

CONTENTS

Preface xiii

1	INTRODUCTION TO COMPOSITE MATERIALS	1
1.1	Introduction	1
1.2	Classification and Characteristics of Composite Materials	2
1.2.1	Fibrous composites	2
1.2.2	Laminated composites	5
1.2.3	Particulate composites	7
1.2.4	Summary	10
1.3	Mechanical Behavior of Composite Materials	10
1.4	Basic Terminology of Laminated Fiber-reinforced Composite Materials	13
1.4.1	Laminae	14
1.4.2	Laminates	16
1.5	Manufacture of Laminated Fiber-reinforced Composite Materials	17
1.5.1	Initial form of constituent materials	17
1.5.2	Manufacturing procedures	17
1.5.3	Quality control	20
1.6	Current and Potential Advantages of Fiber-reinforced Composite Materials	21
1.6.1	Strength and stiffness advantages	22
1.6.2	Cost advantages	24
1.6.3	Current and potential usage of composite materials	25
	References	29
2	MACROMECHANICAL BEHAVIOR OF A LAMINA	31
2.1	Introduction	31
2.2	Stress-Strain Relations for Anisotropic Materials	32

2.3	Engineering Constants for Orthotropic Materials	37
2.4	Restrictions on Elastic Constants	41
2.4.1	Isotropic materials	41
2.4.2	Orthotropic materials	42
	Problem set 2.4	45
2.5	Stress-Strain Relations for Plane Stress in an Orthotropic Material	45
2.6	Stress-Strain Relations for a Lamina of Arbitrary Orientation	47
	Problem set 2.6	56
2.7	Invariant Properties of an Orthotropic Lamina	57
	Problem set 2.7	59
2.8	Strength of an Orthotropic Lamina	59
2.8.1	Strength concepts	59
2.8.2	Experimental determination of strength and stiffness	63
2.8.3	Summary of mechanical properties	70
2.9	Biaxial Strength Theories for an Orthotropic Lamina	71
2.9.1	Maximum stress theory	72
2.9.2	Maximum strain theory	74
2.9.3	Tsai-Hill theory	76
2.9.4	Tsai-Wu tensor theory	80
	Problem set 2.9	83
	References	84

3 MICROMECHANICAL BEHAVIOR OF A LAMINA 85

3.1	Introduction	85
3.2	Mechanics of Materials Approach to Stiffness	90
3.2.1	Determination of E_1	90
3.2.2	Determination of E_2	91
3.2.3	Determination of ν_{12}	94
3.2.4	Determination of G_{12}	94
3.2.5	Summary remarks	97
	Problem set 3.2	97
3.3	Elasticity Approach to Stiffness	98
3.3.1	Introduction	98
3.3.2	Bounding techniques of elasticity	99
3.3.3	Exact solutions	107
3.3.4	Elasticity solutions with contiguity	110
3.3.5	The Halpin-Tsai equations	114
3.3.6	Summary remarks	120
	Problem set 3.3	121

3.4	Comparison of Approaches to Stiffness	122
3.4.1	Particulate composites	122
3.4.2	Fiber-reinforced composites	123
3.4.3	Summary remarks	126
3.5	Mechanics of Materials Approach to Strength	127
3.5.1	Introduction	127
3.5.2	Tensile strength in the fiber direction	128
3.5.3	Compressive strength in the fiber direction	134
	Problem set 3.5	144
3.6	Summary Remarks on Micromechanics	144
	References	145

4 *composites* MACROMECHANICAL BEHAVIOR OF A LAMINATE 147

4.1	Introduction	147
4.2	Classical Lamination Theory	147
4.2.1	Lamina stress-strain behavior	148
4.2.2	Strain and stress variation in a laminate	149
4.2.3	Resultant laminate forces and moments	152
	Problem set 4.2	156
4.3	Special Cases of Laminate Stiffnesses	156
4.3.1	Single-layered configurations	157
4.3.2	Symmetric laminates	160
4.3.3	Antisymmetric laminates	166
4.3.4	Nonsymmetric laminates	170
4.3.5	Summary remarks	171
	Problem set 4.3	172
4.4	Comparison of Theoretical and Experimental Laminate Stiffnesses	173
4.4.1	Inversion of stiffness equations	173
4.4.2	Cross-ply laminate stiffnesses	174
4.4.3	Theoretical and experimental cross-ply laminate stiffnesses	179
4.4.4	Angle-ply laminate stiffnesses	182
4.4.5	Theoretical and experimental angle-ply laminate stiffnesses	186
4.4.6	Summary remarks	187
	Problem set 4.4	187
4.5	Strength of Laminates	188
4.5.1	Introduction	188
4.5.2	Laminate strength analysis procedure	190
4.5.3	Laminate strength criteria	192
4.5.4	Thermal and mechanical stress analysis	193

4.5.5	Strength of cross-ply laminates	198
4.5.6	Strength of angle-ply laminates	205
4.5.7	Summary remarks	208
	Problem set 4.5	210
4.6	Interlaminar Stresses	210
4.6.1	Classical lamination theory	211
4.6.2	Elasticity formulation	213
4.6.3	Elasticity solution results	216
4.6.4	Experimental confirmation of interlaminar stresses	218
4.6.5	Implications of interlaminar stresses	219
	Problem set 4.6	223
4.7	Design of Laminates	223
4.7.1	Invariant laminate stiffness concepts	224
4.7.2	Special results for invariant laminate stiffnesses	227
4.7.3	Use of invariant laminate stiffnesses in design	230
4.7.4	Laminate joints	232
	Problem set 4.7	236
	References	236

5 BENDING, BUCKLING, AND VIBRATION OF LAMINATED PLATES 239

5.1	Introduction	239
5.2	Governing Equations for Bending, Buckling, and Vibration of Laminated Plates	240
5.2.1	Basic restrictions and assumptions	240
5.2.2	Equilibrium equations for laminated plates	243
5.2.3	Buckling equations for laminated plates	245
5.2.4	Vibration equations for laminated plates	247
5.2.5	Solution techniques	247
5.3	Deflection of Simply Supported Laminated Plates under Distributed Lateral Load	248
5.3.1	Specially orthotropic laminates	249
5.3.2	Symmetric angle-ply laminates	250
5.3.3	Antisymmetric cross-ply laminates	254
5.3.4	Antisymmetric angle-ply laminates	256
5.4	Buckling of Simply Supported Laminated Plates under In-Plane Load	259
5.4.1	Specially orthotropic laminates	260
5.4.2	Symmetric angle-ply laminates	262
5.4.3	Antisymmetric cross-ply laminates	264
5.4.4	Antisymmetric angle-ply laminates	267
5.5	Vibration of Simply Supported Laminated Plates	270
5.5.1	Specially orthotropic laminates	271
5.5.2	Symmetric angle-ply laminates	273

5.5.3	Antisymmetric cross-ply laminates	273
5.5.4	Antisymmetric angle-ply laminates	276
5.6	Summary Remarks on Effects of Stiffnesses	279
	Problem Set 5	283
	References	284
6	SUMMARY AND OTHER TOPICS	287
6.1	Review of Chapters 1 through 5	287
6.2	Fatigue	288
6.3	Holes in Laminates	289
6.4	Fracture Mechanics	291
6.4.1	Basic principles of fracture mechanics	293
6.4.2	Application of fracture mechanics to composite materials	296
6.5	Transverse Shear Effects	299
6.5.1	Exact solutions for cylindrical bending	299
6.5.2	Approximate treatment of transverse shear effects	303
6.6	Environmental Effects	310
6.7	Shells	311
6.8	Miscellaneous Topics	311
	References	312
APPENDIX A	MATRICES AND TENSORS	315
A.1	Matrix Algebra	315
A.1.1	Matrix definitions	315
A.1.2	Matrix operations	319
A.2	Tensors	321
A.2.1	Transformation of coordinates	322
A.2.2	Definition of various tensor orders	323
A.2.3	Contracted notation	324
A.2.4	Matrix form of tensor transformations	325
	Reference	326
APPENDIX B	MAXIMA AND MINIMA OF FUNCTIONS OF A SINGLE VARIABLE	327
	Reference	331
APPENDIX C	TYPICAL STRESS-STRAIN CURVES	333
	References	333
	Bibliography	343
	Index	345