Contents

PREFACE xxi

ACKNOWLEDGMENTS xxiii

1 INTRODUCTION 1

1.1 Notation / 1
1.2 Conversion Factors / 2
1.3 Sign Conventions and Consistent Units / 2
1.4 SI Units / 2
1.5 Typical Design Loads and Stresses / 2
Tables for Chapter 1 / 3

2 GEOMETRIC PROPERTIES OF PLANE AREAS 17

2.1 Notation / 17
2.2 Centroids / 18
2.3 Moments of Inertia / 19
Section Moduli / 20
2.4 Polar Moment of Inertia / 21
2.5 Principal Moments of Inertia / 22
2.6 Mohr's Circle for Moments of Inertia / 24
2.7 First Moment of Areas Associated with Shear Stresses in Beams / 28
2.8 Shear Correction Factors / 29
2.9 Torsional Constant / 31
Thin-Walled Sections / 31
2.10 Sectorial Properties / 36
Sectorial Area / 36
First Sectorial Moment / 37
Sectorial Linear Moments / 37

Warping Constant (Sectorial Moment of Inertia) / 37
2.11 Shear Center for Thin-Walled Cross Sections / 38
Open Cross Sections / 39
2.12 Modulus-Weighted Properties for Composite Sections / 41
References / 44
Tables for Chapter 2 / 45

3 STRESS AND STRAIN **89**

3.1 Notation / 90
3.2 Definitions and Types of Stress / 91
3.3 Stress Component Analysis / 92
Sign Convention / 92
Stress Tensor / 93
Plane Stress / 93
Variation of Normal and Shear Stress in Tension / 94
Stress at an Arbitrary Orientation for the Two-Dimensional Case / 95
Principal Stresses and Maximum Shear Stress for the Two-Dimensional Case / 97
Mohr's Circle for a Two-Dimensional State of Stress / 100
Construction of Mohr's Circle / 100
Use of Mohr's Circle / 101
Stress Acting on an Arbitrary Plane in Three-Dimensional Systems / 102
Normal and Shear Stress on an Oblique Plane / 102
Maximum Shear Stress in Three-Dimensional Systems / 103
Mohr's Circle for Three Dimensions / 104
Octahedral Stress / 106
Mean and Deviator Stress / 107
3.4 Relationship between Stress and Internal Forces / 108
Average Shear Stress / 109
3.5 Differential Equations of Equilibrium / 109
3.6 Allowable Stress / 109
3.7 Residual Stress / 110
3.8 Definition of Strain / 110
3.9 Relationship between Strain and Displacement / 112
3.10 Analysis of Strain / 112
3.11 Elastic Stress–Strain Relations / 113
Poisson's Ratio / 113
Hooke's Law / 113

3.12 Stress and Strain in Simple Configurations / 114
Direct Axial Loading (Extension and Compression) / 114
Direct Shear in Connections / 116
Torsion / 116
Normal and Shear Stress of Beams / 120
Deflection of Simple Beams / 122
Stress in Pressure Vessels / 124
3.13 Combined Stresses / 126
3.14 Unsymmetric Bending / 129
Normal Stress / 129
Shear Stress / 131
3.15 Theories of Failure / 134
Concept of Failure / 134
Validity of Theories / 138
3.16 Application of Failure Theories / 139
References / 141
Tables for Chapter 3 / 143

4 MECHANICAL PROPERTIES AND TESTING OF ENGINEERING MATERIALS 149

4.1 Notation / 151
4.2 Material Laws: Stress–Strain Relations / 152
4.3 Tensile Test / 154
4.4 Impact Tests / 159
Notched-Bar Tests / 159
Drop-Weight Test for the Nil-Ductility Temperature / 160
Dynamic Tear Energy Test / 162
4.5 Hardness Tests / 162
Brinell Hardness Test / 163
Vickers Hardness Test / 163
Rockwell Hardness Test / 163
Microhardness Test / 164
4.6 Creep / 165
Cumulative Creep / 167
Simultaneous Creep and Fatigue / 169
4.7 Ferrous Metals / 169
Steel Classification and Specifications / 172
Carbon Steels / 173
Alloy Steels / 174

Stainless Steels / 175
Cast Irons / 176
High-Strength, Low-Alloy Steels / 177
Tool Steels / 177
4.8 Nonferrous Metals / 177
Aluminum / 177
Magnesium / 178
Other Nonferrous Metals / 178
4.9 Plastics / 178
4.10 Ceramics / 179
4.11 Composites / 180
4.12 Biomechanics / 181
Bone Tissue Mechanics / 181
Soft Tissue Mechanics / 182
Factors That Influence Properties / 183
4.13 Biomaterials / 183
Classes of Biomaterials / 184
4.14 Microelectromechanical Systems (MEMS) / 184
4.15 Material Selection / 185
References / 189
Tables for Chapter 4 / 191

5 EXPERIMENTAL STRESS ANALYSIS **235**

5.1 Notation / 235
5.2 Introduction / 236
5.3 Electrical Resistance Strain Gage / 237
5.4 Brittle Coating / 244
5.5 Photoelasticity / 245
References / 245
Tables for Chapter 5 / 247

6 STRESS CONCENTRATION **255**

6.1 Notation / 255
6.2 Stress Concentration Factors / 256
6.3 Effective Stress Concentration Factors / 259
Neuber's Rule / 261
6.4 Designing to Minimize Stress Concentration / 265
References / 271
Tables for Chapter 6 / 273

7 FRACTURE MECHANICS AND FATIGUE 307

7.1 Notation / 308
7.2 Linear Elastic Fracture Mechanics and Applications / 309
General Design by Linear Elastic Fracture Mechanics / 315
7.3 Energy Analysis of Fracture / 326
7.4 *J* Integral / 327
7.5 Fatigue Fracture / 329
7.6 Traditional *S–N* Curve Approach to Fatigue / 330
Stress Concentration / 331
Nonzero Mean Load / 331
Load with Varying Amplitude / 334
Effects of Load, Size, Surface, and Environment / 336
Stress Concentration with a Nonzero Mean Load / 338
7.7 Fracture Mechanics Approach to Fatigue / 340
7.8 Combined Approach / 344
References / 345
Tables for Chapter 7 / 349

8 JOINTS 369

8.1 Notation / 369
8.2 Riveted and Bolted Joints / 371
Joint Failure Mode under Shear Loading / 373
Boiler Joints / 377
Bolted Joints in Machine Design / 377
8.3 Load Analysis of Fastener Groups / 379
8.4 Design of Riveted and Bolted Connections / 382
8.5 Welded Joints and Connections / 390
Types of Welded Joints and Typical Drawing Symbols / 390
Analysis of Welded Joints / 392
References / 395
Tables for Chapter 8 / 397

9 CONTACT STRESSES 413

9.1 Notation / 414
9.2 Hertzian Contact Stresses / 415
Two Bodies in Point Contact / 415
Two Bodies in Line Contact / 429
Contact Stress with Friction / 430
9.3 Contact Fatigue / 432

9.4 Rolling Contact / 432
9.5 Non-Hertzian Contact Stress / 432
9.6 Nanotechnology: Scanning Probe Microscopy / 433
Hertz Model / 433
Sneddon's Model / 434
Derjaguin-Muller-Toporov Theory (DMT) / 434
Johnson-Kendall-Roberts Theory (JKR) / 434
Maugis-Dugdale Model / 434
References / 434
Tables for Chapter 9 / 437

10 DYNAMIC LOADING **451**

10.1 Notation / 452
10.2 Classification and Source of Dynamic Loadings / 453
10.3 Vibration Fundamentals / 453
Simple Kinematics / 453
Harmonic Motion / 454
Single-Degree-of-Freedom System / 456
Damping in Structures / 464
10.4 Natural Frequencies / 465
Approximate Formulas / 467
10.5 Viscoelastic Elements / 471
10.6 Human Body Vibrations / 471
10.7 Impact Formulas / 472
10.8 Energy-Absorbing Characteristics of Structures / 474
10.9 Dynamic Behavior of Materials / 479
10.10 Increasing the Dynamic Strength of Structures and Minimizing Dynamic Effects / 481
Geometric Configuration / 481
Material Properties / 481
Loading / 481
References / 482
Tables for Chapter 10 / 483

11 BEAMS AND COLUMNS **519**

11.1 Notation / 520
11.2 Sign Convention / 521
11.3 Stresses / 522
Normal Stress / 522

Shear Stress / 523
11.4 Simple Beams / 523
Tabulated Formulas / 524
Formulas for Beams with Arbitrary Loading / 526
11.5 Beams with Axial Forces on Elastic Foundations / 528
11.6 Plastic Design / 531
11.7 Buckling Loads and Columns / 531
Columns / 534
Short Bars with Eccentric Loading / 535
11.8 Natural Frequencies and Mode Shapes / 535
11.9 General Beams / 536
Transfer Matrices / 536
11.10 Stiffness and Mass Matrices / 539
Stiffness Matrix / 539
Geometric Stiffness Matrix / 542
Mass Matrix / 542
References / 542
Tables for Chapter 11 / 544

12 TORSION AND EXTENSION OF BARS **619**

12.1 Notation / 619
Torsion / 620
Extension / 621
12.2 Sign Conventions / 621
12.3 Stresses / 622
Torsional Stresses / 622
Hollow Thin-Walled Cross Sections / 622
Thin-Walled Open Sections / 624
Specific Stress Formulas / 624
Extensional Stress / 625
12.4 Simple Bars / 625
Torsion / 625
Extension / 626
Tabulated Formulas / 626
12.5 Natural Frequencies / 626
12.6 General Bars / 627
References / 631
Tables for Chapter 12 / 633

13 FRAMES **661**

13.1 Notation / 662
Notation for Gridworks / 662
13.2 Frames / 663
Formulas / 663
Buckling Loads / 666
Natural Frequencies / 666
Plastic Design / 666
13.3 Gridworks / 667
Static Loading / 668
Buckling Loads / 670
Natural Frequencies / 671
General Grillages / 672
13.4 Matrix Methods / 672
Transfer Matrix Method / 673
Stiffness and Mass Matrices / 673
Stability Analysis / 673
References / 674
Tables for Chapter 13 / 675

14 TORSION OF THIN-WALLED BEAMS **733**

14.1 Notation / 733
14.2 Sign Convention and Definitions / 735
14.3 Stresses / 736
Normal Warping Stress / 736
Shear Warping Stress / 737
14.4 Twisting of Thin-Walled Beams / 738
Formulas for Beams with Arbitrary Loading / 738
14.5 Buckling Loads / 741
14.6 Natural Frequencies / 741
14.7 General Beams / 742
References / 745
Tables for Chapter 14 / 747

15 CROSS-SECTIONAL STRESSES: COMBINED STRESSES **763**

15.1 Notation / 764
15.2 Sign Convention / 764
15.3 Warping Properties / 765

Integration Method / 766
Piecewise Integration Method / 767
15.4 Normal Stresses / 777
Neutral Axis / 777
15.5 Shear Stresses / 782
Shear Center / 783
15.6 Combined Normal and Shear Stresses / 788
Internal Moments / 791
Combined Results / 793
15.7 Finite Element Analysis / 794
References / 795
Tables for Chapter 15 / 797

16 CURVED BARS **801**

16.1 Notation / 802
All Curved Bars / 802
In-Plane Stress and Deformation / 802
Out-of-Plane Stress and Deformation / 803
16.2 In-Plane Stress and Deformation / 804
Sign Convention / 804
Stresses / 805
Simple Curved Bars / 817
Buckling Loads / 817
Natural Frequencies / 818
16.3 Out-of-Plane Stress and Deformation / 818
Sign Convention / 818
Stresses / 818
Simple Curved Bars / 818
Buckling Loads / 819
Natural Frequencies / 819
16.4 General Bars / 819
Rings / 820
References / 822
Tables for Chapter 16 / 823

17 ROTORS **891**

17.1 Notation / 892
17.2 Sign Convention / 894
17.3 Bending Vibration / 894
Whirling of a Single-Mass Rotor / 894

Single-Mass Rotor on Elastic Supports / 899
Uniform Rotating Shaft / 904
Transfer Matrices / 907
Stiffness and Mass Matrices / 911
17.4 Torsional Vibration / 920
17.5 Vibration of a Radial Beam / 921
Bending Vibration / 922
Axial Vibration / 923
References / 925
Tables for Chapter 17 / 927

18 PLATES **977**

18.1 Notation / 978
All Plates / 978
Circular Plates / 979
Rectangular Plates / 979
18.2 Circular Plates / 980
Stresses / 980
Simple Circular Plates / 980
Complex Circular Plates / 982
Tabulated Formulas / 983
Formulas for Plates with Arbitrary Loading / 984
Buckling Loads / 985
Natural Frequencies / 986
General Circular Plates / 988
Large Deflections of Circular Plates / 990
18.3 Rectangular Plates / 991
Stresses / 991
Governing Differential Equations / 991
Tabulated Formulas / 993
Formulas for Plates with Arbitrary Loading / 995
Buckling Loads / 996
Natural Frequencies / 997
General Rectangular Plates / 998
Large Deflections of Rectangular Plates / 1000
18.4 Other Plates / 1002
References / 1002
Tables for Chapter 18 / 1005

19 THICK SHELLS AND DISKS 1131

19.1 Definitions and Notation / 1131
Thick Cylinders / 1132
Thick Spherical Shells / 1133
Disks / 1133
19.2 Stresses / 1133
Thick Cylinders / 1134
Thick Spherical Shells / 1134
Nonpressurized Rotating Disk of Constant Thickness / 1135
19.3 Design of Cylinders with Internal Pressure / 1137
19.4 Simple Shells and Disks / 1141
Thick Cylinders / 1141
Thick Spherical Shells / 1144
Disks / 1145
19.5 Natural Frequencies / 1146
19.6 General Shells and Disks / 1146
References / 1150
Tables for Chapter 19 / 1151

20 THIN SHELLS 1185

20.1 Definitions / 1185
Notation / 1186
20.2 Membrane Shells of Revolution / 1188
20.3 Shells of Revolution with Bending / 1191
20.4 Multiple-Segment Shells of Revolution / 1197
20.5 Other Shells / 1204
20.6 Stability / 1205
20.7 Natural Frequencies / 1208
Circular Cylindrical Shells / 1208
Conical Shells / 1214
Spherical Shells / 1216
References / 1216
Tables for Chapter 20 / 1219

APPENDIX
I FUNDAMENTAL MATHEMATICS 1319

I.1 Algebraic Operations / 1321
Algebraic Laws / 1321
Exponents / 1321

Roots / 1321
Logarithms / 1321
Series / 1322
Binomial Theorem / 1323
I.2 Complex Numbers / 1323
Rules for Calculations / 1324
I.3 Plane Trigonometry / 1324
Definitions / 1324
Laws of Sines, Cosines, and Tangents / 1325
Identities / 1326
Equilateral Triangle / 1328
Right Triangle / 1328
Inverse Trigonometric Functions / 1328
Exponential Relations: Euler's Equation / 1330
I.4 Hyperbolic Functions / 1330
Definitions / 1330
Identities / 1330
I.5 Coordinate Systems / 1331
Rectangular Coordinate System / 1331
Direction Cosines / 1333
Unit Vectors on a Boundary Curve / 1333
Curvature Formulas / 1335
Basic Formulas in Plane Analytic Geometry / 1336
I.6 Quadratic Equations / 1338
I.7 System of Linear Equations / 1338
Determinants / 1338
Cramer's Rule / 1339
I.8 Differential and Integral Calculus / 1340
Basic Operations / 1340
Differentiation of Functions with Multiple Variables / 1341
Integral Formulas / 1341
Integral Theorems / 1341
I.9 Laplace Transform / 1343
I.10 Representation of Functions by Series / 1343
Taylor's Series for Single Variable / 1343
Maclaurin's Series / 1343
Taylor's Series for Two Variables / 1344
Fourier Series / 1344
Series Expansions of Some Common Functions / 1345

I.11 Matrix Algebra / 1346
Definitions / 1346
Laws / 1347
Basic Operations / 1347
Determinants / 1349
Eigenvalues and Eigenvectors / 1349
I.12 Numerical Methods / 1351
Linear Interpolation Method to Solve $f(x) = 0$ / 1351
Newton's Method / 1351
Zeros of a Polynomial / 1352
Gauss Algorithm / 1353
Numerical Integration / 1354
Tables for Appendix I / 1357

APPENDIX
II STRUCTURAL MEMBERS 1369

II.1 Engineering Beam Theory: Differential Form of Governing Equations / 1370
Geometric Relationships / 1370
Material Laws / 1372
Equations of Equilibrium / 1373
Displacement Form of Governing Differential Equations / 1374
Mixed Form of Governing Differential Equations / 1376
Stress Formulas / 1378
II.2 Sign Convention for Beams / 1378
II.3 Solution of Governing Equations for a Beam Element / 1380
First-Order Form of Governing Equations / 1381
Effect of Applied Loading / 1387
II.4 Principle of Virtual Work: Integral Form of Governing Equations / 1389
Virtual Work / 1389
Statement of the Principle of Virtual Work / 1390
II.5 Stiffness Matrix / 1391
Definition of Stiffness Matrices / 1391
Determination of Stiffness Matrices / 1393
Properties of Stiffness Matrices / 1399
II.6 Mass Matrices / 1400
II.7 Dynamic Stiffness Matrices / 1402
II.8 Geometric Stiffness Matrices / 1402
References / 1403

APPENDIX
III STRUCTURAL SYSTEMS **1405**

III.1 Transfer Matrix Method / 1406
Loading and In-Span Conditions / 1408
Introduction of Boundary Conditions / 1410
Stability / 1417
Free Vibrations / 1422
Steady-State Motion / 1434
Indeterminate In-Span Conditions / 1435
Numerical Difficulties / 1438
III.2 General Structural Systems / 1440
Coordinate Systems, Definitions, and Degrees of Freedom / 1441
Coordinate Transformations / 1444
III.3 Displacement Method / 1446
Displacement Method Based on the Principle of Virtual Work / 1446
Direct Derivation of Global Displacement Equations / 1450
System Stiffness Matrix Assembled by Summation / 1451
Characteristics of Stiffness Matrices / 1451
Incorporation of Boundary Conditions / 1452
Reactions and Internal Forces, Stress Resultants, and Stresses / 1452
Frames / 1453
Structures with Distributed Loads / 1460
Special Intermediate Conditions / 1466
III.4 Force Method / 1466
III.5 Stability Based on the Displacement Method / 1467
III.6 Free Vibrations Based on the Displacement Method / 1470
Mass Matrix / 1471
Eigenvalue Problem / 1471
Frequency-Dependent Stiffness and Mass Matrices / 1477
III.7 Transient Responses / 1483
References / 1485
Tables for Appendix III / 1487

INDEX **1491**