620.118mal3rded

Contents

Preface to the Third Edition xv

Author xvii

Chapter 1 Introduction 1

1.1 Definition 1
1.2 General Characteristics 2
1.3 Applications 6
1.3.1 Aircraft and Military Applications 6
1.3.2 Space Applications 12
1.3.3 Automotive Applications 12
1.3.4 Sporting Goods Applications 18
1.3.5 Marine Applications 20
1.3.6 Infrastructure 21
1.4 Material Selection Process 23
References 26
Problems 27

Chapter 2 Materials 31

2.1 Fibers 33
2.1.1 Glass Fibers 42
2.1.2 Carbon Fibers 46
2.1.3 Aramid Fibers 54
2.1.4 Extended Chain Polyethylene Fibers 55
2.1.5 Natural Fibers 56
2.1.6 Boron Fibers 57
2.1.7 Ceramic Fibers 58
2.2 Matrix 60
2.2.1 Polymer Matrix 60
2.2.1.1 Thermoplastic and Thermoset Polymers 62
2.2.1.2 Unique Characteristics of Polymeric Solids 63
2.2.1.3 Creep and Stress Relaxation 65
2.2.1.4 Heat Deflection Temperature 65
2.2.1.5 Selection of Matrix: Thermosets vs. Thermoplastics 67

2.2.2 Metal Matrix 69
2.2.3 Ceramic Matrix 70
2.3 Thermoset Matrix 71
2.3.1 Epoxy 71
2.3.2 Polyester 76
2.3.3 Vinyl Ester 81
2.3.4 Bismaleimides and Other Thermoset Polyimides 83
2.3.5 Cyanate Ester 84
2.4 Thermoplastic Matrix 85
2.4.1 Polyether Ether Ketone 85
2.4.2 Polyphenylene Sulfide 87
2.4.3 Polysulfone 87
2.4.4 Thermoplastic Polyimides 88
2.5 Fiber Surface Treatments 89
2.5.1 Glass Fibers 89
2.5.2 Carbon Fibers 93
2.5.3 Kevlar Fibers 94
2.6 Fillers and Other Additives 94
2.7 Incorporation of Fibers into Matrix 95
2.7.1 Prepregs 96
2.7.2 Sheet-Molding Compounds 96
2.7.3 Incorporation of Fibers into Thermoplastic Resins 99
2.8 Fiber Content, Density, and Void Content 102
2.9 Fiber Architecture 105
References 108
Problems 110

Chapter 3 Mechanics 119

3.1 Fiber–Matrix Interactions in a Unidirectional Lamina 120
3.1.1 Longitudinal Tensile Loading 120
3.1.1.1 Unidirectional Continuous Fibers 120
3.1.1.2 Unidirectional Discontinuous Fibers 125
3.1.1.3 Microfailure Modes in Longitudinal Tension 134
3.1.2 Transverse Tensile Loading 138
3.1.3 Longitudinal Compressive Loading 144
3.1.4 Transverse Compressive Loading 146
3.2 Characteristics of a Fiber-Reinforced Lamina 147
3.2.1 Fundamentals 147
3.2.1.1 Coordinate Axes 147
3.2.1.2 Notations 148
3.2.1.3 Stress and Strain Transformations in a Thin Lamina under Plane Stress 150
3.2.1.4 Isotropic, Anisotropic, and Orthotropic Materials 151

3.2.2 Elastic Properties of a Lamina 155
3.2.2.1 Unidirectional Continuous Fiber 0° Lamina 155
3.2.2.2 Unidirectional Continuous Fiber Angle-Ply Lamina 160
3.2.2.3 Unidirectional Discontinuous Fiber 0° Lamina 161
3.2.2.4 Randomly Oriented Discontinuous Fiber Lamina 163
3.2.3 Coefficients of Linear Thermal Expansion 166
3.2.4 Stress–Strain Relationships for a Thin Lamina 167
3.2.4.1 Isotropic Lamina 167
3.2.4.2 Orthotropic Lamina 168
3.2.5 Compliance and Stiffness Matrices 173
3.2.5.1 Isotropic Lamina 173
3.2.5.2 Specially Orthotropic Lamina ($\theta = 0°$ or 90°) 174
3.2.5.3 General Orthotropic Lamina ($\theta \neq 0°$ or 90°) 175
3.3 Laminated Structure 180
3.3.1 From Lamina to Laminate 180
3.3.2 Lamination Theory 183
3.3.2.1 Assumptions 183
3.3.2.2 Laminate Strains 183
3.3.2.3 Laminate Forces and Moments 184
3.3.2.4 Elements in Stiffness Matrices 186
3.3.2.5 Midplane Strains and Curvatures 194
3.3.2.6 Lamina Strains and Stresses Due to Applied Loads 200
3.3.2.7 Thermal Strains and Stresses 203
3.4 Interlaminar Stresses 211
References 217
Problems 218

Chapter 4 Performance 233

4.1 Static Mechanical Properties 233
4.1.1 Tensile Properties 233
4.1.1.1 Test Method and Analysis 233
4.1.1.2 Unidirectional Laminates 238
4.1.1.3 Cross-Ply Laminates 239
4.1.1.4 Multidirectional Laminates 242
4.1.1.5 Woven Fabric Laminates 245
4.1.1.6 Sheet-Molding Compounds 248
4.1.1.7 Interply Hybrid Laminates 249
4.1.2 Compressive Properties 253
4.1.3 Flexural Properties 257
4.1.4 In-Plane Shear Properties 261
4.1.5 Interlaminar Shear Strength 267

4.2 Fatigue Properties 269
4.2.1 Fatigue Test Methods 270
4.2.2 Fatigue Performance 273
4.2.2.1 Tension–Tension Fatigue 273
4.2.2.2 Flexural Fatigue 276
4.2.2.3 Interlaminar Shear Fatigue 278
4.2.2.4 Torsional Fatigue 279
4.2.2.5 Compressive Fatigue 279
4.2.3 Variables in Fatigue Performance 281
4.2.3.1 Effect of Material Variables 281
4.2.3.2 Effect of Mean Stress 283
4.2.3.3 Effect of Frequency 286
4.2.3.4 Effect of Notches 288
4.2.4 Fatigue Damage Mechanisms in Tension–Tension Fatigue Tests 290
4.2.4.1 Continuous Fiber 0° Laminates 290
4.2.4.2 Cross-Ply and Other Multidirectional Continuous Fiber Laminates 292
4.2.4.3 SMC-R Laminates 294
4.2.5 Fatigue Damage and Its Consequences 295
4.2.6 Postfatigue Residual Strength 301
4.3 Impact Properties 303
4.3.1 Charpy, Izod, and Drop-Weight Impact Test 304
4.3.2 Fracture Initiation and Propagation Energies 307
4.3.3 Material Parameters 309
4.3.4 Low-Energy Impact Tests 313
4.3.5 Residual Strength After Impact 316
4.3.6 Compression-After-Impact Test 317
4.4 Other Properties 318
4.4.1 Pin-Bearing Strength 318
4.4.2 Damping Properties 321
4.4.3 Coefficient of Thermal Expansion 321
4.4.4 Thermal Conductivity 324
4.5 Environmental Effects 325
4.5.1 Elevated Temperature 325
4.5.2 Moisture 327
4.5.2.1 Moisture Concentration 328
4.5.2.2 Physical Effects of Moisture Absorption 332
4.5.2.3 Changes in Performance Due to Moisture and Temperature 333
4.6 Long-Term Properties 337
4.6.1 Creep 337
4.6.1.1 Creep Data 338

4.6.1.2 Long-Term Creep Behavior 339
4.6.1.3 Schapery Creep and Recovery Equations 342
4.6.2 Stress Rupture 343
4.7 Fracture Behavior and Damage Tolerance 345
4.7.1 Crack Growth Resistance 345
4.7.2 Delamination Growth Resistance 349
4.7.2.1 Mode I Delamination 350
4.7.2.2 Mode II Delamination 352
4.7.3 Methods of Improving Damage Tolerance 354
4.7.3.1 Matrix Toughness 354
4.7.3.2 Interleaving 355
4.7.3.3 Stacking Sequence 356
4.7.3.4 Interply Hybridization 356
4.7.3.5 Through-the-Thickness Reinforcement 356
4.7.3.6 Ply Termination 357
4.7.3.7 Edge Modification 357
References 358
Problems 364

Chapter 5 Manufacturing 377

5.1 Fundamentals 377
5.1.1 Degree of Cure 378
5.1.2 Viscosity 381
5.1.3 Resin Flow 384
5.1.4 Consolidation 386
5.1.5 Gel-Time Test 387
5.1.6 Shrinkage 388
5.1.7 Voids 389
5.2 Bag-Molding Process 389
5.3 Compression Molding 394
5.4 Pultrusion 403
5.5 Filament Winding 408
5.6 Liquid Composite Molding Processes 416
5.6.1 Resin Transfer Molding 416
5.6.2 Structural Reaction Injection Molding 418
5.7 Other Manufacturing Processes 420
5.7.1 Resin Film Infusion 420
5.7.2 Elastic Reservoir Molding 421
5.7.3 Tube Rolling 422
5.8 Manufacturing Processes for Thermoplastic Matrix Composites 422
5.9 Quality Inspection Methods 427
5.9.1 Raw Materials 427
5.9.2 Cure Cycle Monitoring 428

5.9.3 Cured Composite Part 429
5.9.3.1 Radiography 430
5.9.3.2 Ultrasonic 430
5.9.3.3 Acoustic Emission 433
5.9.3.4 Acousto-Ultrasonic 435
5.9.3.5 Thermography 436
5.10 Cost Issues 438
References 440
Problems 442

Chapter 6 Design 451

6.1 Failure Prediction 451
6.1.1 Failure Prediction in a Unidirectional Lamina 451
6.1.1.1 Maximum Stress Theory 453
6.1.1.2 Maximum Strain Theory 456
6.1.1.3 Azzi–Tsai–Hill Theory 459
6.1.1.4 Tsai–Wu Failure Theory 460
6.1.2 Failure Prediction for Unnotched Laminates 463
6.1.2.1 Consequence of Lamina Failure 464
6.1.2.2 Ultimate Failure of a Laminate 466
6.1.3 Failure Prediction in Random Fiber Laminates 467
6.1.4 Failure Prediction in Notched Laminates 468
6.1.4.1 Stress Concentration Factor 468
6.1.4.2 Hole Size Effect on Strength 469
6.1.5 Failure Prediction for Delamination Initiation 474
6.2 Laminate Design Considerations 475
6.2.1 Design Philosophy 475
6.2.2 Design Criteria 476
6.2.3 Design Allowables 478
6.2.4 General Design Guidelines 481
6.2.4.1 Laminate Design for Strength 482
6.2.4.2 Laminate Design for Stiffness 484
6.2.5 Finite Element Analysis 485
6.3 Joint Design 486
6.3.1 Mechanical Joints 487
6.3.2 Bonded Joints 490
6.4 Design Examples 492
6.4.1 Design of a Tension Member 492
6.4.2 Design of a Compression Member 494
6.4.3 Design of a Beam 496
6.4.4 Design of a Torsional Member 501
6.5 Application Examples 504

6.5.1 Inboard Ailerons on Lockheed L-1011 Aircraft 504
6.5.2 Composite Pressure Vessels 507
6.5.3 Corvette Leaf Springs 509
6.5.4 Tubes for Space Station Truss Structure 511
References 516
Problems 518

Chapter 7 Metal, Ceramic, and Carbon Matrix Composites 523

7.1 Metal Matrix Composites 524
7.1.1 Mechanical Properties 524
7.1.1.1 Continuous-Fiber MMC 526
7.1.1.2 Discontinuously Reinforced MMC 528
7.1.2 Manufacturing Processes 533
7.1.2.1 Continuously Reinforced MMC 533
7.1.2.2 Discontinuously Reinforced MMC 534
7.2 Ceramic Matrix Composites 538
7.2.1 Micromechanics 539
7.2.2 Mechanical Properties 542
7.2.2.1 Glass Matrix Composites 542
7.2.2.2 Polycrystalline Ceramic Matrix 544
7.2.3 Manufacturing Processes 545
7.2.3.1 Powder Consolidation Process 545
7.2.3.2 Chemical Processes 547
7.3 Carbon Matrix Composites 548
References 551
Problems 553

Chapter 8 Polymer Nanocomposites 557

8.1 Nanoclay 557
8.2 Carbon Nanofibers 561
8.3 Carbon Nanotubes 564
8.3.1 Structure 564
8.3.2 Production of Carbon Nanotubes 567
8.3.3 Functionalization of Carbon Nanotubes 569
8.3.4 Mechanical Properties of Carbon Nanotubes 570
8.3.5 Carbon Nanotube–Polymer Composites 571
8.3.6 Properties of Carbon Nanotube–Polymer Composites 572
References 576
Problems 578

Appendixes
A.1 Woven Fabric Terminology 581
A.2 Residual Stresses in Fibers and Matrix in a Lamina Due to Cooling 583
Reference 585
A.3 Alternative Equations for the Elastic and Thermal Properties of a Lamina 586
References 586
A.4 Halpin–Tsai Equations 587
References 588
A.5 Typical Mechanical Properties of Unidirectional Continuous Fiber Composites 589
A.6 Properties of Various SMC Composites 590
A.7 Finite Width Correction Factor for Isotropic Plates 591
A.8 Determination of Design Allowables 592
A.8.1 Normal Distribution 592
A.8.2 Weibull Distribution 592
Reference 593
A.9 Typical Mechanical Properties of Metal Matrix Composites 594
A.10 Useful References 595
A.10.1 Text and Reference Books 595
A.10.2 Leading Journals on Composite Materials 596
A.10.3 Professional Societies Associated with Conferences and Publications on Composite Materials 596
A.11 List of Selected Computer Programs 597

Index 599