

# Brief Contents

*Preface* xv

## **Part 1 Basics 2**

**1 Introduction to Mechanical Engineering Design 3**

**2 Materials 41**

**3 Load and Stress Analysis 85**

**4 Deflection and Stiffness 161**

## **Part 2 Failure Prevention 226**

**5 Failures Resulting from Static Loading 227**

**6 Fatigue Failure Resulting from Variable Loading 273**

## **Part 3 Design of Mechanical Elements 350**

**7 Shafts and Shaft Components 351**

**8 Screws, Fasteners, and the Design of Nonpermanent Joints 401**

**9 Welding, Bonding, and the Design of Permanent Joints 467**

**10 Mechanical Springs 509**

**11 Rolling-Contact Bearings 561**

**12 Lubrication and Journal Bearings 609**

**13 Gears—General 665**

**14 Spur and Helical Gears 725**

**15 Bevel and Worm Gears 777**

**16 Clutches, Brakes, Couplings, and Flywheels 817**

**17 Flexible Mechanical Elements 871**

**18 Power Transmission Case Study 925**

**Part 4 Special Topics 944**

**19 Finite-Element Analysis 945**

**20 Geometric Dimensioning and Tolerancing 969**

**Appendixes**

**A Useful Tables 1011**

**B Answers to Selected Problems 1067**

*Index* 1073

**Deflection**

**Stiffness**

Investment Casting

Hot-Working Process

Cold-Working Process

The Heat Treatment of Steel

Alloy Steels

Corrosion-Resistant Steels

Castings Materials

Nonferrous Metals

Plastics

Composite Materials

Materials Selection

Long Columns

Intermediate-Length Columns

Load and Stress Analysis

Equilibrium and Free-Body Diagrams

Shear Force and Bending Moments

Beams

Singularity Functions

Stress

Failure Prevention

Moire's Circle for Plane Stress

Failures Resulting from Static Loading

Elastic Strain

Uniformly Distributed Stresses

Normal Stresses for Beams in Bending

Shear Stresses for Beams in Bending

Torsion

Stress Concentration

Maximum-Normal-Stress Theory

Introduction to Mechanical Engineering Design

Design and Fabrication of the Design Process

Design Tools and Resources

Approach to Design Analysis and Standards

Economics and Life-Cycle Costs

Safety and Reliability

The Strength of Materials

The Linear-Elastic Theory

Design Factor and Factor of Safety

Reliability and Probability of Failure

Relating the Design Factor to Reliability

Dimensions and Tolerances

Units

Calculations and Significant Figures

Design Topic Interdependencies

Power Transmission Case Study

Fluctuating Stresses

Problems

Torsional Strength under Fluctuating Stresses

Combination of Loading Modes

Varying, Fluctuating Stresses; Cumulative Material Damage

The Statistical Significance of Materials

Roam Maps and Inverse Problems

Strength of Materials

Hardness

3-19 Contact Stresses  
3-20 Summary  
Problems  
4  
4-1 Shell Molding  
4-2 Investment Casting  
4-3 Powder-Metalurgy Process  
4-4 Hot-Working Process  
4-5 Cold-Working Process  
4-6 The Heat Treatment of Steel  
4-7 Alloy Steels  
4-8 Corrosion-Resistant Steels  
4-9 Castings Materials  
4-10 Nonferrous Metals  
4-11 Plastics  
4-12 Composite Materials  
4-13 Materials Selection  
4-14 Long Columns  
4-15 Intermediate-Length Columns  
4-16 Load and Stress Analysis  
4-17 Equilibrium and Free-Body Diagrams  
4-18 Shear Force and Bending Moments  
4-19 Beams  
4-20 Singularity Functions  
4-21 Stress  
4-22 Failure Prevention  
4-23 Moire's Circle for Plane Stress  
4-24 Failures Resulting from Static Loading  
4-25 Elastic Strain  
4-26 Uniformly Distributed Stresses  
4-27 Normal Stresses for Beams in Bending  
4-28 Shear Stresses for Beams in Bending  
4-29 Torsion  
4-30 Stress Concentration  
4-31 Maximum-Normal-Stress Theory  
4-32 Introduction to Mechanical Engineering Design  
4-33 Design and Fabrication of the Design Process  
4-34 Design Tools and Resources  
4-35 Approach to Design Analysis and Standards  
4-36 Economics and Life-Cycle Costs  
4-37 Safety and Reliability  
4-38 The Strength of Materials  
4-39 The Linear-Elastic Theory  
4-40 Design Factor and Factor of Safety  
4-41 Reliability and Probability of Failure  
4-42 Relating the Design Factor to Reliability  
4-43 Dimensions and Tolerances  
4-44 Units  
4-45 Calculations and Significant Figures  
4-46 Design Topic Interdependencies  
4-47 Power Transmission Case Study  
4-48 Fluctuating Stresses  
4-49 Problems  
4-50 Torsional Strength under Fluctuating Stresses  
4-51 Combination of Loading Modes  
4-52 Varying, Fluctuating Stresses; Cumulative Material Damage  
4-53 The Statistical Significance of Materials  
4-54 Roam Maps and Inverse Problems  
4-55 Strength of Materials  
4-56 Hardness

**Part 2**

# Contents

Preface xv

## Part 1 Basics 2

### 1 Introduction to Mechanical Engineering Design 3

- 1-1 Design 4
- 1-2 Mechanical Engineering Design 5
- 1-3 Phases and Interactions of the Design Process 5
- 1-4 Design Tools and Resources 8
- 1-5 The Design Engineer's Professional Responsibilities 10
- 1-6 Standards and Codes 12
- 1-7 Economics 13
- 1-8 Safety and Product Liability 15
- 1-9 Stress and Strength 16
- 1-10 Uncertainty 16
- 1-11 Design Factor and Factor of Safety 18
- 1-12 Reliability and Probability of Failure 20
- 1-13 Relating the Design Factor to Reliability 24
- 1-14 Dimensions and Tolerances 27
- 1-15 Units 31
- 1-16 Calculations and Significant Figures 32
- 1-17 Design Topic Interdependencies 33
- 1-18 Power Transmission Case Study Specifications 34
- Problems 36

### 2 Materials 41

- 2-1 Material Strength and Stiffness 42
- 2-2 The Statistical Significance of Material Properties 46
- 2-3 Strength and Cold Work 49
- 2-4 Hardness 52

- 2-5 Impact Properties 53
- 2-6 Temperature Effects 54
- 2-7 Numbering Systems 56
- 2-8 Sand Casting 57
- 2-9 Shell Molding 57
- 2-10 Investment Casting 58
- 2-11 Powder-Metallurgy Process 58
- 2-12 Hot-Working Processes 58
- 2-13 Cold-Working Processes 59
- 2-14 The Heat Treatment of Steel 60
- 2-15 Alloy Steels 63
- 2-16 Corrosion-Resistant Steels 64
- 2-17 Casting Materials 65
- 2-18 Nonferrous Metals 67
- 2-19 Plastics 70
- 2-20 Composite Materials 71
- 2-21 Materials Selection 72
- Problems 79

### 3 Load and Stress Analysis 85

- 3-1 Equilibrium and Free-Body Diagrams 86
- 3-2 Shear Force and Bending Moments in Beams 89
- 3-3 Singularity Functions 91
- 3-4 Stress 93
- 3-5 Cartesian Stress Components 93
- 3-6 Mohr's Circle for Plane Stress 94
- 3-7 General Three-Dimensional Stress 100
- 3-8 Elastic Strain 101
- 3-9 Uniformly Distributed Stresses 102
- 3-10 Normal Stresses for Beams in Bending 103
- 3-11 Shear Stresses for Beams in Bending 108
- 3-12 Torsion 115
- 3-13 Stress Concentration 124

- 3-14** Stresses in Pressurized Cylinders 127
- 3-15** Stresses in Rotating Rings 129
- 3-16** Press and Shrink Fits 130
- 3-17** Temperature Effects 131
- 3-18** Curved Beams in Bending 132
- 3-19** Contact Stresses 136
- 3-20** Summary 140
- Problems** 141
- 4 Deflection and Stiffness** 161
- 4-1** Spring Rates 162
- 4-2** Tension, Compression, and Torsion 163
- 4-3** Deflection Due to Bending 164
- 4-4** Beam Deflection Methods 166
- 4-5** Beam Deflections by Superposition 167
- 4-6** Beam Deflections by Singularity Functions 170
- 4-7** Strain Energy 176
- 4-8** Castigliano's Theorem 178
- 4-9** Deflection of Curved Members 183
- 4-10** Statically Indeterminate Problems 189
- 4-11** Compression Members—General 195
- 4-12** Long Columns with Central Loading 195
- 4-13** Intermediate-Length Columns with Central Loading 198
- 4-14** Columns with Eccentric Loading 198
- 4-15** Struts or Short Compression Members 200
- 4-16** Elastic Stability 204
- 4-17** Shock and Impact 205
- Problems** 206
- Part 2 Failure Prevention** 226
- 5 Failures Resulting from Static Loading** 227
- 5-1** Static Strength 230
- 5-2** Stress Concentration 231
- 5-3** Failure Theories 233
- 5-4** Maximum-Shear-Stress Theory for Ductile Materials 233
- 5-5** Distortion-Energy Theory for Ductile Materials 235
- 5-6** Coulomb-Mohr Theory for Ductile Materials 242
- 5-7** Failure of Ductile Materials Summary 245
- 5-8** Maximum-Normal-Stress Theory for Brittle Materials 249
- 5-9** Modifications of the Mohr Theory for Brittle Materials 249
- 5-10** Failure of Brittle Materials Summary 252
- 5-11** Selection of Failure Criteria 252
- 5-12** Introduction to Fracture Mechanics 253
- 5-13** Important Design Equations 262
- Problems** 264
- 6 Fatigue Failure Resulting from Variable Loading** 273
- 6-1** Introduction to Fatigue in Metals 274
- 6-2** Approach to Fatigue Failure in Analysis and Design 280
- 6-3** Fatigue-Life Methods 281
- 6-4** The Stress-Life Method 281
- 6-5** The Strain-Life Method 284
- 6-6** The Linear-Elastic Fracture Mechanics Method 286
- 6-7** The Endurance Limit 290
- 6-8** Fatigue Strength 291
- 6-9** Endurance Limit Modifying Factors 294
- 6-10** Stress Concentration and Notch Sensitivity 303
- 6-11** Characterizing Fluctuating Stresses 308
- 6-12** Fatigue Failure Criteria for Fluctuating Stress 311
- 6-13** Torsional Fatigue Strength under Fluctuating Stresses 325
- 6-14** Combinations of Loading Modes 325
- 6-15** Varying, Fluctuating Stresses; Cumulative Fatigue Damage 329
- 6-16** Surface Fatigue Strength 335
- 6-17** Road Maps and Important Design Equations for the Stress-Life Method 338
- Problems** 341

**Part 3 Design of Mechanical Elements** 350

**7 Shafts and Shaft Components** 351

- 7-1 Introduction 352
- 7-2 Shaft Materials 352
- 7-3 Shaft Layout 353
- 7-4 Shaft Design for Stress 358
- 7-5 Deflection Considerations 371
- 7-6 Critical Speeds for Shafts 375
- 7-7 Miscellaneous Shaft Components 380
- 7-8 Limits and Fits 387
- 1-1 Problems 392

**8 Screws, Fasteners, and the Design of Nonpermanent Joints** 401

- 8-1 Thread Standards and Definitions 402
- 8-2 The Mechanics of Power Screws 406
- 8-3 Threaded Fasteners 414
- 8-4 Joints—Fastener Stiffness 416
- 8-5 Joints—Member Stiffness 419
- 8-6 Bolt Strength 424
- 8-7 Tension Joints—The External Load 427
- 8-8 Relating Bolt Torque to Bolt Tension 429
- 8-9 Statically Loaded Tension Joint with Preload 432
- 8-10 Gasketed Joints 436
- 8-11 Fatigue Loading of Tension Joints 436
- 8-12 Bolted and Riveted Joints Loaded in Shear 443
- Problems 451

**9 Welding, Bonding, and the Design of Permanent Joints** 467

- 9-1 Welding Symbols 468
- 9-2 Butt and Fillet Welds 470
- 9-3 Stresses in Welded Joints in Torsion 474
- 9-4 Stresses in Welded Joints in Bending 479

- 9-5 The Strength of Welded Joints 481
- 9-6 Static Loading 484
- 9-7 Fatigue Loading 488
- 9-8 Resistance Welding 490
- 9-9 Adhesive Bonding 490
- Problems 499

**10 Mechanical Springs** 509

- 10-1 Stresses in Helical Springs 510
- 10-2 The Curvature Effect 511
- 10-3 Deflection of Helical Springs 512
- 10-4 Compression Springs 512
- 10-5 Stability 514
- 10-6 Spring Materials 515
- 10-7 Helical Compression Spring Design for Static Service 520
- 10-8 Critical Frequency of Helical Springs 526
- 10-9 Fatigue Loading of Helical Compression Springs 528
- 10-10 Helical Compression Spring Design for Fatigue Loading 531
- 10-11 Extension Springs 534
- 10-12 Helical Coil Torsion Springs 542
- 10-13 Belleville Springs 549
- 10-14 Miscellaneous Springs 550
- 10-15 Summary 552
- Problems 552

**11 Rolling-Contact Bearings** 561

- 11-1 Bearing Types 562
- 11-2 Bearing Life 565
- 11-3 Bearing Load Life at Rated Reliability 566
- 11-4 Reliability versus Life—The Weibull Distribution 568
- 11-5 Relating Load, Life, and Reliability 569
- 11-6 Combined Radial and Thrust Loading 571
- 11-7 Variable Loading 577
- 11-8 Selection of Ball and Cylindrical Roller Bearings 580
- 11-9 Selection of Tapered Roller Bearings 583
- 11-10 Design Assessment for Selected Rolling-Contact Bearings 592

- 11-11** Lubrication 596
- 11-12** Mounting and Enclosure 597
- Problems** 601
- 12 Lubrication and Journal Bearings** 609
- 12-1** Types of Lubrication 610
- 12-2** Viscosity 611
- 12-3** Petroff's Equation 613
- 12-4** Stable Lubrication 615
- 12-5** Thick-Film Lubrication 616
- 12-6** Hydrodynamic Theory 617
- 12-7** Design Considerations 621
- 12-8** The Relations of the Variables 623
- 12-9** Steady-State Conditions in Self-Contained Bearings 637
- 12-10** Clearance 640
- 12-11** Pressure-Fed Bearings 642
- 12-12** Loads and Materials 648
- 12-13** Bearing Types 650
- 12-14** Thrust Bearings 651
- 12-15** Boundary-Lubricated Bearings 652
- Problems** 660
- 13 Gears—General** 665
- 13-1** Types of Gears 666
- 13-2** Nomenclature 667
- 13-3** Conjugate Action 669
- 13-4** Involute Properties 670
- 13-5** Fundamentals 670
- 13-6** Contact Ratio 676
- 13-7** Interference 677
- 13-8** The Forming of Gear Teeth 679
- 13-9** Straight Bevel Gears 682
- 13-10** Parallel Helical Gears 683
- 13-11** Worm Gears 687
- 13-12** Tooth Systems 688
- 13-13** Gear Trains 690
- 13-14** Force Analysis—Spur Gearing 697
- 13-15** Force Analysis—Bevel Gearing 701
- 13-16** Force Analysis—Helical Gearing 704
- 13-17** Force Analysis—Worm Gearing 706
- Problems** 712
- 14 Spur and Helical Gears** 725
- 14-1** The Lewis Bending Equation 726
- 14-2** Surface Durability 735
- 14-3** AGMA Stress Equations 737
- 14-4** AGMA Strength Equations 739
- 14-5** Geometry Factors  $I$  and  $J$  ( $Z_I$  and  $Y_J$ ) 743
- 14-6** The Elastic Coefficient  $C_p$  ( $Z_E$ ) 748
- 14-7** Dynamic Factor  $K_v$  748
- 14-8** Overload Factor  $K_o$  750
- 14-9** Surface Condition Factor  $C_f$  ( $Z_R$ ) 750
- 14-10** Size Factor  $K_s$  751
- 14-11** Load-Distribution Factor  $K_m$  ( $K_H$ ) 751
- 14-12** Hardness-Ratio Factor  $C_H$  ( $Z_W$ ) 753
- 14-13** Stress-Cycle Factors  $Y_N$  and  $Z_N$  754
- 14-14** Reliability Factor  $K_R$  ( $Y_Z$ ) 755
- 14-15** Temperature Factor  $K_T$  ( $Y_\theta$ ) 756
- 14-16** Rim-Thickness Factor  $K_B$  756
- 14-17** Safety Factors  $S_F$  and  $S_H$  757
- 14-18** Analysis 757
- 14-19** Design of a Gear Mesh 767
- Problems** 772
- 15 Bevel and Worm Gears** 777
- 15-1** Bevel Gearing—General 778
- 15-2** Bevel-Gear Stresses and Strengths 780
- 15-3** AGMA Equation Factors 783
- 15-4** Straight-Bevel Gear Analysis 795
- 15-5** Design of a Straight-Bevel Gear Mesh 798
- 15-6** Worm Gearing—AGMA Equation 801
- 15-7** Worm-Gear Analysis 805
- 15-8** Designing a Worm-Gear Mesh 809
- 15-9** Buckingham Wear Load 812
- Problems** 813
- 16 Clutches, Brakes, Couplings, and Flywheels** 817
- 16-1** Static Analysis of Clutches and Brakes 819
- 16-2** Internal Expanding Rim Clutches and Brakes 824

<b>16-3</b>	External Contracting Rim Clutches and Brakes	832
<b>16-4</b>	Band-Type Clutches and Brakes	836
<b>16-5</b>	Frictional-Contact Axial Clutches	837
<b>16-6</b>	Disk Brakes	841
<b>16-7</b>	Cone Clutches and Brakes	845
<b>16-8</b>	Energy Considerations	848
<b>16-9</b>	Temperature Rise	849
<b>16-10</b>	Friction Materials	853
<b>16-11</b>	Miscellaneous Clutches and Couplings	856
<b>16-12</b>	Flywheels	858
	<b>Problems</b>	863
<b>17</b>	<b>Flexible Mechanical Elements</b>	871
<b>17-1</b>	Belts	872
<b>17-2</b>	Flat- and Round-Belt Drives	875
<b>17-3</b>	V Belts	890
<b>17-4</b>	Timing Belts	898
<b>17-5</b>	Roller Chain	899
<b>17-6</b>	Wire Rope	908
<b>17-7</b>	Flexible Shafts	916
	<b>Problems</b>	917
<b>18</b>	<b>Power Transmission Case Study</b>	925
<b>18-1</b>	Design Sequence for Power Transmission	927
<b>18-2</b>	Power and Torque Requirements	928
<b>18-3</b>	Gear Specification	928
<b>18-4</b>	Shaft Layout	935
<b>18-5</b>	Force Analysis	937
<b>18-6</b>	Shaft Material Selection	937
<b>18-7</b>	Shaft Design for Stress	938
<b>18-8</b>	Shaft Design for Deflection	938
<b>18-9</b>	Bearing Selection	939
<b>18-10</b>	Key and Retaining Ring Selection	940
<b>18-11</b>	Final Analysis	943
	<b>Problems</b>	943

<b>Part 4</b>	<b>Special Topics</b>	944
<b>19</b>	<b>Finite-Element Analysis</b>	945
<b>19-1</b>	The Finite-Element Method	947
<b>19-2</b>	Element Geometries	949
<b>19-3</b>	The Finite-Element Solution Process	951
<b>19-4</b>	Mesh Generation	954
<b>19-5</b>	Load Application	956
<b>19-6</b>	Boundary Conditions	957
<b>19-7</b>	Modeling Techniques	958
<b>19-8</b>	Thermal Stresses	961
<b>19-9</b>	Critical Buckling Load	961
<b>19-10</b>	Vibration Analysis	963
<b>19-11</b>	Summary	964
	<b>Problems</b>	966
<b>20</b>	<b>Geometric Dimensioning and Tolerancing</b>	969
<b>20-1</b>	Dimensioning and Tolerancing Systems	970
<b>20-2</b>	Definition of Geometric Dimensioning and Tolerancing	971
<b>20-3</b>	Datums	976
<b>20-4</b>	Controlling Geometric Tolerances	981
<b>20-5</b>	Geometric Characteristic Definitions	985
<b>20-6</b>	Material Condition Modifiers	994
<b>20-7</b>	Practical Implementation	996
<b>20-8</b>	GD&T in CAD Models	1001
<b>20-9</b>	Glossary of GD&T Terms	1002
	<b>Problems</b>	1005
	<b>Appendixes</b>	
<b>A</b>	<b>Useful Tables</b>	1011
<b>B</b>	<b>Answers to Selected Problems</b>	1067
	<b>Index</b>	1073