

Ninth Edition

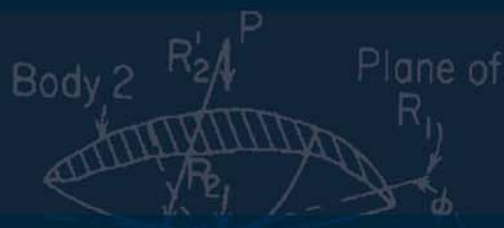
# Roark's Formulas

for

# Stress

and

# Strain



Richard G. Budynas and Ali M. Sadegh



# Roark's Formulas for Stress and Strain

---

## About the Authors

**Richard G. Budynas (deceased)** was professor emeritus of mechanical engineering at the Rochester Institute of Technology. He was the author of *Advanced Strength and Applied Stress Analysis*, Second Edition (McGraw-Hill, 1999), and coauthor of *Shigley's Mechanical Engineering Design*, Ninth Edition (McGraw-Hill, 2011).

**Ali M. Sadegh** is professor of mechanical engineering, former chairman of the department, and the founder and director of the Center for Advanced Engineering Design and Development at the City College of the City University of New York. He is a Fellow of ASME and SME. He is a PE and CMfgE with over 40 years of experience in academia and practicing mechanical engineering design. He led the development of the 11th and 12th editions of *Mark's Standard Handbook for Mechanical Engineers* (McGraw-Hill, 2007, 2018).

# Roark's Formulas for Stress and Strain

---

**RICHARD G. BUDYNAS**

**ALI M. SADEGH**

Ninth Edition



New York Chicago San Francisco  
Athens London Madrid  
Mexico City Milan New Delhi  
Singapore Sydney Toronto

Copyright © 2020, 2012, 2002, 1989, 1975, 1965, 1954, 1943 by McGraw-Hill Education. All rights reserved. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

ISBN: 978-1-26-045376-8

MHID: 1-26-045376-6

The material in this eBook also appears in the print version of this title: ISBN: 978-1-26-045375-1,

MHID: 1-26-045375-8.

eBook conversion by codeMantra

Version 1.0

All trademarks are trademarks of their respective owners. Rather than put a trademark symbol after every occurrence of a trademarked name, we use names in an editorial fashion only, and to the benefit of the trademark owner, with no intention of infringement of the trademark. Where such designations appear in this book, they have been printed with initial caps.

McGraw-Hill Education eBooks are available at special quantity discounts to use as premiums and sales promotions or for use in corporate training programs. To contact a representative, please visit the Contact Us page at [www.mhprofessional.com](http://www.mhprofessional.com).

Information contained in this work has been obtained by McGraw-Hill Education from sources believed to be reliable. However, neither McGraw-Hill Education nor its authors guarantee the accuracy or completeness of any information published herein, and neither McGraw-Hill Education nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill Education and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.

## TERMS OF USE

This is a copyrighted work and McGraw-Hill Education and its licensors reserve all rights in and to the work. Use of this work is subject to these terms. Except as permitted under the Copyright Act of 1976 and the right to store and retrieve one copy of the work, you may not decompile, disassemble, reverse engineer, reproduce, modify, create derivative works based upon, transmit, distribute, disseminate, sell, publish or sublicense the work or any part of it without McGraw-Hill Education's prior consent. You may use the work for your own noncommercial and personal use; any other use of the work is strictly prohibited. Your right to use the work may be terminated if you fail to comply with these terms.

THE WORK IS PROVIDED "AS IS." McGRAW-HILL EDUCATION AND ITS LICENSORS MAKE NO GUARANTEES OR WARRANTIES AS TO THE ACCURACY, ADEQUACY OR COMPLETENESS OF OR RESULTS TO BE OBTAINED FROM USING THE WORK, INCLUDING ANY INFORMATION THAT CAN BE ACCESSED THROUGH THE WORK VIA HYPERLINK OR OTHERWISE, AND EXPRESSLY DISCLAIM ANY WARRANTY, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. McGraw-Hill Education and its licensors do not warrant or guarantee that the functions contained in the work will meet your requirements or that its operation will be uninterrupted or error free. Neither McGraw-Hill Education nor its licensors shall be liable to you or anyone else for any inaccuracy, error or omission, regardless of cause, in the work or for any damages resulting therefrom. McGraw-Hill Education has no responsibility for the content of any information accessed through the work. Under no circumstances shall McGraw-Hill Education and/or its licensors be liable for any indirect, incidental, special, punitive, consequential or similar damages that result from the use of or inability to use the work, even if any of them has been advised of the possibility of such damages. This limitation of liability shall apply to any claim or cause whatsoever whether such claim or cause arises in contract, tort or otherwise.

# Contents

---

**Preface to the Ninth Edition** ix

**Preface to the First Edition** xi

**List of Tables** xiii

## **CHAPTER 1**

Introduction 1

- 1.1 Terminology 1
- 1.2 State Properties, Units, and Conversions 1
- 1.3 Contents 3
- 1.4 References 13

## **CHAPTER 2**

Stress and Strain: Important Relationships 15

- 2.1 Stress 15
- 2.2 Strain and the Stress–Strain Relations 19
- 2.3 Stress Transformations 22
- 2.4 Strain Transformations 34
- 2.5 Mohr’s Circle 34
- 2.6 Mohr’s Circles for 3D Stress Analysis 37
- 2.7 Tables 40
- 2.8 References 44

## **CHAPTER 3**

The Behavior of Bodies under Stress 45

- 3.1 Methods of Loading 45
- 3.2 Elasticity; Proportionality of Stress and Strain 46
- 3.3 Factors Affecting Elastic Properties 47
- 3.4 Load Deformation Relation for a Body 48
- 3.5 Plasticity 48
- 3.6 Creep and Rupture under Long-Time Loading 48
- 3.7 Criteria of Elastic Failure and of Rupture 50
- 3.8 Fatigue 53
- 3.9 Brittle Fracture 57
- 3.10 Stress Concentration 58
- 3.11 Effect of Form and Scale on Strength; Rupture Factor 60
- 3.12 Prestressing 61
- 3.13 Elastic Stability 62
- 3.14 Tables: Mechanical Properties of Materials 65
- 3.15 References 78

## **CHAPTER 4**

Principles and Analytical Methods 81

- 4.1 Equations of Motion and of Equilibrium 81
- 4.2 Principle of Superposition 81

- 4.3 Principle of Reciprocal Deflections 82
- 4.4 Method of Consistent Deformations (Strain Compatibility) 82
- 4.5 Energy Methods 82
- 4.6 Castigliano’s Theorem 83
- 4.7 Dimensional Analysis 89
- 4.8 Remarks on the Use of Formulas 90
- 4.9 References 92

## **CHAPTER 5**

Numerical Methods 93

- 5.1 The Finite Difference Method 93
- 5.2 The Finite Element Method 94
- 5.3 The Boundary Element Method 99
- 5.4 Zeroes of Polynomials 105
- 5.5 Solution of Differential Equations 106
- 5.6 Numerical Integration 106
- 5.7 References 107
- 5.8 Additional Uncited References for Finite Elements 108
- 5.9 Additional Uncited References for Boundary Elements 108

## **CHAPTER 6**

Experimental Methods 109

- 6.1 Measurement Techniques 109
- 6.2 Electrical Resistance Strain Gages 114
- 6.3 Detection of Plastic Yielding 124
- 6.4 Analogies 124
- 6.5 Wheatstone Bridge 125
- 6.6 Nondestructive Testing 126
- 6.7 Tables 129
- 6.8 References 135

## **CHAPTER 7**

Tension, Compression, Shear, and Combined Stress 137

- 7.1 Bar under Axial Tension (or Compression); Common Case 137
- 7.2 Bar under Tension (or Compression); Special Cases 139
- 7.3 Composite Members 141
- 7.4 Trusses 143
- 7.5 Body under Pure Shear Stress 145
- 7.6 Cases of Direct Shear Loading 147
- 7.7 Combined Stress 147

**CHAPTER 8****Beams; Flexure of Straight Bars 151**

- 8.1 Straight Beams (Common Case) Elastically Stressed 151
- 8.2 Composite Beams and Bimetallic Strips 161
- 8.3 Three-Moment Equation 164
- 8.4 Rigid Frames 165
- 8.5 Beams on Elastic Foundations 170
- 8.6 Deformation Due to the Elasticity of Fixed Supports 174
- 8.7 Beams under Simultaneous Axial and Transverse Loading 175
- 8.8 Beams of Variable Section 179
- 8.9 Slotted Beams 185
- 8.10 Beams of Relatively Great Depth 185
- 8.11 Beams of Relatively Great Width 189
- 8.12 Beams with Wide Flanges; Shear Lag 192
- 8.13 Beams with Very Thin Webs 193
- 8.14 Beams Not Loaded in Plane of Symmetry; Flexural Center 194
- 8.15 Straight Uniform Beams (Common Case); Ultimate Strength 196
- 8.16 Plastic, or Ultimate Strength, Design 199
- 8.17 Tables 203
- 8.18 References 266

**CHAPTER 9****Curved Beams 269**

- 9.1 Bending in the Plane of the Curve 269
- 9.2 Deflection of Curved Beams 276
- 9.3 Circular Rings and Arches 284
- 9.4 Elliptical Rings 293
- 9.5 Curved Beams Loaded Normal to Plane of Curvature 294
- 9.6 Tables 300
- 9.7 References 348

**CHAPTER 10****Torsion 349**

- 10.1 Straight Bars of Uniform Circular Section under Pure Torsion 349
- 10.2 Bars of Noncircular Uniform Section under Pure Torsion 350
- 10.3 Effect of End Constraint 355
- 10.4 Effect of Longitudinal Stresses 362
- 10.5 Ultimate Strength of Bars in Torsion 363
- 10.6 Torsion of Curved Bars; Helical Springs 363
- 10.7 Tables 366
- 10.8 References 384

**CHAPTER 11****Flat Plates 387**

- 11.1 Common Case 387
- 11.2 Bending of Uniform-Thickness Plates with Circular Boundaries 388

- 11.3 Circular-Plate Deflection Due to Shear 392
- 11.4 Bimetallic Plates 393
- 11.5 Nonuniform Loading of Circular Plates 397
- 11.6 Circular Plates on Elastic Foundations 397
- 11.7 Circular Plates of Variable Thickness 398
- 11.8 Disk Springs 400
- 11.9 Narrow Ring under Distributed Torque about Its Axis 401
- 11.10 Bending of Uniform-Thickness Plates with Straight Boundaries 402
- 11.11 Effect of Large Deflection; Diaphragm Stresses 403
- 11.12 Plastic Analysis of Plates 407
- 11.13 Ultimate Strength 407
- 11.14 Tables 409
- 11.15 References 458

**CHAPTER 12****Columns and Other Compression Members 463**

- 12.1 Columns; Common Case 463
- 12.2 Local Buckling 467
- 12.3 Strength of Latticed Columns 471
- 12.4 Eccentric Loading; Initial Curvature 472
- 12.5 Columns under Combined Compression and Bending 474
- 12.6 Thin Plates with Stiffeners 476
- 12.7 Short Prisms under Eccentric Loading 478
- 12.8 Table 481
- 12.9 References 483

**CHAPTER 13****Shells of Revolution; Pressure Vessels; Pipes 485**

- 13.1 Circumstances and General State of Stress 485
- 13.2 Thin Shells of Revolution under Distributed Loadings Producing Membrane Stresses Only 485
- 13.3 Thin Shells of Revolution under Concentrated or Discontinuous Loadings Producing Bending and Membrane Stresses 488
- 13.4 Thin Multielement Shells of Revolution 500
- 13.5 Thin Shells of Revolution under External Pressure 511
- 13.6 Thick Shells of Revolution 513
- 13.7 Pipe on Supports at Intervals 515
- 13.8 Tables 517
- 13.9 References 581

**CHAPTER 14****Bodies under Direct Bearing and Shear Stress 585**

- 14.1 Stress Due to Pressure between Elastic Bodies 585
- 14.2 Rivets and Riveted Joints 589
- 14.3 Miscellaneous Cases 592
- 14.4 Table 595
- 14.5 References 598



**CHAPTER 15**

Elastic Stability 601

- 15.1 General Considerations 601
- 15.2 Buckling of Bars 602
- 15.3 Buckling of Flat and Curved Plates 604
- 15.4 Buckling of Shells 605
- 15.5 Tables 608
- 15.6 References 626

**CHAPTER 16**

Dynamic and Temperature Stresses 631

- 16.1 Dynamic Loadings; General Conditions 631
- 16.2 Body in a Known State of Motion 631
- 16.3 Impact and Sudden Loading 639
- 16.4 Impact and Sudden Loading; Approximate Formulas 640
- 16.5 Remarks on Stress Due to Impact 642
- 16.6 Vibration 643
- 16.7 Temperature Stresses 648
- 16.8 Tables 653
- 16.9 References 669

**CHAPTER 17**

Stress Concentration 671

- 17.1 Static Stress and Strain Concentration Factors 671
- 17.2 Stress Concentration Reduction Methods 676
- 17.3 Tables 679
- 17.4 References 695

**CHAPTER 18**

Fatigue and Fracture 697

- 18.1 Fatigue in Materials 697
- 18.2 Fatigue Testing 698
- 18.3 Fatigue and Crack Growth 700
- 18.4 Creep 700
- 18.5 Fracture Mechanics 701
- 18.6 The Stress Intensity Factor 703
- 18.7 Fracture Toughness 706
- 18.8 Crack Tip Plasticity 708
- 18.9 The Energy Balance Approach of Fracture 709
- 18.10 The  $J$  Integral 710
- 18.11 Tables 712
- 18.12 References 722

**CHAPTER 19**

Stresses in Fasteners, Joints, and Gears 723

- 19.1 Welding 723
- 19.2 Analysis of Welded Joints 725
- 19.3 Strength of Welded Joints 728

- 19.4 Riveted and Bolted Joints 733
- 19.5 Shearing and Failure Modes in Riveted Joints 733
- 19.6 Eccentric Loading of Riveted Joints 735
- 19.7 Bolt Strength and Design 738
- 19.8 Gearing and Gear Stress 739
- 19.9 References 741

**CHAPTER 20**

Composite Materials 743

- 20.1 Composite Materials Classifications and Components 743
- 20.2 Mechanics of Composite Materials 746
- 20.3 Macromechanics of a Layer (Lamina) 746
- 20.4 Micromechanics of a Layer (Lamina) 749
- 20.5 Failure Criterion for a Layer (Lamina) 752
- 20.6 Macromechanics of a Laminate 756
- 20.7 Classical Lamination Theory 757
- 20.8 Macromechanics of a Laminate: Stress and Strain in a Laminate 758
- 20.9 Inversion of Stiffness Equation in a Laminate 765
- 20.10 Example of Stresses and Strains in a Laminate 766
- 20.11 Strength and Failure Analyses of Laminate 769
- 20.12 Composite Sandwich Structures 773
- 20.13 Composite Cellular Structures 775
- 20.14 Tables 777
- 20.15 References 782

**CHAPTER 21**

Solid Biomechanics 785

- 21.1 Introduction 785
- 21.2 Biomechanics of Bone 785
- 21.3 Biomechanics of Articular Cartilage 790
- 21.4 Biomechanics of Tendons and Ligaments 791
- 21.5 Biomechanics of Muscles 793
- 21.6 Biomechanics of Joints 795
- 21.7 Biomechanics of the Knee 795
- 21.8 Biomechanics of the Hip 797
- 21.9 Biomechanics of the Spine 800
- 21.10 Biomechanics of the Lumbar Spine 802
- 21.11 Biomechanics of the Cervical Spine 806
- 21.12 Biomechanics of the Shoulder 809
- 21.13 Biomechanics of the Elbow 810
- 21.14 Human Factors in Design 811
- 21.15 Implants and Prostheses 814
- 21.16 Hip Implants 814
- 21.17 Knee Implants 816
- 21.18 Other Implants 817
- 21.19 Biomaterials 817
- 21.20 Tables 820
- 21.21 References 824
- 21.22 Glossary 826

**APPENDIX A**

Properties of a Plane Area 827

**APPENDIX B**

Mathematical Formulas and Matrices 847

**APPENDIX C**

Glossary 875

Index 885

# Preface to the Ninth Edition

---

It is recognized that recent high-powered computers incorporated in computational mechanics such as finite element methods have advanced and facilitated design and stress and strain analyses of mechanical and structural systems. While numerical methods are widely used in engineering practice, the very essence of engineering is rooted in the power of classical closed-form solutions and established analytical methods. In addition, for optimization, parametric design, and for understanding the mechanical behavior of a system, a closed-form analytical solution is advantageous to a numerical solution.

Since the publication of the 8th edition of *Roark's Formulas for Stress and Strain*, 10 years ago, we have witnessed significant advances in engineering methodology in solving stress analysis problems. This has motivated the authors to embark on an improved edition of this book.

Thus in preparation of this 9th edition, the authors had three continuing objectives: first, to modernize with newly designed artwork and update the contents as required, second, to introduce new topics and chapters that will maintain the high standard of this book, and finally, to improve upon the material retained from the 8th edition. The 9th edition of Roark's is intended to make available a compact, comprehensive summary of the formulas and principles pertaining to strength of materials for both practicing engineers and engineering students.

This book is intended primarily to be a reference book that is authoritative and covers the field of stress and strain analyses in a comprehensive manner. Similar to the 8th edition, the tabular format is continued in this edition. This format has been particularly successful when implementing problem solutions on user-friendly computer software such as MATLAB, MathCAD, TK Solver, and Excel. Commercial packages are available which integrate the abovementioned software with Roark's. Tabulated coefficients are in dimensionless form for convenience in using either system of units. Design formulas drawn from works published in the past remain in the system units originally published or quoted.

The authors are mindful of the competing requirements to offer the user a broad spectrum of information that has made this book so useful for over 80 years. Therefore, in this edition, the authors have included a number of new topics in the chapters. The main organizational change in the 9th edition is that majority of tables are published in portrait format for ease of reading. Other changes/additions included in the 9th edition are as follows:

- Chapter 2, Stress and Strain: Important Relationships: A new section on three-dimensional Mohr's circle analysis for simple configurations is added.
- Chapter 3, The Behavior of Bodies under Stress: Mechanical properties of some constructional steel including modulus of elasticity of materials and yield strength are added. In addition, a section on factor of safety is also added.
- Chapter 4, Principles and Analytical Methods: The energy method "Castigliano's theorem" for deflections calculation is revised, and more examples are added.
- Chapter 5, Numerical Methods: The numerical methods "finite element method" and "boundary element method" with more references are updated and revised.

- Chapter 6, Experimental Methods: A new section “Nondestructive Testing” for quantitatively characterizing mechanical properties is added.
- Chapter 16, Dynamic and Temperature Stresses: Tables of natural frequencies of cylindrical shells and springs are added.
- Chapter 17, Stress Concentration: The table for stress concentration factor is expanded.
- Chapter 18, Fatigue and Fracture: A new section on fatigue with a table of fatigue limits of materials and a new section on creep with a table of creep of materials at high temperature are added.
- Chapter 19, Stresses in Fasteners, Joints, and Gears: A new section “Bolt Strength and Design” and a new section Gearing and Gear Stress are added.
- Chapter 20, Composite Materials: Two new sections “Composite Sandwich Structures” and “Composite Cellular Structures” are added. In addition, a table of Mechanical Properties of Graphite-Polymer Composite Material with Different Volume Fraction and several new references are added.
- Chapter 21, Solid Biomechanics: Biomechanics is updated and revised, and artificial intervertebral discs are discussed.
- The references and publications of most chapters are expanded and updated.
- All the chapters are redesigned to make a much better user experience including: adding color to the figures and tables; newly designed artwork and headings; and portrait format of majority of tables for ease of reading.

The authors would especially like to thank those individuals, publishers, institutions, and corporations who have generously given permission to use material in this and previous editions, and the many dedicated readers and users of *Roark's Formulas for Stress and Strain*.

Meticulous care has been exercised to avoid errors. However, if any are inadvertently included in this newly designed printing, the authors will appreciate being informed so that these errors can be eliminated in subsequent printings of this edition.

*Richard G. Budynas*  
*Ali M. Sadegh*

# Preface to the First Edition

---

This book was written for the purpose of making available a compact, adequate summary of the formulas, facts, and principles pertaining to strength of materials. It is intended primarily as a reference book and represents an attempt to meet what is believed to be a present need of the designing engineer.

This need results from the necessity for more accurate methods of stress analysis imposed by the trend of engineering practice. That trend is toward greater speed and complexity of machinery, greater size and diversity of structures, and greater economy and refinement of design. In consequence of such developments, familiar problems, for which approximate solutions were formerly considered adequate, are now frequently found to require more precise treatment, and many less familiar problems, once of academic interest only, have become of great practical importance. The solutions and data desired are often to be found only in advanced treatises or scattered through an extensive literature, and the results are not always presented in such form as to be suited to the requirements of the engineer. To bring together as much of this material as is likely to prove generally useful and to present it in convenient form have been the author's aim.

The scope and management of the book are indicated by the contents. In Part 1 are defined all terms whose exact meanings might otherwise not be clear. In Part 2 certain useful general principles are stated; analytical and experimental methods of stress analysis are briefly described; and information concerning the behavior of material under stress is given. In Part 3 the behavior of structural elements under various conditions of loading is discussed, and extensive tables of formulas for the calculation of stress, strain, and strength are given.

Because they are not believed to serve the purpose of this book, derivations of formulas and detailed explanations, such as are appropriate in a textbook, are omitted, but a sufficient number of examples are included to illustrate the application of the various formulas and methods. Numerous references to more detailed discussions are given, but for the most part these are limited to sources that are generally available, and no attempt has been made to compile an exhaustive bibliography.

That such a book as this derives almost wholly from the work of others is self-evident, and it is the author's hope that due acknowledgment has been made of the immediate sources of all material presented here. To the publishers and others who have generously permitted the use of material, he wishes to express his thanks. The helpful criticisms and suggestions of his colleagues, Professors E. R. Maurer, M. O. Withey, J. B. Kommers, and K. F. Wendt, are gratefully acknowledged. A considerable number of the tables of formulas have been published from time to time in *Product Engineering*, and the opportunity thus afforded for criticism and study of arrangement has been of great advantage.

Finally, it should be said that, although every care has been taken to avoid errors, it would be oversanguine to hope that none had escaped detection; for any suggestions that readers may make concerning needed corrections, the author will be grateful.

Raymond J. Roark

*This page intentionally left blank*

# List of Tables

---

Table 1.1	Units Appropriate to Structural Analysis (p. 2)
Table 1.2	SI Units (p. 3)
Table 1.3	Multiples and Submultiples of SI Units (p. 4)
Table 1.4	SI Conversion Table (pp. 4–5)
Table 1.5	Multiplication Factors to Convert from USCU Units to SI Units (pp. 5–6)
Table 1.6	Conversion Factors (pp. 7–13)
Table 2.1	Material Properties (p. 40)
Table 2.2	Transformation Matrices for Positive Rotations About an Axis (p. 40)
Table 2.3	Transformation Equations and Principle Stress Formulas (p. 41)
Table 2.4	Mohr’s Circle for Some Common States of Stress (pp. 42–44)
Table 3.1	Modulus of Elasticity Relationships (p. 66)
Table 3.2	Material Classification, Names, and Abbreviations (pp. 66–67)
Table 3.3	Moduli and Strength of Materials (p. 68)
Table 3.4	Temperature Effects of Elastic Modulus (p. 69)
Table 3.5	Extended Mechanical Properties at Room Temperature (p. 70)
Table 3.6	Hardness Test Indenters (p. 71)
Table 3.7	ANSI Carbon Steel Mechanical Characteristics (pp. 71–73)
Table 3.8	Coefficients of Thermal Expansion (pp. 73–75)
Table 3.9	Elastic Constants of Selected Polycrystalline Ceramics (pp. 75–76)
Table 3.10	Mechanical Properties of Some Constructional Steels (p. 77)
Table 3.11	Representative Average Mechanical Properties of Cold-Drawn Steel (p. 78)
Table 3.12	Material Properties of Fibers Used in Composites (p. 78)
Table 5.1	Sample Finite Element Library (p. 98)
Table 6.1	Change in Resistance with Strain for Various Strain Gage Element Materials (p. 129)
Table 6.2	Properties of Various Strain Gage Grid Materials (p. 129)
Table 6.3	Strain Gage Rosette Equations Applied to a Specimen of a Linear, Isotropic Material (pp. 130–131)
Table 6.4	Corrections for the Transverse Sensitivity of Electrical Resistance Strain Gages (pp. 132–133)
Table 6.5	Strain Gauge Equations for Several Types of Bridge Configurations (p. 134)
Table 8.1	Shear, Moment, Slope, and Deflection Formulas for Elastic Straight Beams (pp. 203–212)
Table 8.2	Reaction and Deflection Formulas for In-Plane Loading of Elastic Frames (pp. 213–218)
Table 8.3	Numerical Values for Functions Used in Table 8.5 (pp. 219–220)
Table 8.4	Numerical Values for Denominators Used in Table 8.5 (pp. 220–221)
Table 8.5	Shear, Moment, Slope, and Deflection Formulas for Finite-Length Beams on Elastic Foundations (pp. 222–228)
Table 8.6	Shear, Moment, Slope, and Deflection Formulas for Semi-Infinite Beams on Elastic Foundations (pp. 229–231)
Table 8.7(a)	Reaction and Deflection Coefficients for Beams Under Simultaneous Axial and Transverse Loading: Cantilver End Support (p. 232)

- Table 8.7(b) Reaction and Deflection Coefficients for Beams Under Simultaneous Axial and Transverse Loading: Simply Supported Ends (pp. 232–233)
- Table 8.7(c) Reaction and Deflection Coefficients for Beams Under Simultaneous Axial and Transverse Loading: Left End Simply Supported, Right End Fixed (pp. 233–234)
- Table 8.7(d) Reaction and Deflection Coefficient for Beams Under Simultaneous Axial and Transverse Loading: Fixed Ends (p. 234)
- Table 8.8 Shear, Moment, Slope, and Deflection Formulas for Beams Under Simultaneous Axial Compression and Transverse Loading (pp. 235–244)
- Table 8.9 Shear, Moment, Slope, and Deflection Formulas for Beams Under Simultaneous Axial Tension and Transverse Loading (pp. 245–246)
- Table 8.10 Beams Restrained Against Horizontal Displacement at the Ends (p. 247)
- Table 8.11(a) Reaction and Deflection Coefficients for Tapered Beams (pp. 248–250)
- Table 8.11(b) Reaction and Deflection Coefficients for Tapered Beams (pp. 251–253)
- Table 8.11(c) Reaction and Deflection Coefficients for Tapered Beams (pp. 254–256)
- Table 8.11(d) Reaction and Deflection Coefficients for Tapered Beams (pp. 257–259)
- Table 8.12 Position of Flexural Center  $Q$  for Different Sections (pp. 260–261)
- Table 8.13 Collapse Loads with Plastic Hinge Locations for Straight Beams (pp. 262–265)
- Table 9.1 Formulas for Curved Beams Subjected to Bending in the Plane of the Curve (pp. 300–306)
- Table 9.2 Formulas for Circular Rings (pp. 307–318)
- Table 9.3 Reaction and Deformation Formulas for Circular Arches (pp. 319–328)
- Table 9.4 Formulas for Curved Beams of Compact Cross Section Loaded Normal to the Plane of Curvature (pp. 329–347)
- Table 10.1 Formulas for Torsional Deformation and Stress (pp. 366–374)
- Table 10.2 Formulas for Torsional Properties and Stresses in Thin-Walled Open Cross Sections (pp. 375–377)
- Table 10.3 Formulas for the Elastic Deformations of Uniform Thin-Walled Open Members Under Torsional Loading (pp. 378–384)
- Table 11.1 Numerical Values for Functions Used in Table 11.2 (pp. 409–410)
- Table 11.2 Formulas for Flat Circular Plates of Constant Thickness (pp. 411–444)
- Table 11.3 Shear Deflections for Flat Circular Plates of Constant Thickness (pp. 445–446)
- Table 11.4 Formulas for Flat Plates with Straight Boundaries and Constant Thickness (pp. 447–458)
- Table 12.1 Formulas for Short Prisms Loaded Eccentrically; Stress Reversal Impossible (pp. 481–483)
- Table 13.1 Formulas for Membrane Stresses and Deformations in Thin-Walled Pressure Vessels (pp. 517–522)
- Table 13.2 Shear, Moment, Slope, and Deflection Formulas for Long and Short Thin-Walled Cylindrical Shells under Axisymmetric Loading (pp. 523–527)
- Table 13.3 Formulas for Bending and Membrane Stresses and Deformations in Thin-Walled Pressure Vessels (pp. 528–542)
- Table 13.4 Formulas for Discontinuity Stresses and Deformations at the Junctions of Shells and Plates (pp. 543–578)
- Table 13.5 Formulas for Thick-Walled Vessels Under Internal and External Loading (pp. 579–580)
- Table 14.1 Formulas for Stress and Strain Due to Pressure on or between Elastic Bodies (pp. 595–598)



Table 15.1	Formulas for Elastic Stability of Bars, Rings, and Beams (pp. 608–615)
Table 15.2	Formulas for Elastic Stability of Plates and Shells (pp. 616–625)
Table 16.1	Natural Frequencies of Vibration for Continuous Members (pp. 653–655)
Table 16.2	Natural Frequencies of Vibration of Various Systems (pp. 656–664)
Table 16.3	Spring Constants (pp. 665–667)
Table 16.4	Longitudinal Wavespeed and $K_m$ for Engineering Materials (pp. 667–668)
Table 17.1	Stress Concentration Factors for Elastic Stress ( $K_t$ ) (pp. 679–688)
Table 17.2	Graphs for Stress Concentration Factors (pp. 689–694)
Table 18.1	Typical Fatigue Limits for Reverse Bending Load (p. 700)
Table 18.2	Values of Factor $C$ and Exponent $m$ in Eq. (18.3-1) (p. 701)
Table 18.3	Stresses in Metals at High Temperature for Two Given Creep Rates (p. 702)
Table 18.4	Fracture Toughness of Some Materials (p. 706)
Table 19.1	Minimum Weld Metal Properties (p. 728)
Table 19.2	Minimum Fillet Weld Size $w$ (p. 729)
Table 19.3	Allowable Loads for Various Sizes of Fillet Welds (p. 729)
Table 19.4	Treating a Weld as a Line (pp. 731–732)
Table 20.1	Density, Strength, and Stiffness of Selected Fibers (p. 745)
Table 20.2	Fiber and Matrix Materials Used in a Composite (p. 745)
Table 20.3	The Mechanical Properties of Unidirectional Reinforced Composite Materials (p. 752)
Table 20.4	Fibers and Matrix Materials and Their Applications (p. 777)
Table 20.5	Properties of Key Reinforcing Fibers (p. 777)
Table 20.6	Properties of Selected Thermosetting and Thermoplastic Matrices (p. 778)
Table 20.7	Effect of Fiber Form and Volume Fraction on Mechanical Properties of E-Glass-Reinforced Polyester (p. 778)
Table 20.8	Mechanical Properties of Selected Unidirectional Polymer Matrix Composites (p. 778)
Table 20.9	Mechanical Properties of Selected Quasi-Isotropic Polymer Matrix Composites (p. 779)
Table 20.10	Fracture Toughness of Structural Alloys, Monolithic Ceramics, and Ceramic Matrix Composites (p. 779)
Table 20.11	Mechanical Properties of Selected Unidirectional Continuous Fiber-Reinforced Metal Matrix Composites (p. 779)
Table 20.12	Mechanical Properties of Silicon Carbide Particle-Reinforced Aluminum (p. 779)
Table 20.13	Physical Properties of Selected Unidirectional Composites and Monolithic Metals (p. 780)
Table 20.14	Physical Properties of Isotropic and Quasi-Isotropic Composites and Monolithic Materials Used in Electronic Packaging (p. 780)
Table 20.15	Physical Properties of Selected Unidirectional Polymer Matrix Composites (p. 781)
Table 20.16	Physical Properties of Selected Quasi-Isotropic Polymer Matrix Composites (p. 781)
Table 20.17	Physical Properties of Silicon Carbide Particle-Reinforced Aluminum (p. 781)
Table 20.18	Mechanical Properties of Graphite-Polymer Composite Material with Different Volume Fraction (p. 782)
Table 20.19	Mechanical Properties of Glass-Polymer Composite Material with Different Volume Fraction (p. 782)

Table 21.1	Elastic Moduli and Ultimate Strength of Cortical Bone, from Ref. 51 (p. 788)
Table 21.2	Representative Properties of the Human Articular Cartilage Taken from the Lateral Condyle of the Femur, from Ref. 35 (p. 791)
Table 21.3	Representative Properties of Human Tendon and Ligament under Tensile Loading, from Refs. 31 and 61 (p. 792)
Table 21.4	Mechanical Properties of a Vertebral Body, A: Cortical Bone, and B: Trabecular Bone, from Ref. 20 (p. 804)
Table 21.5	Mechanical Properties of Spinal Elements, from Ref. 20 (p. 804)
Table 21.6	Anthropometric Data from Dreyfuss (Ref. 21) (p. 812)
Table 21.7	Significant Physical Properties of Different Biomaterials (p. 820)
Table 21.8	Compositions of Surface-Active Glasses and Glass Ceramics in Weight Percent, Data from Ref. 66 (p. 820)
Table 21.9	Properties of Polyethylene, Data from ASTM F 648, and Ref. 67 (p. 821)
Table 21.10	Chemical and Mechanical Properties of Alumina for Implants, Data from Ref. 18 (p. 821)
Table 21.11	Mechanical Properties of Cortical Bone, 316L Stainless Steel, Cobalt–Chromium Alloy, Titanium, and Titanium-6-Aluminum-4-Vanadium (p. 821)
Table 21.12	Properties of Bones at Different Age (p. 822)
Table 21.13	Typical Mechanical Properties of Polymer-Carbon Composites (Three-Point Bending) (p. 822)
Table 21.14	Mechanical Properties of Some Degradable Polymers (pp. 822–823)
Table 21.15	Representative Mechanical Properties of Commercial Sutures (p. 823)
Table A.1	Properties of Sections (pp. 829–839)
Table A.2	Moment of Inertia of Sections (pp. 840–844)
Table A.3	Moment of Inertia of Uniform Objects (pp. 845–846)

# Roark's Formulas for Stress and Strain

---

*This page intentionally left blank*

# CHAPTER 1

---

## Introduction

---

The widespread use of personal computers, which have the power to solve problems solvable in the past only on mainframe computers, has influenced the tabulated format of this book. Computer programs for structural analysis, employing techniques such as the finite element method and the boundary element method, are also available for general use. These programs are very powerful; however, in many cases, elements of structural systems can be analyzed quite effectively independently without the need for an elaborate finite element model. In some instances, finite element models or programs are verified by comparing their solutions with the results given in a book such as this. Contained within this book are simple, accurate, and thorough tabulated formulations that can be applied to the stress analysis of a comprehensive range of structural components.

This chapter serves to introduce the reader to the terminology, state property units and conversions, and contents of the book.

### 1.1 TERMINOLOGY

Definitions of terms used throughout the book can be found in the glossary in App. C.

### 1.2 STATE PROPERTIES, UNITS, AND CONVERSIONS

The basic state properties associated with stress analysis include the following: geometrical properties such as length, area, volume, centroid, center of gravity, and second-area moment (area moment of inertia); material properties such as mass density, modulus of elasticity, Poisson's ratio, and thermal expansion coefficient; loading properties such as force, moment, and force distributions (e.g., force per unit length, force per unit area, and force per unit volume); other properties associated with loading, including energy, work, and power; and stress analysis properties such as deformation, strain, and stress.

Two basic systems of units are employed in the field of stress analysis: SI units and USCU units.\* SI units are mass-based units using the kilogram (kg), meter (m), second (s), and Kelvin (K) or degree Celsius ( $^{\circ}\text{C}$ ) as the fundamental units of mass, length, time, and temperature, respectively. Other SI units, such as that used for force, the Newton ( $\text{kg}\cdot\text{m}/\text{s}^2$ ), are derived quantities. USCU units are force-based units using the pound force (lbf),

---

\*SI and USCU are abbreviations for the International System of Units (from the French *Système International d'Unités*) and the United States Customary Units, respectively.

TABLE 1.1 Units Appropriate to Structural Analysis\*

Quantity	International Metric (SI)	U.S. Customary
Length	(meter) m	(foot) ft
Force and weight, $W$	(newton) N(kg-m/s <sup>2</sup> )	(pound) lbf
Time	s	s
Angle	rad	rad
Second area moment	m <sup>4</sup>	ft <sup>4</sup>
Mass	kg	lbf-s <sup>2</sup> /ft (slug)
Area	m <sup>2</sup>	ft <sup>2</sup>
Mass moment of inertia	kg-m <sup>2</sup>	lbf-s <sup>2</sup> -ft
Moment	N-m	lbf-ft
Volume	m <sup>3</sup>	ft <sup>3</sup>
Mass density	kg/m <sup>3</sup>	lbf-s <sup>2</sup> /ft <sup>4</sup>
Stiffness of linear spring	N/m	lbf/ft
Stiffness of rotary spring	N-m/rad	lbf-ft/rad
Temperature	K (Kelvin)	°F (degrees Fahrenheit)
Torque, work, energy	N-m (Joule)	lbf-ft
Stiffness of torsional spring	N-m/rad	lbf-ft/rad
Stress or pressure	N/m <sup>2</sup> (pascal)	lbf/ft <sup>2</sup> (psi)

\*In stress analysis, the unit of length used most often is the inch.

inch (in) or foot (ft), second (s), and degree Fahrenheit (°F) as the fundamental units of force, length, time, and temperature, respectively. Other USCU units, such as that used for mass, the slug (lbf-s<sup>2</sup>/ft) or the nameless lbf-s<sup>2</sup>/in, are derived quantities. Table 1.1 gives a listing of the primary SI and USCU units used for structural analysis. Other SI units are given in Table 1.2. Certain prefixes may be appropriate, depending on the size of the quantity. Common prefixes are given in Table 1.3. For example, the modulus of elasticity of carbon steel is approximately 207 GPa = 207 × 10<sup>9</sup> Pa = 207 × 10<sup>9</sup> N/m<sup>2</sup>. Prefixes are normally used with SI units. However, there are cases where prefixes are also used with USCU units. Some examples are the kpsi (1 kpsi = 10<sup>3</sup> psi = 10<sup>3</sup> lbf/in<sup>2</sup>), kip (1 kip = 1 kilopound = 1,000 lbf), and Mpsi (1 Mpsi = 10<sup>6</sup> psi).

Depending on the application, different units may be specified. It is important that the analyst be aware of all the implications of the units and make consistent use of them. For example, if you are building a model from a CAD file in which the design dimensional units are given in mm, it is unnecessary to change the system of units or to scale the model to units of m. However, if in this example the input forces are in Newtons, then the output stresses will be in N/mm<sup>2</sup>, which is correctly expressed as MPa. If in this example applied moments are to be specified, the units should be N-mm. For deflections in this example, the modulus of elasticity  $E$  should also be specified in MPa and the output deflections will be in mm.

Tables 1.4 and 1.5 present the conversions from USCU units to SI units and vice versa for some common state property units. The more detailed conversion units are given in Table 1.6.

TABLE 1.2 SI Units

Quantity	Unit (SI)	Formula
<b>Base Units</b>		
Length	meter (m)	
Mass	kilogram (kg)	
Time	second (s)	
Thermodynamic temperature	Kelvin (K)	
<b>Supplementary Units</b>		
Plane angle	radian (rad)	
Solid angle	steradian (sr)	
<b>Derived Units</b>		
Acceleration	meter per second square	$m/s^2$
Angular acceleration	radian per second square	$rad/s^2$
Angular velocity	radian per second	$rad/s$
Area	square meter	$m^2$
Density	kilogram per cubic meter	$kg/m^3$
Energy	joule (J)	N-m
Force	Newton (N)	$kg-m/s^2$
Frequency	hertz (Hz)	1/s
Power	watt (W)	J/s
Pressure	Pascal (Pa)	$N/m^2$
Quantity of heat	joule (J)	N-m
Stress	Pascal (Pa)	$N/m^2$
Thermal conductivity	watt per meter-Kelvin	$W/(m-K)$
Velocity	meter per second	m/s
Viscosity dynamic	Pascal-second	Pa-s
Viscosity kinematic	square meter per second	$m^2/s$
Work	joule (J)	N-m

## 1.3 CONTENTS

Following the introduction, the state of stress and the important relationships associated with stress and strain and their transformations including Mohr's circle is described in Chap. 2. The behavior of bodies under stress is presented in Chap. 3. Chapter 4 describes equation of motion and equilibrium of solid and analytical methods of solving for the stresses and deflections in an elastic body, including the energy methods. Numerical methods such as Finite Element Method and Boundary Element Method are presented in Chap. 5. The experimental methods for stress and strain measurements are presented in Chap. 6. Many topics associated with the stress analysis of structural components, including direct tension, compression, shear, and combined stresses; bending of straight and curved beams; torsion; bending of flat plates; columns and other compression members; shells of revolution, pressure vessels, and pipes; direct bearing and shear stress; elastic stability;

TABLE 1.3 Multiples and Submultiples of SI Units

Prefix	Symbol		Multiplying Factor
exa	E	$10^{18}$	1 000 000 000 000 000 000
peta	P	$10^{15}$	1 000 000 000 000 000
tera	T	$10^{12}$	1 000 000 000 000
giga	G	$10^9$	1 000 000 000
mega	M	$10^6$	1 000 000
kilo	k	$10^3$	1 000
hecto	h	$10^2$	100
deca	da	10	10
deci	d	$10^{-1}$	0.1
centi	c	$10^{-2}$	0.01
milli	m	$10^{-3}$	0.001
micro	$\mu$	$10^{-6}$	0.000 001
nano	n	$10^{-9}$	0.000 000 001
pico	p	$10^{-12}$	0.000 000 000 001
femto	f	$10^{-15}$	0.000 000 000 000 001
atto	a	$10^{-18}$	0.000 000 000 000 000 001

TABLE 1.4 SI Conversion Table

SI Units	From SI to English	From English to SI
<b>Length</b>		
kilometer (km) = 1000 m	1 km = 0.621 mi	1 mi = 1.609 km
meter (m) = 100 cm	1 m = 3.281 ft	1 ft = 0.305 m
centimeter (cm) = 0.01 m	1 cm = 0.394 in	1 in = 2.540 cm
millimeter (mm) = 0.001 m	1 mm = 0.039 in	1 in = 25.4 mm
micrometer ( $\mu\text{m}$ ) = 0.000 001 m	1 $\mu\text{m}$ = $3.93 \times 10^{-5}$ in	1 in = 25,400 $\mu\text{m}$
nanometer (nm) = 0.000 000 001 m	1 nm = $3.93 \times 10^{-8}$ in	1 in = 25,400,000 nm
<b>Area</b>		
square kilometer ( $\text{km}^2$ ) = 100 hectares	1 $\text{km}^2$ = 0.386 $\text{mi}^2$	1 $\text{mi}^2$ = 2.590 $\text{km}^2$
hectare (ha) = 10,000 $\text{m}^2$	1 ha = 2.471 acres	1 acre = 0.405 ha
square meter ( $\text{m}^2$ ) = 10,000 $\text{cm}^2$	1 $\text{m}^2$ = 10.765 $\text{ft}^2$	1 $\text{ft}^2$ = 0.093 $\text{m}^2$
square centimeter ( $\text{cm}^2$ ) = 100 $\text{mm}^2$	1 $\text{cm}^2$ = 0.155 $\text{in}^2$	1 $\text{in}^2$ = 6.452 $\text{cm}^2$
<b>Volume</b>		
liter (L) = 1000 mL = 1 $\text{dm}^3$	1 L = 1.057 fl qt	1 fl qt = 0.946 L
milliliter (mL) = 0.001 L = 1 $\text{cm}^3$	1 mL = 0.034 fl oz	1 fl oz = 29.575 mL
microliter ( $\mu\text{L}$ ) = 0.000 001 L	1 $\mu\text{L}$ = $3.381 \times 10^{-5}$ fl oz	1 fl oz = 29,575 $\mu\text{L}$

(Continued)



TABLE 1.4 SI Conversion Table (Continued)

SI Units	From SI to English	From English to SI
<b>Mass</b>		
kilogram (kg) = 1000 g	1 kg = 2.205 lb	1 lb = 0.454 kg
gram (g) = 1000 mg	1 g = 0.035 oz	1 oz = 28.349 g
milligram (mg) = 0.001 g	1 mg = $3.52 \times 10^{-5}$ oz	1 oz = 28,349 mg
microgram ( $\mu\text{g}$ ) = 0.000 001 g	1 $\mu\text{g}$ = $3.52 \times 10^{-8}$ oz	1 oz = 28,349,523 $\mu\text{g}$

TABLE 1.5 Multiplication Factors to Convert from USCU Units to SI Units

To Convert from	To	Multiply by
<b>Mass</b>		
ounce (avoirdupois)	kilogram (kg)	$2.834952 \times 10^{-2}$
pound (avoirdupois)	kilogram (kg)	$4.535924 \times 10^{-1}$
ton (short, 2000 lb)	kilogram (kg)	$9.071847 \times 10^2$
ton (long, 2240 lb)	kilogram (kg)	$1.016047 \times 10^3$
kilogram (kg)	ounce (avoirdupois)	$3.527396 \times 10^1$
kilogram (kg)	pound (avoirdupois)	2.204622
kilogram (kg)	ton (short, 2000 lb)	$1.102311 \times 10^{-3}$
kilogram (kg)	ton (long, 2240 lb)	$9.842064 \times 10^{-4}$
<b>Mass Per Unit Length</b>		
pound per foot (lb/ft)	kilogram per meter (kg/m)	1.488164
pound per inch (lb/in)	kilogram per meter (kg/m)	$1.785797 \times 10^1$
kilogram per meter (kg/m)	pound per foot (lb/ft)	$6.719689 \times 10^{-1}$
kilogram per meter (kg/m)	pound per inch (lb/in)	$5.599741 \times 10^{-2}$
<b>Mass Per Unit Area</b>		
pound per square foot (lb/ft <sup>2</sup> )	kilogram per square meter (kg/m <sup>2</sup> )	4.882428
kilogram per square meter (kg/m <sup>2</sup> )	pound per square foot (lb/ft <sup>2</sup> )	$2.048161 \times 10^{-1}$
<b>Mass Per Unit Volume</b>		
pound per cubic foot (lb/ft <sup>3</sup> )	kilogram per cubic meter (kg/m <sup>3</sup> )	$1.601846 \times 10^1$
pound per cubic inch (lb/in <sup>3</sup> )	kilogram per cubic meter (kg/m <sup>3</sup> )	$2.767990 \times 10^4$
kilogram per cubic meter (kg/m <sup>3</sup> )	pound per cubic foot (lb/ft <sup>3</sup> )	$6.242797 \times 10^{-2}$
kilogram per cubic meter (kg/m <sup>3</sup> )	pound per cubic inch (lb/in <sup>3</sup> )	$3.612730 \times 10^{-5}$
pound per cubic foot (lb/ft <sup>3</sup> )	pound per cubic inch (lb/in <sup>3</sup> )	$1.728000 \times 10^3$
<b>Length</b>		
foot (ft)	meter (m)	$3.048000 \times 10^{-1}$
inch (in)	meter (m)	$2.540000 \times 10^{-2}$
mil	meter (m)	$2.540000 \times 10^{-5}$
inch (in)	micrometer ( $\mu\text{m}$ )	$2.540000 \times 10^4$
meter (m)	foot (ft)	3.28084
meter (m)	inch (in)	$3.937008 \times 10^1$
meter (m)	mil	$3.937008 \times 10^4$
micrometer ( $\mu\text{m}$ )	inch (in)	$3.937008 \times 10^{-5}$

(Continued)

TABLE 1.5 Multiplication Factors to Convert from USCU Units to SI Units (Continued)

To Convert from	To	Multiply by
<b>Area</b>		
foot <sup>2</sup>	square meter (m <sup>2</sup> )	$9.290304 \times 10^{-2}$
inch <sup>2</sup>	square meter (m <sup>2</sup> )	$6.451600 \times 10^{-4}$
circular mil	square meter (m <sup>2</sup> )	$5.067075 \times 10^{-10}$
square centimeter (cm <sup>2</sup> )	square inch (in <sup>2</sup> )	$1.550003 \times 10^{-1}$
square meter (m <sup>2</sup> )	foot <sup>2</sup>	$1.076391 \times 10^1$
square meter (m <sup>2</sup> )	inch <sup>2</sup>	$1.550003 \times 10^3$
square meter (m <sup>2</sup> )	circular mil	$1.973525 \times 10^9$
<b>Volume</b>		
foot <sup>3</sup>	cubic meter (m <sup>3</sup> )	$2.831685 \times 10^{-2}$
inch <sup>3</sup>	cubic meter (m <sup>3</sup> )	$1.638706 \times 10^{-5}$
cubic centimeter (cm <sup>3</sup> )	cubic inch (in <sup>3</sup> )	$6.102374 \times 10^{-2}$
cubic meter (m <sup>3</sup> )	foot <sup>3</sup>	$3.531466 \times 10^1$
cubic meter (m <sup>3</sup> )	inch <sup>3</sup>	$6.102376 \times 10^4$
gallon (U.S. liquid)	cubic meter (m <sup>3</sup> )	$3.785412 \times 10^{-3}$
<b>Force</b>		
pounds-force (lbf)	newtons (N)	4.448222
<b>Pressure or Stress</b>		
pound force per square inch (lbf/in <sup>2</sup> )(psi)	pascal (Pa)	$6.894757 \times 10^3$
kip per square inch (kip/in <sup>2</sup> )(ksi)	pascal (Pa)	$6.894757 \times 10^6$
pound force per square inch (lbf/in <sup>2</sup> )(psi)	megapascal (MPa)	$6.894757 \times 10^{-3}$
pascal (Pa)	pound force per square inch (psi)	$1.450377 \times 10^{-4}$
pascal (Pa)	kip per square inch (ksi)	$1.450377 \times 10^{-7}$
megapascals (MPa)	pound force per square inch (lbf/in <sup>2</sup> ) (psi)	$1.450377 \times 10^2$
<b>Section Properties</b>		
section modulus S (in <sup>3</sup> )	S (m <sup>3</sup> )	$1.638706 \times 10^{-5}$
moment of inertia I (in <sup>4</sup> )	I (m <sup>4</sup> )	$4.162314 \times 10^{-7}$
modulus of elasticity E (psi)	E (Pa)	$6.894757 \times 10^3$
section modulus S (m <sup>3</sup> )	S (in <sup>3</sup> )	$6.102374 \times 10^4$
moment of inertia I (m <sup>4</sup> )	I (in <sup>4</sup> )	$2.402510 \times 10^6$
modulus of elasticity E (Pa)	E (psi)	$1.450377 \times 10^{-4}$
<b>Temperature</b>		
degree Fahrenheit	degree Celsius	$t^{\circ}\text{C} = (t^{\circ}\text{F} - 32)/1.8$
degree Celsius	degree Fahrenheit	$t^{\circ}\text{F} = 1.8 t^{\circ}\text{C} + 32$
<b>Angle</b>		
degree	radian (rad)	$1.745329 \times 10^{-2}$
radian (rad)	degree	$5.729578 \times 10^1$

TABLE 1.6 Conversion Factors

To Convert from	To	Multiply by
acceleration of free fall, standard ( $g_n$ )	meter per second square ( $m/s^2$ )	9.80665
acre (based on U.S. survey foot)	square meter ( $m^2$ )	$4.046873 \times 10^3$
acre foot (based on U.S. survey foot)	cubic meter ( $m^3$ )	$1.233489 \times 10^3$
atmosphere, standard (atm)	pascal (Pa)	$1.01325 \times 10^5$
atmosphere, standard (atm)	kilopascal (kPa)	$1.01325 \times 10^2$
atmosphere, technical (at)	pascal (Pa)	$9.80665 \times 10^4$
atmosphere, technical (at)	kilopascal (kPa)	$9.80665 \times 10^1$
bar (bar)	pascal (Pa)	$1.0 \times 10^5$
bar (bar)	kilopascal (kPa)	$1.0 \times 10^2$
barn (b)	square meter ( $m^2$ )	$1.0 \times 10^{-28}$
barrel [for petroleum, 42 gallons (U.S.)] (bbl)	cubic meter ( $m^3$ )	$1.589873 \times 10^{-1}$
barrel [for petroleum, 42 gallons (U.S.)] (bbl)	liter (L)	$1.589873 \times 10^2$
calorie <sub>IT</sub> ( $cal_{IT}$ )	joule (J)	4.1868
calorie <sub>th</sub> ( $cal_{th}$ )	joule (J)	4.184
calorie (cal) (mean)	joule (J)	4.19002
calorie (15°C) ( $cal_{15}$ )	joule (J)	4.18580
calorie (20°C) ( $cal_{20}$ )	joule (J)	4.18190
centimeter of mercury (0°C)	pascal (Pa)	$1.33322 \times 10^3$
centimeter of mercury (0°C)	kilopascal (kPa)	1.33322
centimeter of mercury, conventional (cmHg)	pascal (Pa)	$1.333224 \times 10^3$
centimeter of mercury, conventional (cmHg)	kilopascal (kPa)	1.333224
centimeter of water (4°C)	pascal (Pa)	$9.80638 \times 10^1$
centimeter of water, conventional ( $cmH_2O$ )	pascal (Pa)	$9.80665 \times 10^1$
centipoise (cP)	pascal second (Pa-s)	$1.0 \times 10^{-3}$
centistokes (cSt)	meter square per second ( $m^2/s$ )	$1.0 \times 10^{-6}$
chain (based on U.S. survey foot) (ch)	meter (m)	$2.011684 \times 10^1$
circular mil	square meter ( $m^2$ )	$5.067075 \times 10^{-10}$
cubic foot ( $ft^3$ )	cubic meter ( $m^3$ )	$2.831685 \times 10^{-2}$
cubic foot per minute ( $ft^3/min$ )	cubic meter per second ( $m^3/s$ )	$4.719474 \times 10^{-4}$
cubic foot per minute ( $ft^3/min$ )	liter per second (L/s)	$4.719474 \times 10^{-1}$
cubic foot per second ( $ft^3/s$ )	cubic meter per second ( $m^3/s$ )	$2.831685 \times 10^{-2}$
cubic inch ( $in^3$ )	cubic meter ( $m^3$ )	$1.638706 \times 10^{-5}$

(Continued)

TABLE 1.6 Conversion Factors (Continued)

To Convert from	To	Multiply by
cubic inch per minute (in <sup>3</sup> /min)	cubic meter per second (m <sup>3</sup> /s)	$2.731177 \times 10^{-7}$
cubic mile (mi <sup>3</sup> )	cubic meter (m <sup>3</sup> )	$4.168182 \times 10^9$
cubic yard (yd <sup>3</sup> )	cubic meter (m <sup>3</sup> )	$7.645549 \times 10^{-1}$
cubic yard per minute (yd <sup>3</sup> /min)	cubic meter per second (m <sup>3</sup> /s)	$1.274258 \times 10^{-2}$
cup (U.S.)	cubic meter (m <sup>3</sup> )	$2.365882 \times 10^{-4}$
cup (U.S.)	liter (L)	$2.365882 \times 10^{-1}$
cup (U.S.)	milliliter (mL)	$2.365882 \times 10^2$
day (d)	second (s)	$8.64 \times 10^4$
day (sidereal)	second (s)	$8.616409 \times 10^4$
degree (angle) (°)	radian (rad)	$1.745329 \times 10^{-2}$
degree Celsius (temperature) (°C)	kelvin (K)	$T/K = t/°C + 273.15$
degree Celsius (temperature interval) (°C)	kelvin (K)	1.0
degree centigrade (temperature)	degree Celsius (°C)	$t/°C \approx t/\text{deg. cent.}$
degree centigrade (temperature interval)	degree Celsius (°C)	1.0
degree Fahrenheit (temperature) (°F)	degree Celsius (°C)	$t/°C = (t/°F - 32)/1.8$
degree Fahrenheit (temperature) (°F)	kelvin (K)	$T/K = (t/°F + 459.67)/1.8$
dyne (dyn)	newton (N)	$1.0 \times 10^{-5}$
dyne centimeter (dyn-cm)	newton meter (N-m)	$1.0 \times 10^{-7}$
dyne per square centimeter (dyn/cm <sup>2</sup> )	pascal (Pa)	$1.0 \times 10^{-1}$
fermi	femtometer (fm)	1.0
fluid ounce (U.S.) (fl oz)	cubic meter (m <sup>3</sup> )	$2.957353 \times 10^{-5}$
fluid ounce (U.S.) (fl oz)	milliliter (mL)	$2.957353 \times 10^1$
foot (ft)	meter (m)	$3.048 \times 10^{-1}$
foot (U.S. survey) (ft)	meter (m)	$3.048006 \times 10^{-1}$
foot of mercury, conventional (ftHg)	pascal (Pa)	$4.063666 \times 10^4$
foot of mercury, conventional (ftHg)	kilopascal (kPa)	$4.063666 \times 10^1$
foot of water (39.2°F)	pascal (Pa)	$2.98898 \times 10^3$
foot of water (39.2°F)	kilopascal (kPa)	2.98898
foot of water, conventional (ftH <sub>2</sub> O)	pascal (Pa)	$2.989067 \times 10^3$
foot of water, conventional (ftH <sub>2</sub> O)	kilopascal (kPa)	2.989067
foot per hour (ft/h)	meter per second (m/s)	$8.466667 \times 10^{-5}$
foot per minute (ft/min)	meter per second (m/s)	$5.08 \times 10^{-3}$
foot per second (ft/s)	meter per second (m/s)	$3.048 \times 10^{-1}$
foot per second square (ft/s <sup>2</sup> )	meter per second square (m/s <sup>2</sup> )	$3.048 \times 10^{-1}$

(Continued)

TABLE 1.6 Conversion Factors (Continued)

To Convert from	To	Multiply by
foot poundal	joule (J)	$4.214011 \times 10^{-2}$
foot pound-force (ft-lbf)	joule (J)	1.355818
foot pound-force per hour (ft-lbf/h)	watt (W)	$3.766161 \times 10^{-4}$
foot pound-force per minute (ft-lbf/min)	watt (W)	$2.259697 \times 10^{-2}$
foot pound-force per second (ft-lbf/s)	watt (W)	1.355818
foot to the fourth power (ft <sup>4</sup> )	meter to the fourth power (m <sup>4</sup> )	$8.630975 \times 10^{-3}$
gal (gal)	meter per second square (m/s <sup>2</sup> )	$1.0 \times 10^{-2}$
gallon [Canadian and U.K. (Imperial)] (gal)	cubic meter (m <sup>3</sup> )	$4.54609 \times 10^{-3}$
gallon [Canadian and U.K. (Imperial)] (gal)	liter (L)	4.54609
gallon (U.S.) (gal)	cubic meter (m <sup>3</sup> )	$3.785412 \times 10^{-3}$
gallon (U.S.) (gal)	liter (L)	3.785412
gallon (U.S.) per day (gal/d)	cubic meter per second (m <sup>3</sup> /s)	$4.381264 \times 10^{-8}$
gallon (U.S.) per day (gal/d)	liter per second (L/s)	$4.381264 \times 10^{-5}$
gallon (U.S.) per horsepower hour [gal/(hp-h)]	cubic meter per joule (m <sup>3</sup> /J)	$1.410089 \times 10^{-9}$
gallon (U.S.) per horsepower hour [gal/(hp-h)]	liter per joule (L/J)	$1.410089 \times 10^{-6}$
gallon (U.S.) per minute (gpm)(gal/min)	cubic meter per second (m <sup>3</sup> /s)	$6.309020 \times 10^{-5}$
gallon (U.S.) per minute (gpm)(gal/min)	liter per second (L/s)	$6.309020 \times 10^{-2}$
gon (also called grade) (gon)	radian (rad)	$1.570796 \times 10^{-2}$
gon (also called grade) (gon)	degree (angle) (°)	$9.0 \times 10^{-1}$
grain (gr)	kilogram (kg)	$6.479891 \times 10^{-5}$
grain (gr)	milligram (mg)	$6.479891 \times 10^1$
grain per gallon (U.S.) (gr/gal)	kilogram per cubic meter (kg/m <sup>3</sup> )	$1.711806 \times 10^{-2}$
grain per gallon (U.S.) (gr/gal)	milligram per liter (mg/L)	$1.711806 \times 10^1$
gram-force per square centimeter (gf/cm <sup>2</sup> )	pascal (Pa)	$9.80665 \times 10^1$
gram per cubic centimeter (g/cm <sup>3</sup> )	kilogram per cubic meter (kg/m <sup>3</sup> )	$1.0 \times 10^3$
hectare (ha)	square meter (m <sup>2</sup> )	$1.0 \times 10^4$
horsepower (550 ft-lbf/s) (hp)	watt (W)	$7.456999 \times 10^2$
horsepower (boiler)	watt (W)	$9.80950 \times 10^3$
horsepower (electric)	watt (W)	$7.46 \times 10^2$
horsepower (metric)	watt (W)	$7.354988 \times 10^2$

(Continued)

TABLE 1.6 Conversion Factors (Continued)

To Convert from	To	Multiply by
horsepower (U.K.)	watt (W)	$7.4570 \times 10^2$
horsepower (water)	watt (W)	$7.46043 \times 10^2$
hour (h)	second (s)	$3.6 \times 10^3$
inch (in)	meter (m)	$2.54 \times 10^{-2}$
inch (in)	centimeter (cm)	2.54
inch of mercury (32°F)	pascal (Pa)	$3.38638 \times 10^3$
inch of mercury (32°F)	kilopascal (kPa)	3.38638
inch of mercury (60°F)	pascal (Pa)	$3.37685 \times 10^3$
inch of mercury (60°F)	kilopascal (kPa)	3.37685
inch of mercury, conventional (inHg)	pascal (Pa)	$3.386389 \times 10^3$
inch of mercury, conventional (inHg)	kilopascal (kPa)	3.386389
inch of water (39.2°F)	pascal (Pa)	$2.49082 \times 10^2$
inch of water (60°F)	pascal (Pa)	$2.4884 \times 10^2$
inch of water, conventional (inH <sub>2</sub> O)	pascal (Pa)	$2.490889 \times 10^2$
inch per second (in/s)	meter per second (m/s)	$2.54 \times 10^{-2}$
kelvin (K)	degree Celsius (°C)	$t/^{\circ}\text{C} = T/\text{K} - 273.15$
kilogram-force (kgf)	newton (N)	9.80665
kilogram-force meter (kgf-m)	newton meter (N-m)	9.80665
kilogram-force per square centimeter (kgf/cm <sup>2</sup> )	pascal (Pa)	$9.80665 \times 10^4$
kilogram-force per square centimeter (kgf/cm <sup>2</sup> )	kilopascal (kPa)	$9.80665 \times 10^1$
kilogram-force per square meter (kgf/m <sup>2</sup> )	pascal (Pa)	9.80665
kilogram-force per square millimeter (kgf/mm <sup>2</sup> )	pascal (Pa)	$9.80665 \times 10^6$
kilogram-force per square millimeter (kgf/mm <sup>2</sup> )	megapascal (MPa)	9.80665
kilogram-force second square per meter (kgf-s <sup>2</sup> /m)	kilogram (kg)	9.80665
light year (l.y.)	meter (m)	$9.46073 \times 10^{15}$
liter (L)	cubic meter (m <sup>3</sup> )	$1.0 \times 10^{-3}$
microinch	meter (m)	$2.54 \times 10^{-8}$
microinch	micrometer (μm)	$2.54 \times 10^{-2}$
micron (μ)	meter (m)	$1.0 \times 10^{-6}$
micron (μ)	micrometer (μm)	1.0
mil (0.001 in)	meter (m)	$2.54 \times 10^{-5}$
mil (0.001 in)	millimeter (mm)	$2.54 \times 10^{-2}$

(Continued)