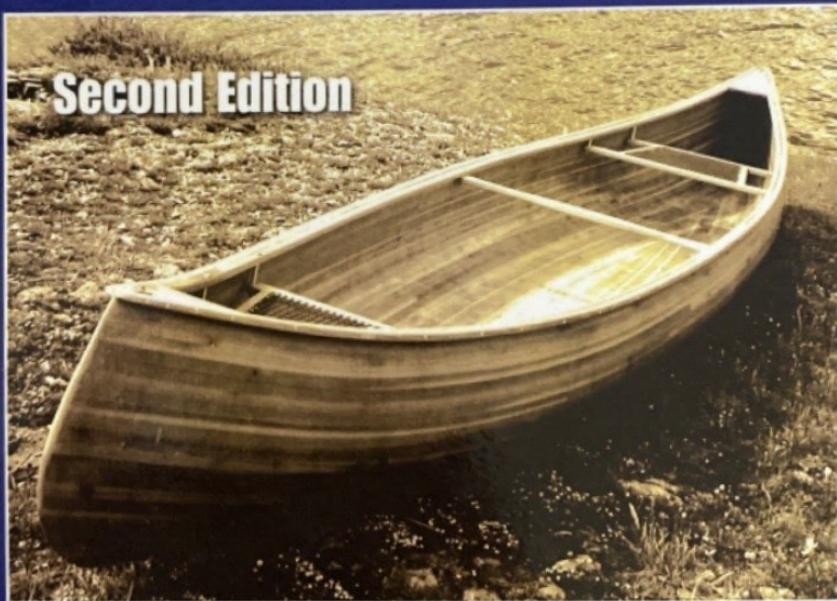


# Engineering Design with Polymers and Composites

Second Edition



James C. Gerdeen, PhD, PE  
Ronald A. L. Rorrer, PhD, PE

 CRC Press  
Taylor & Francis Group

---

# Contents

Preface.....	xiii
Acknowledgment .....	xv
Authors.....	xvii
<b>Chapter 1 Introduction .....</b>	<b>1</b>
1.1    Introduction .....	1
1.2    History of Polymers.....	2
1.3    History of Composites.....	4
1.4    Examples of Polymers and Composites in Use .....	5
1.5    Definitions and Classifications .....	7
1.6    Identification of Plastics .....	9
1.7    Raw Materials and Production of Polymers.....	11
1.8    Chemical Structures .....	14
1.9    Glass Transition and Melting Temperatures.....	21
Homework Problems.....	25
References .....	26
<b>Chapter 2 Mechanical Properties of Polymers .....</b>	<b>27</b>
2.1    Introduction .....	27
2.2    Tensile Properties .....	27
2.2.1    Elongation.....	29
2.2.2    Elastic Modulus.....	30
2.2.3    Ultimate Tensile Strength.....	30
2.2.4    Yield Strength.....	30
2.3    Static Failure Theories .....	33
2.4    Creep Properties .....	38
2.5    Relaxation Properties .....	40
2.6    Dynamic Properties.....	40
2.6.1    Dynamic Tests.....	40
2.6.2    Dynamic Modulus and Damping .....	42
2.6.3    Dynamic Property Data .....	44
2.7    Large Strain Definitions .....	47
2.8    Analysis of Damping .....	47
2.9    Time Hardening Creep .....	50
2.10    Isochronous Creep Curves .....	51
Homework Problems.....	51
References .....	54

<b>Chapter 3</b>	<b>Viscoelastic Behavior of Polymers.....</b>	<b>55</b>
3.1	Mechanical Models .....	55
3.2	Mathematical Models .....	57
3.3	The Maxwell Fluid .....	57
3.4	The Kelvin Solid.....	60
3.5	The Four-Parameter Model .....	63
3.6	The Boltzmann Superposition Principle .....	64
3.7	Advanced Viscoelastic Models.....	67
3.8	The Viscoelastic Correspondence Principle.....	69
3.9	The Time-Temperature Equivalence Principle.....	71
	Homework Problems.....	74
	References .....	79
<b>Chapter 4</b>	<b>Creep and Fatigue Failure .....</b>	<b>81</b>
4.1	Creep Failure under Tension.....	81
4.2	Creep Failure under Compression.....	83
4.3	Fatigue of Polymers.....	85
4.4	Notch Sensitivity under Fatigue .....	90
4.5	Creep Buckling of Shells.....	91
	Homework Problems.....	92
	References .....	93
<b>Chapter 5</b>	<b>Impact Strength and Fracture Toughness.....</b>	<b>95</b>
5.1	Impact Strength .....	95
5.1.1	Thickness Effects .....	100
5.1.2	Rate Effects .....	101
5.1.3	Combined Stiffness and Impact Properties.....	102
5.2	Fracture Toughness.....	105
5.2.1	Brittle Fracture .....	106
5.2.2	Ductile Fracture.....	109
5.2.3	General Theory of Fracture Instability .....	110
5.3	Analysis of the Charpy and Izod Impact Tests Using Fracture Mechanics.....	115
5.4	Analysis of Impact Specimens at the Nanoscale .....	116
	Homework Problems.....	117
	References .....	119
<b>Chapter 6</b>	<b>Selection of Polymers for Design Applications.....</b>	<b>121</b>
6.1	Introduction .....	121
6.2	Basic Material Properties .....	121
6.3	Performance Parameters.....	122
6.4	Loading Conditions and Geometrical Configurations .....	122

6.5	Availability of Materials.....	122
6.6	A Rectangular Beam in Bending .....	123
6.7	Weighting-Factor Analysis .....	125
6.8	Thermal Gradient through a Beam .....	126
6.9	Rating Factors for Various Loading Requirements.....	128
6.10	Design Optimization .....	129
6.10.1	Graphical Solution.....	130
6.10.2	Computer Solution.....	135
6.10.3	Microsoft Excel Solver Routine .....	137
6.11	Computer Database Design Selection Procedure.....	140
6.11.1	Example Problem of Impact of a Beam .....	142
	Homework Problems.....	142
	References .....	143
<b>Chapter 7</b>	<b>Design Applications of Some Polymers.....</b>	<b>145</b>
7.1	Phenolic Resins with Fillers .....	145
7.2	Polycarbonate .....	147
7.3	Example Design with PC: Fan Impeller Blade.....	147
7.3.1	Creep Strain.....	149
7.3.2	Impact Failure .....	150
7.4	Example Design with PC: Snap/Fit Design.....	151
7.5	Example Design of PVC Pipe.....	152
7.6	Design with Fluorocarbon Resins .....	156
	Homework Problems.....	158
	References .....	159
<b>Chapter 8</b>	<b>Composite Material Mechanics.....</b>	<b>161</b>
8.1	Introduction .....	161
8.2	Composite Material Nomenclature and Definitions.....	161
8.3	Analysis of Composite Structures .....	165
8.3.1	Micromechanics of a Unidirectional Fiber-Reinforced Composite Layer (Lamina) .....	167
8.3.1.1	Determination of Apparent Longitudinal Young's Modulus .....	168
8.3.1.2	Determination of Major Poisson's Ratio of Unidirectional Lamina .....	171
8.3.1.3	Apparent Transverse Young's Modulus....	172
8.3.1.4	Apparent Shear Modulus .....	174
8.3.1.5	Summary of Results from Micromechanics Analysis of Lamina Elastic Moduli .....	176
8.3.1.6	Prediction of Tensile Strength in Fiber Direction .....	177

8.3.2	Macromechanics of a Unidirectional Fiber-Reinforced Composite Layer of Lamina .....	178
8.3.2.1	Stress-Strain Relationships for Isotropic Materials .....	179
8.3.2.2	Anisotropic Materials: Contracted Notation .....	180
8.3.2.3	Orthotropic Lamina: Hooke's Law in Principal Material Coordinates .....	181
8.3.2.4	Stress (Strain) Relationships for Off-Axis Orientation.....	184
8.4	Experimental Determination of Engineering Elastic Constants .....	190
	Homework Problems.....	194
	Bibliography .....	195
	References .....	195
<b>Chapter 9</b>	<b>Composite Laminate Failure .....</b>	<b>197</b>
9.1	Strength Properties and Failure Theories.....	197
9.1.1	A Review of Failure Theories for Isotropic Materials .....	197
9.1.2	Strength and Failure Theories for an Orthotropic Lamina.....	199
9.1.3	Failure by Fiber Pullout.....	205
9.2	Stiffness of Laminated Composites .....	206
9.2.1	Sandwich Beam.....	206
9.2.2	Orthotropic Plate.....	208
9.2.3	Laminated Plates.....	211
9.3	Thermal Stresses .....	216
9.4	Summary .....	216
	Homework Problems.....	217
	Bibliography .....	219
	References .....	219
<b>Chapter 10</b>	<b>Polymer Processing .....</b>	<b>221</b>
10.1	Extrusion .....	221
10.2	Manufacture of PVC Pipe by Extrusion .....	223
10.3	Injection Molding .....	226
10.4	Thermosforming .....	228
10.5	Blow Molding .....	229
10.5.1	Inflation .....	232
10.5.2	Cooling Phase.....	236
	Homework Problems .....	241
	References .....	242

<b>Chapter 11 Adhesion of Polymers and Composites.....</b>	<b>243</b>
11.1 Introduction .....	243
11.2 Fundamentals of Adhesion.....	243
11.2.1 Wetting and Work of Adhesion.....	243
11.2.2 Measurement of Adhesion.....	246
11.2.3 Viscoelasticity of Adhesion.....	249
11.3 Adhesives.....	250
11.3.1 Common Polymeric Adhesives .....	250
11.3.2 Polymers as Matrix Materials ( <i>In Situ</i> Adhesives) in Polymeric Composites.....	252
11.4 Enhancement of Adhesion in Composites.....	253
11.5 Curing of Adhesives .....	254
11.6 Summary .....	257
Homework Problems.....	257
References .....	258
 <b>Chapter 12 Polymer Fusing and Other Assembly Techniques.....</b>	 <b>259</b>
12.1 Introduction .....	259
12.2 Heated Tool Welding .....	260
12.3 Ultrasonic Welding .....	261
12.3.1 Joint Design.....	262
12.3.2 Staking .....	266
12.4 Friction Welding .....	267
12.4.1 Linear Vibration and Orbital Welding .....	267
12.4.2 Spin Welding .....	269
12.5 Laser Welding.....	269
12.6 Hot Gas.....	272
12.7 Resistance Welding .....	273
12.8 Induction Welding .....	274
12.9 Mechanical Fastener Connections.....	276
12.9.1 Screws.....	276
12.9.2 Inserts .....	278
Homework Problems.....	279
References .....	279
 <b>Chapter 13 Tribology of Polymers and Composites .....</b>	 <b>281</b>
13.1 Introduction .....	281
13.2 Contact Mechanics .....	282
13.3 Surface Topography.....	284
13.4 Friction .....	285
13.4.1 Static and Dynamic Coefficients of Friction.....	288
13.4.2 Adhesive and Abrasive Friction .....	289
13.5 Wear.....	289
13.5.1 Archard Wear Law .....	290

13.6	PV Limit .....	291
13.7	Rolling and Sliding .....	292
13.8	Modification of Polymers for Friction and Wear Performance .....	293
13.8.1	Internal Lubricants .....	293
13.8.2	Reinforcements .....	295
13.9	Composites .....	295
13.10	Wear of Composites .....	299
13.11	Heat Generation in Sliding Polymer Systems .....	300
13.11.1	Bulk Surface-Temperature Calculations .....	301
13.11.2	Flash Temperature .....	301
13.12	Special Considerations .....	302
13.12.1	Polymer-on-Polymer Sliding .....	302
13.12.2	Coatings .....	302
13.12.3	Effect of Surface Topography on Friction and Wear .....	302
13.12.4	Effect of Environment (Temperature, Humidity, Gases, and Liquids, etc.) on Friction and Wear .....	302
13.12.5	Friction-Induced Vibration .....	303
13.13	Simulative Laboratory Testing .....	304
	Homework Problems .....	305
	References .....	305
<b>Chapter 14</b>	<b>Damping and Isolation with Polymers and Composites .....</b>	<b>307</b>
14.1	Introduction .....	307
14.2	Relevance of the Thermomechanical Spectrum .....	308
14.3	Damping Methods of Material Modification (Cross-linking, $M_w$ , Structure) Polymers, and Composites Used in Damping and Isolation .....	309
14.3.1	Reduced Frequency Nomograph .....	310
14.4	Materials for Damping and Isolation .....	311
14.5	Fundamentals of Vibration Damping and Isolation .....	313
14.5.1	Dynamics of Vibrating Structures (Continuous and Discrete or Point) .....	313
14.6	Role of Dampers .....	319
14.7	Damping Layers .....	320
14.7.1	Application of Dampers and Isolators: Discrete Design of Dampers and Isolators for Equipment .....	320
	Homework Problems .....	323
	References .....	323
<b>Chapter 15</b>	<b>Rapid Prototyping with Polymers .....</b>	<b>325</b>
15.1	Introduction .....	325
15.2	Rapid Product Development, Tooling, and Manufacture .....	325

15.3 RP Techniques.....	326
15.4 RP Materials.....	332
15.4.1 Materials Used in FDM by Stratasys .....	332
15.4.2 Materials Used in SLA.....	334
15.4.3 Materials Used in LOM .....	334
15.4.4 Materials Used in SLS .....	334
15.5 Applications.....	334
Homework Problems .....	339
References .....	340
 <b>Chapter 16 Piezoelectric Polymers .....</b>	 341
16.1 Introduction .....	341
16.2 Piezoelectric Strain Behavior .....	342
16.3 Piezoelectric Material Properties .....	345
16.4 Hysteresis.....	346
16.5 Composites .....	348
Homework Problems.....	356
Further Reading.....	357
References .....	357
 <b>Appendix A: Conversion Factors.....</b>	 359
<b>Appendix B: Area Moments of Inertia .....</b>	361
<b>Appendix C: Beam Reactions and Displacements.....</b>	363
<b>Appendix D: Laminate MATLAB® or Octave Code.....</b>	367
<b>Appendix E: Sample Input/Output for Laminate Program .....</b>	377
<b>Appendix F: Composite Materials Properties .....</b>	383
<b>Appendix G: Thermal and Electrical Properties .....</b>	385
<b>Index.....</b>	389