korea Switzerland Thailand Turkey Ukraine Vietnam

Copyright © 1994, 2006 by Oxford University Press, Inc.

Published by Oxford University Press, Inc.
198 Madison Avenue, New York, New York 10016
<http://www.oup.com>

Oxford is a registered trademark of Oxford University Press

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior permission of Oxford University Press.

Library of Congress Cataloging-in-Publication Data

Daniel, Isaac M.
Engineering mechanics of composite materials / Isaac M. Daniel, Ori Ishai.—2nd ed.
p. cm.
ISBN 978-0-19-515097-1

1. Composite materials—Mechanical properties. 2. Composite materials—Testing.
I. Ishai, Ori. II. Title.

TA418.9.C6D28 2005
620.1'183—dc22

2004065462

Printing number: 9 8 7 6

Printed in the United States of America
on acid-free paper

*To my wife, Elaine
my children, Belinda, Rebecca, and Max
and the memory of my parents, Mordochai and Bella Daniel*
Isaac M. Daniel

*To my wife, Yael
and my children, Michal, Tami, Eran, and Yuval*
Ori Ishai

Contents

PREFACE TO THE SECOND EDITION xv

PREFACE TO THE FIRST EDITION xvii

1. INTRODUCTION	1
1.1 Definition and Characteristics	1
1.2 Historical Development	2
1.3 Applications	3
1.4 Overview of Advantages and Limitations of Composite Materials	13
1.4.1 Micromechanics	14
1.4.2 Macromechanics	14
1.4.3 Mechanical Characterization	14
1.4.4 Structural Design, Analysis, and Optimization	14
1.4.5 Manufacturing Technology	15
1.4.6 Maintainability, Serviceability, and Durability	15
1.4.7 Cost Effectiveness	15
1.5 Significance and Objectives of Composite Materials Science and Technology	16
1.6 Current Status and Future Prospects	16
References	17
2. BASIC CONCEPTS, MATERIALS, PROCESSES, AND CHARACTERISTICS	18
2.1 Structural Performance of Conventional Materials	18
2.2 Geometric and Physical Definitions	18
2.2.1 Type of Material	18
2.2.2 Homogeneity	19
2.2.3 Heterogeneity or Inhomogeneity	19
2.2.4 Isotropy	19
2.2.5 Anisotropy/Orthotropy	20
2.3 Material Response Under Load	20
2.4 Types and Classification of Composite Materials	24

2.5	Lamina and Laminate—Characteristics and Configurations	26
2.6	Scales of Analysis—Micromechanics and Macromechanics	27
2.7	Basic Lamina Properties	29
2.8	Degrees of Anisotropy	30
2.9	Constituent Materials	30
2.9.1	Reinforcement	30
2.9.2	Matrices	33
2.10	Material Forms—Prepregs	35
2.11	Manufacturing Methods for Composite Materials	36
2.11.1	Autoclave Molding	37
2.11.2	Filament Winding	37
2.11.3	Resin Transfer Molding	38
2.12	Properties of Typical Composite Materials	40
	<i>References</i>	42

3. ELASTIC BEHAVIOR OF COMPOSITE LAMINA—MICROMECHANICS 43

3.1	Scope and Approaches	43
3.2	Micromechanics Methods	45
3.2.1	Mechanics of Materials Methods	46
3.2.2	Bounding Methods	46
3.2.3	Semiempirical Methods	48
3.3	Geometric Aspects and Elastic Symmetry	49
3.4	Longitudinal Elastic Properties—Continuous Fibers	49
3.5	Transverse Elastic Properties—Continuous Fibers	51
3.6	In-Plane Shear Modulus	56
3.7	Longitudinal Properties—Discontinuous (Short) Fibers	58
3.7.1	Elastic Stress Transfer Model—Shear Lag Analysis (Cox)	58
3.7.2	Semiempirical Relation (Halpin)	60

References 60

Problems 61

4. ELASTIC BEHAVIOR OF COMPOSITE LAMINA—MACROMECHANICS 63

4.1	Stress-Strain Relations	63
4.1.1	General Anisotropic Material	63
4.1.2	Specially Orthotropic Material	66
4.1.3	Transversely Isotropic Material	67
4.1.4	Orthotropic Material Under Plane Stress	69
4.1.5	Isotropic Material	71
4.2	Relations Between Mathematical and Engineering Constants	71
4.3	Stress-Strain Relations for a Thin Lamina (Two-Dimensional)	76

4.4 Transformation of Stress and Strain (Two-Dimensional)	77
4.5 Transformation of Elastic Parameters (Two-Dimensional)	78
4.6 Transformation of Stress-Strain Relations in Terms of Engineering Constants (Two-Dimensional)	81
4.7 Transformation Relations for Engineering Constants (Two-Dimensional)	83
4.8 Transformation of Stress and Strain (Three-Dimensional)	88
4.8.1 General Transformation	88
4.8.2 Rotation About 3-Axis	89
4.9 Transformation of Elastic Parameters (Three-Dimensional)	90
<i>References</i>	92
<i>Problems</i>	92

5. STRENGTH OF UNIDIRECTIONAL LAMINA—MICROMECHANICS 98

5.1 Introduction	98
5.2 Longitudinal Tension—Failure Mechanisms and Strength	98
5.3 Longitudinal Tension—Ineffective Fiber Length	102
5.4 Longitudinal Compression	105
5.5 Transverse Tension	110
5.6 Transverse Compression	113
5.7 In-Plane Shear	114
5.8 Out-of-Plane Loading	115
5.9 General Micromechanics Approach	116
<i>References</i>	116
<i>Problems</i>	117

6. STRENGTH OF COMPOSITE LAMINA—MACROMECHANICS 120

6.1 Introduction	120
6.2 Failure Theories	122
6.3 Maximum Stress Theory	123
6.4 Maximum Strain Theory	126
6.5 Energy-Based Interaction Theory (Tsai-Hill)	128
6.6 Interactive Tensor Polynomial Theory (Tsai-Wu)	130
6.7 Failure-Mode-Based Theories (Hashin-Rotem)	135
6.8 Failure Criteria for Textile Composites	137
6.9 Computational Procedure for Determination of Lamina Strength—Tsai-Wu Criterion (Plane Stress Conditions)	139
6.10 Evaluation and Applicability of Lamina Failure Theories	143
<i>References</i>	148
<i>Problems</i>	149

7. ELASTIC BEHAVIOR OF MULTIDIRECTIONAL LAMINATES	158
7.1 Basic Assumptions	158
7.2 Strain-Displacement Relations	158
7.3 Stress-Strain Relations of a Layer Within a Laminate	160
7.4 Force and Moment Resultants	161
7.5 General Load-Deformation Relations: Laminate Stiffnesses	163
7.6 Inversion of Load-Deformation Relations: Laminate Compliances	165
7.7 Symmetric Laminates	167
7.7.1 Symmetric Laminates with Isotropic Layers	168
7.7.2 Symmetric Laminates with Specially Orthotropic Layers (Symmetric Crossply Laminates)	169
7.7.3 Symmetric Angle-Ply Laminates	170
7.8 Balanced Laminates	171
7.8.1 Antisymmetric Laminates	172
7.8.2 Antisymmetric Crossply Laminates	172
7.8.3 Antisymmetric Angle-Ply Laminates	174
7.9 Orthotropic Laminates: Transformation of Laminate Stiffnesses and Compliances	175
7.10 Quasi-isotropic Laminates	177
7.11 Design Considerations	179
7.12 Laminate Engineering Properties	181
7.12.1 Symmetric Balanced Laminates	181
7.12.2 Symmetric Laminates	182
7.12.3 General Laminates	184
7.13 Computational Procedure for Determination of Engineering Elastic Properties	189
7.14 Comparison of Elastic Parameters of Unidirectional and Angle-Ply Laminates	190
7.15 Carpet Plots for Multidirectional Laminates	191
7.16 Textile Composite Laminates	192
7.17 Modified Lamination Theory—Effects of Transverse Shear	193
7.18 Sandwich Plates	196
<i>References</i>	200
<i>Problems</i>	200
8. HYGROTHERMAL EFFECTS	204
8.1 Introduction	204
8.1.1 Physical and Chemical Effects	205
8.1.2 Effects on Mechanical Properties	205
8.1.3 Hygrothermoelastic (HTE) Effects	205
8.2 Hygrothermal Effects on Mechanical Behavior	205
8.3 Coefficients of Thermal and Moisture Expansion of a Unidirectional Lamina	208
8.4 Hygrothermal Strains in a Unidirectional Lamina	212

8.5	Hygrothermoelastic Load-Deformation Relations	213
8.6	Hygrothermoelastic Deformation-Load Relations	215
8.7	Hygrothermal Load-Deformation Relations	216
8.8	Coefficients of Thermal and Moisture Expansion of Multidirectional Laminates	216
8.9	Coefficients of Thermal and Moisture Expansion of Balanced/Symmetric Laminates	217
8.10	Physical Significance of Hygrothermal Forces and Moments	219
8.11	Hygrothermal Isotropy and Stability	220
8.12	Coefficients of Thermal Expansion of Unidirectional and Multidirectional Carbon/Epoxy Laminates	224
8.13	Hygrothermoelastic Stress Analysis of Multidirectional Laminates	225
8.14	Residual Stresses	227
8.15	Warpage	232
8.16	Computational Procedure for Hygrothermoelastic Analysis of Multidirectional Laminates	235
	<i>References</i>	237
	<i>Problems</i>	239

9. STRESS AND FAILURE ANALYSIS OF MULTIDIRECTIONAL LAMINATES 243

9.1	Introduction	243
9.2	Types of Failure	244
9.3	Stress Analysis and Safety Factors for First Ply Failure of Symmetric Laminates (In-Plane Loading)	244
9.4	Strength Components for First Ply Failure of Symmetric Laminates	246
9.5	Computational Procedure for Stress and Failure Analysis of General Multidirectional Laminates (First Ply Failure)	252
9.6	Comparison of Strengths of Unidirectional and Angle-Ply Laminates (First Ply Failure)	253
9.7	Carpet Plots for Strength of Multidirectional Laminates (First Ply Failure)	254
9.8	Effect of Hygrothermal History on Strength of Multidirectional Laminates (First Ply Failure; Tsai-Wu Criterion)	255
9.9	Computational Procedure for Stress and Failure Analysis of Multidirectional Laminates Under Combined Mechanical and Hygrothermal Loading (First Ply Failure; Tsai-Wu Criterion)	258
9.10	Micromechanics of Progressive Failure	260
9.11	Progressive and Ultimate Laminate Failure—Laminate Efficiency	265
9.12	Analysis of Progressive and Ultimate Laminate Failure	267
9.12.1	Determination of First Ply Failure (FPF)	267
9.12.2	Discounting of Damaged Plies	268
9.12.3	Stress Analysis of the Damaged Laminate	268
9.12.4	Second Ply Failure	268