MECHANICS OF MATERIALS

EIGHTH EDITION

R. C. HIBBELER

Prentice Hall
Boston Columbus Indianapolis New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montréal Toronto
Delhi Mexico City São Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

Vice President and Editorial Director, ECS: *Marcia Horton*
Senior Acquisitions Editor: *Tacy Quinn*
Editorial Assistant: *Coleen McDonald*
Executive Marketing Manager: *Tim Galligan*
Senior Managing Editor: *Scott Disanno*
Project Manager: *Rose Kernan*
Senior Operations Supervisor: *Alan Fischer*
Operations Specialist: *Lisa McDowell*
Art Director: *Kenny Beck*
Text and Cover Designer: *Kenny Beck*
Photo Researcher: *Marta Samsel*
Cover Images: High rise crane: Martin Mette/Shutterstock; close up of crane with heavy load: Mack7777/Shutterstock; close up of hoisting rig and telescopic arm of mobile crane: 36clicks/Shutterstock
Media Director: *Daniel Sandin*

Credits and acknowledgments borrowed from other sources and reproduced, with permission, in this textbook appear on appropriate page within text (or on page xvii).

Copyright © 2011, 2008, 2005, 2003, 2001 by R. C. Hibbeler. Published by Pearson Prentice Hall. All rights reserved. Manufactured in the United States of America. This publication is protected by Copyright, and permission should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission(s) to use material from this work, please submit a written request to Pearson Education, Inc., Permissions Department, 1 Lake Street, Upper Saddle River, NJ 07458.

Many of the designations by manufacturers and seller to distinguish their products are claimed as trademarks. Where those designations appear in this book, and the publisher was aware of a trademark claim, the designations have been printed in initial caps or all caps.

10 9 8 7 6 5 4 3 2 1

Prentice Hall
is an imprint of

PEARSON

www.pearsonhighered.com

ISBN 10: 0-13-602230-8
ISBN 13: 978-0-13-602230-5

To the Student

With the hope that this work will stimulate
an interest in Engineering Mechanics
and provide an acceptable guide to its understanding.

PREFACE

It is intended that this book provide the student with a clear and thorough presentation of the theory and application of the principles of mechanics of materials. To achieve this objective, over the years this work has been shaped by the comments and suggestions of hundreds of reviewers in the teaching profession, as well as many of the author's students. The eighth edition has been significantly enhanced from the previous edition, and it is hoped that both the instructor and student will benefit greatly from these improvements.

New to This Edition

- **Updated Content.** Some portions of the text have been rewritten in order to enhance clarity and be more succinct. In this regard, some new examples have been added and others have been modified to provide more emphasis on the application of important concepts. Also, the artwork has been improved throughout the book to support these changes.
- **New Photos.** The relevance of knowing the subject matter is reflected by the real-world applications depicted in over 44 new or updated photos placed throughout the book. These photos generally are used to explain how the relevant principles apply to real-world situations and how materials behave under load.
- **Fundamental Problems.** These problem sets are located just after each group of example problems. They offer students simple applications of the concepts covered in each section and, therefore, provide them with the chance to develop their problem-solving skills before attempting to solve any of the standard problems that follow. The fundamental problems may be considered as extended examples, since the key equations and answers are all listed in the back of the book. Additionally, when assigned, these problems offer students an excellent means of preparing for exams, and they can be used at a later time as a review when studying for the Fundamentals of Engineering Exam.
- **Conceptual Problems.** Throughout the text, usually at the end of each chapter, there is a set of problems that involve conceptual situations related to the application of the principles contained in the chapter. These analysis and design problems are intended to engage the students in thinking through a real-life situation as depicted in a photo. They can be assigned after the students have developed some expertise in the subject matter and they work well either for individual or team projects.
- **New Problems.** There are approximately 35%, or about 550, new problems added to this edition, which involve applications to many different fields of engineering. Also, this new edition now has approximately 134 more problems than in the previous edition.

• **Problems with Hints.** With the additional homework problems in this new edition, every problem indicated with a bullet (•) before the problem number, includes a suggestion, key equation, or additional numerical result that is given along with the answer in the back of the book. These problems further encourage students to solve problems on their own by providing them with additional checks to the solution.

Contents

The subject matter is organized into 14 chapters. Chapter 1 begins with a review of the important concepts of statics, followed by a formal definition of both normal and shear stress, and a discussion of normal stress in axially loaded members and average shear stress caused by direct shear.

In Chapter 2 normal and shear strain are defined, and in Chapter 3 a discussion of some of the important mechanical properties of materials is given. Separate treatments of axial load, torsion, and bending are presented in Chapters 4, 5, and 6, respectively. In each of these chapters, both linear-elastic and plastic behavior of the material are considered. Also, topics related to stress concentrations and residual stress are included. Transverse shear is discussed in Chapter 7, along with a discussion of thin-walled tubes, shear flow, and the shear center. Chapter 8 includes a discussion of thin-walled pressure vessels and provides a partial review of the material covered in the previous chapters, such that the state of stress results from combined loadings. In Chapter 9 the concepts for transforming multiaxial states of stress are presented. In a similar manner, Chapter 10 discusses the methods for strain transformation, including the application of various theories of failure. Chapter 11 provides a means for a further summary and review of previous material by covering design applications of beams and shafts. In Chapter 12 various methods for computing deflections of beams and shafts are covered. Also included is a discussion for finding the reactions on these members if they are statically indeterminate. Chapter 13 provides a discussion of column buckling, and lastly, in Chapter 14 the problem of impact and the application of various energy methods for computing deflections are considered.

Sections of the book that contain more advanced material are indicated by a star (*). Time permitting, some of these topics may be included in the course. Furthermore, this material provides a suitable reference for basic principles when it is covered in other courses, and it can be used as a basis for assigning special projects.

Alternative Method of Coverage. Some instructors prefer to cover stress and strain transformations *first,* before discussing specific applications of axial load, torsion, bending, and shear. One possible method for doing this would be first to cover stress and its transformation, Chapter 1 and Chapter 9, followed by strain and its transformation, Chapter 2 and the first part of Chapter 10. The discussion and example problems in these later chapters have been

styled so that this is possible. Also, the problem sets have been subdivided so that this material can be covered without prior knowledge of the intervening chapters. Chapters 3 through 8 can then be covered with no loss in continuity.

Hallmark Elements

Organization and Approach. The contents of each chapter are organized into well-defined sections that contain an explanation of specific topics, illustrative example problems, and a set of homework problems. The topics within each section are placed into subgroups defined by titles. The purpose of this is to present a structured method for introducing each new definition or concept and to make the book convenient for later reference and review.

Chapter Contents. Each chapter begins with a full-page illustration that indicates a broad-range application of the material within the chapter. The "Chapter Objectives" are then provided to give a general overview of the material that will be covered.

Procedures for Analysis. Found after many of the sections of the book, this unique feature provides the student with a logical and orderly method to follow when applying the theory. The example problems are solved using this outlined method in order to clarify its numerical application. It is to be understood, however, that once the relevant principles have been mastered and enough confidence and judgment have been obtained, the student can then develop his or her own procedures for solving problems.

Photographs. Many photographs are used throughout the book to enhance conceptual understanding and explain how the principles of mechanics of materials apply to real-world situations.

Important Points. This feature provides a review or summary of the most important concepts in a section and highlights the most significant points that should be realized when applying the theory to solve problems.

Example Problems. All the example problems are presented in a concise manner and in a style that is easy to understand.

Homework Problems. Numerous problems in the book depict realistic situations encountered in engineering practice. It is hoped that this realism will both stimulate the student's interest in the subject and provide a means for developing the skill to reduce any such problem from its physical description to a model or a symbolic representation to which principles may be applied. Throughout the book there is an approximate balance of problems using either SI or FPS units. Furthermore, in any set, an attempt has been made to arrange the problems in order of increasing difficulty. The answers to all but every fourth problem are listed in the back of the book. To alert the user to a

problem without a reported answer, an asterisk(*) is placed before the problem number. Answers are reported to three significant figures, even though the data for material properties may be known with less accuracy. Although this might appear to be a poor practice, it is done simply to be consistent and to allow the student a better chance to validate his or her solution. A solid square (■) is used to identify problems that require a numerical analysis or a computer application.

Appendices. The appendices of the book provide a source for review and a listing of tabular data. Appendix A provides information on the centroid and the moment of inertia of an area. Appendices B and C list tabular data for structural shapes, and the deflection and slopes of various types of beams and shafts.

Accuracy Checking. The Eighth Edition has undergone our rigorous Triple Accuracy Checking review. In addition to the author's review of all art pieces and pages, the text was checked by the following individuals:

- Scott Hendricks, Virginia Polytechnic University
- Karim Nohra, University of South Florida
- Kurt Norlin, Laurel Tech Integrated Publishing Services
- Kai Beng Yap, Engineering Consultant

Acknowledgments

Over the years, this text has been shaped by the suggestions and comments of many of my colleagues in the teaching profession. Their encouragement and willingness to provide constructive criticism are very much appreciated and it is hoped that they will accept this anonymous recognition. A note of thanks is given to the reviewers.

Akthem Al-Manaseer, *San Jose State University*
Yabin Liao, *Arizona State University*
Cliff Lissenden, *Penn State*
Gregory M. Odegard, *Michigan Technological University*
John Oyler, *University of Pittsburgh*
Roy Xu, *Vanderbilt University*
Paul Ziehl, *University of South Carolina*

There are a few people that I feel deserve particular recognition. A long-time friend and associate, Kai Beng Yap, was of great help to me in checking the entire manuscript and helping to prepare the problem solutions. A special note of thanks also goes to Kurt Norlin of Laurel Tech Integrated Publishing Services in this regard. During the production process I am thankful for the assistance of Rose Kernan, my production editor for many years, and to my wife, Conny, and daughter,

Mary Ann, for their help in proofreading and typing, that was needed to prepare the manuscript for publication.

I would also like to thank all my students who have used the previous edition and have made comments to improve its contents.

I would greatly appreciate hearing from you if at any time you have any comments or suggestions regarding the contents of this edition.

Russell Charles Hibbeler
hibbeler@bellsouth.net

Resources for Instructors

- **Instructor's Solutions Manual.** An instructor's solutions manual was prepared by the author. The manual includes homework assignment lists and was also checked as part of the accuracy checking program.
- **Presentation Resources.** All art from the text is available in PowerPoint slide and JPEG format. These files are available for download from the Instructor Resource Center at http://www.pearsonhighered. com. If you are in need of a login and password for this site, please contact your local Pearson Prentice Hall representative.
- **Video Solutions.** Developed by Professor Edward Berger, University of Virginia, video solutions located on the Companion Website offer step-by-step solution walkthroughs of representative homework problems from each section of the text. Make efficient use of class time and office hours by showing students the complete and concise problem solving approaches that they can access anytime and view at their own pace. The videos are designed to be a flexible resource to be used however each instructor and student prefers. A valuable tutorial resource, the videos are also helpful for student self-evaluation as students can pause the videos to check their understanding and work alongside the video. Access the videos at http://www.pearsonhighered.com/hibbeler and follow the links for the *Mechanics of Materials* text.

Resources for Students

- **Companion Website**—The Companion Website, located at http://www.pearsonhighered.com/hibbeler includes opportunities for practice and review including:
  - **Video Solutions**—Complete, step-by-step solution walkthroughs of representative homework problems from each section. Videos offer:
    - **Fully Worked Solutions**—Showing every step of representative homework problems, to help students make vital connections between concepts.
    - **Self-Paced Instruction**—Students can navigate each problem and select, play, rewind, fast-forward, stop, and jump-to-sections within each problem's solution.
    - **24/7 Access**—Help whenever students need it with over 20 hours of helpful review.

An access code for the *Mechanics of Materials,* Eighth Edition website was included with this text. To redeem the code and gain access to the site, go to http://www.pearsonhighered.com/hibbeler and follow the directions on the access code card. Access can also be purchased directly from the site.

CONTENTS

1 Stress 3

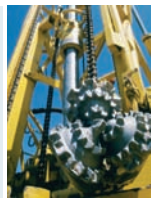
Chapter Objectives 3
1.1 Introduction 3
1.2 Equilibrium of a Deformable Body 4
1.3 Stress 22
1.4 Average Normal Stress in an Axially Loaded Bar 24
1.5 Average Shear Stress 32
1.6 Allowable Stress 46
1.7 Design of Simple Connections 47

2 Strain 65

Chapter Objectives 65
2.1 Deformation 65
2.2 Strain 66

3 Mechanical Properties of Materials 81

Chapter Objectives 81
3.1 The Tension and Compression Test 81
3.2 The Stress–Strain Diagram 83
3.3 Stress–Strain Behavior of Ductile and Brittle Materials 87
3.4 Hooke's Law 90
3.5 Strain Energy 92
3.6 Poisson's Ratio 102
3.7 The Shear Stress–Strain Diagram 104
***3.8** Failure of Materials Due to Creep and Fatigue 107



4 Axial Load 119

Chapter Objectives 119
4.1 Saint-Venant's Principle 119
4.2 Elastic Deformation of an Axially Loaded Member 122
4.3 Principle of Superposition 136
4.4 Statically Indeterminate Axially Loaded Member 137
4.5 The Force Method of Analysis for Axially Loaded Members 143
4.6 Thermal Stress 151
4.7 Stress Concentrations 158
***4.8** Inelastic Axial Deformation 162
***4.9** Residual Stress 164

5 Torsion 179

Chapter Objectives 179
5.1 Torsional Deformation of a Circular Shaft 179
5.2 The Torsion Formula 182
5.3 Power Transmission 190
5.4 Angle of Twist 200
5.5 Statically Indeterminate Torque-Loaded Members 214
***5.6** Solid Noncircular Shafts 221
***5.7** Thin-Walled Tubes Having Closed Cross Sections 224
5.8 Stress Concentration 234
***5.9** Inelastic Torsion 237
***5.10** Residual Stress 239

6 Bending 255

Chapter Objectives 255
6.1 Shear and Moment Diagrams 255
6.2 Graphical Method for Constructing Shear and Moment Diagrams 262
6.3 Bending Deformation of a Straight Member 281
6.4 The Flexure Formula 285
6.5 Unsymmetric Bending 302
*6.6 Composite Beams 312
*6.7 Reinforced Concrete Beams 315
*6.8 Curved Beams 319
6.9 Stress Concentrations 326
*6.10 Inelastic Bending 335

7 Transverse Shear 359

Chapter Objectives 359
7.1 Shear in Straight Members 359
7.2 The Shear Formula 361
7.3 Shear Flow in Built-Up Members 378
7.4 Shear Flow in Thin-Walled Members 387
*7.5 Shear Center For Open Thin-Walled Members 392

8 Combined Loadings 405

Chapter Objectives 405
8.1 Thin-Walled Pressure Vessels 405
8.2 State of Stress Caused by Combined Loadings 412

9 Stress Transformation 437

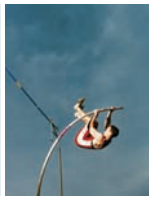
Chapter Objectives 437
9.1 Plane-Stress Transformation 437
9.2 General Equations of Plane-Stress Transformation 442
9.3 Principal Stresses and Maximum In-Plane Shear Stress 445
9.4 Mohr's Circle—Plane Stress 461
9.5 Absolute Maximum Shear Stress 473

10 Strain Transformation 485

Chapter Objectives 485
10.1 Plane Strain 485
10.2 General Equations of Plane-Strain Transformation 486
*10.3 Mohr's Circle—Plane Strain 494
*10.4 Absolute Maximum Shear Strain 502
10.5 Strain Rosettes 504
10.6 Material-Property Relationships 508
*10.7 Theories of Failure 520

11 Design of Beams and Shafts 537

Chapter Objectives 537
11.1 Basis for Beam Design 537
11.2 Prismatic Beam Design 540
*11.3 Fully Stressed Beams 554
*11.4 Shaft Design 558

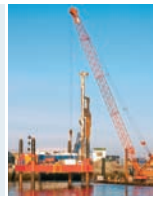


12 Deflection of Beams and Shafts 569

Chapter Objectives 569
12.1 The Elastic Curve 569
12.2 Slope and Displacement by Integration 573
***12.3** Discontinuity Functions 593
***12.4** Slope and Displacement by the Moment-Area Method 604
12.5 Method of Superposition 619
12.6 Statically Indeterminate Beams and Shafts 627
12.7 Statically Indeterminate Beams and Shafts—Method of Integration 628
***12.8** Statically Indeterminate Beams and Shafts—Moment-Area Method 633
12.9 Statically Indeterminate Beams and Shafts—Method of Superposition 639

13 Buckling of Columns 657

Chapter Objectives 657
13.1 Critical Load 657
13.2 Ideal Column with Pin Supports 660
13.3 Columns Having Various Types of Supports 666
***13.4** The Secant Formula 678
***13.5** Inelastic Buckling 684
***13.6** Design of Columns for Concentric Loading 692
***13.7** Design of Columns for Eccentric Loading 703



14 Energy Methods 715

Chapter Objectives 715
14.1 External Work and Strain Energy 715
14.2 Elastic Strain Energy for Various Types of Loading 720
14.3 Conservation of Energy 733
***14.4** Impact Loading 740
***14.5** Principle of Virtual Work 751
***14.6** Method of Virtual Forces Applied to Trusses 755
***14.7** Method of Virtual Forces Applied to Beams 762
***14.8** Castigliano's Theorem 771
***14.9** Castigliano's Theorem Applied to Trusses 773
***14.10** Castigliano's Theorem Applied to Beams 776

Appendices

A. Geometric Properties of an Area 784
A.1 Centroid of an Area 784
A.2 Moment of Inertia for an Area 787
A.3 Product of Inertia for an Area 791
A.4 Moments of Inertia for an Area about Inclined Axes 794
A.5 Mohr's Circle for Moments of Inertia 797
B. Geometric Properties of Structural Shapes 800
C. Slopes and Deflections of Beams 808

Fundamental Problems Partial Solutions and Answers 810
Answers To Selected Problems 828
Index 854

CREDITS

Chapter 1, Close up of iron girders. Jack Sullivan\Alamy Images.

Chapter 2, Photoelastic phenomena: tension in a screw mount. Alfred Pasieka\Alamy Images.

Chapter 3, A woman stands near a collapsed bridge in one of the worst earthquake-hit areas of Yingxiu town in Wenchuan county, in China's southwestern province of Sichuan on June 2, 2008. UN Secretary of State Condoleezza Rice on June 29 met children made homeless by the devastating earthquake that hit southwest China last month and praised the country's response to the disaster. LIU JIN/Stringer\Getty Images, Inc. AFP.

Chapter 3 text, Cup and cone steel. Alamy Images.

Chapter 4, Rotary bit on portable oil drilling rig. © Lowell Georgia/ CORBIS. All Rights Reserved.

Chapter 5, Steam rising from soils and blurred spinning hollow stem auger. Alamy Images.

Chapter 6, Steel framework at construction site. Corbis RF.

Chapter 7, Train wheels on track. Jill Stephenson\Alamy Images.

Chapter 7 text, Highway flyover. Gari Wyn Williams\Alamy Images.

Chapter 8, Ski lift with snow covered mountain in background. Shutterstock.

Chapter 9, Turbine blades. Chris Pearsall\Alamy Images.

Chapter 10, Complex stresses developed within an airplane wing. Courtesy of Measurements Group, Inc. Raleigh, North Carolina, 27611, USA.

Chapter 11, Metal frame and yellow crane. Stephen Finn\Alamy Images.

Chapter 12, Man pole vaulting in desert. © Patrick Giardino/CORBIS. All Rights Reserved.

Chapter 13, Water storage tower. John Dorado\Shutterstock.

Chapter 14, Shot of jack-up-pile-driver and floating crane. John MacCooey\Alamy Images.

Other images provided by the author.