

FIFTH EDITION

# Applied Strength of Materials

Robert L. Mott



CRC Press  
Taylor & Francis Group

# APPLIED STRENGTH OF MATERIALS

Fifth Edition

Robert L. Mott, P.E.

University of Dayton

CRC Press  
Taylor & Francis Group  
6000 Broken Sound Parkway NW, Suite 300  
Boca Raton, FL 33487-2742

© 2015 by Taylor & Francis Group, LLC  
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper  
Version Date: 20141114

International Standard Book Number-13: 978-1-4987-2591-0 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access [www.copyright.com](http://www.copyright.com) (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

**Trademark Notice:** Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

---

**Library of Congress Cataloging-in-Publication Data**

---

Mott, Robert L.  
Applied strength of materials/Robert L. Mott.—5th ed.  
p. cm.  
Includes bibliographical references and index.  
ISBN-13: 978-0-13-236849-0  
ISBN-10: 0-13-236849-8  
1. Strength of materials. I. Title

TA405.M883 2008  
620.1912—dc22

2007027383

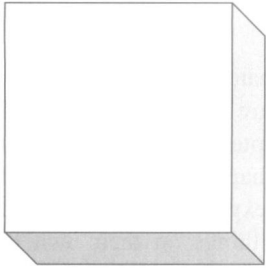
---

Visit the Taylor & Francis Web site at  
<http://www.taylorandfrancis.com>

and the CRC Press Web site at  
<http://www.crcpress.com>

# **APPLIED STRENGTH OF MATERIALS**





# Preface

## Objectives of the Book

*Applied Strength of Materials*, Fifth Edition, provides comprehensive coverage of the important topics in strength of materials with an emphasis on applications, problem solving, and design of structural members, mechanical devices, and systems. The book is written for the student in a course called Strength of Materials, Mechanics of Materials, or Solid Mechanics in an engineering technology program at the baccalaureate or associate degree level or in an applied engineering program.

This book provides good readability for the student, appropriate coverage of the principles of strength of materials for the faculty member teaching the subject, and a problem-solving and design approach that is useful for the practicing designer or engineer. Educational programs in the mechanical, civil, construction, architectural, industrial, and manufacturing fields will find the book suitable for an introductory course in strength of materials.

## Style

This text emphasizes the *applications* of the principles of strength of materials to mechanical, manufacturing, structural, and construction problems while providing a firm understanding of those principles. At the same time, the *limitations* on the use of analysis techniques are emphasized to ensure that they are applied properly. Both analysis and design approaches are used in the book.

Units are a mixture of SI metric and U.S. Customary units, in keeping with the dual usage evident in U.S. industry and construction.

## Prerequisites

Students should be able to apply the principles of statics prior to using this book. For review, there is a summary of the main techniques of the analysis of forces and momentum in the Appendix. Several example problems are included that are similar to the statics needed to solve practice problems in this book.

While not essential, it is recommended that students have completed an introductory course in calculus. As called for by accrediting agencies, calculus is used to develop the key principles and formulas used in this book. The application of the formulas and most problem-solving and design techniques can be accomplished without the use of calculus.

## Features of the Book

**The Big Picture.** Students should see the relevance of the material they study. They should be able to visualize where devices and systems that they are familiar with depend on the principles of strength of materials. For this reason each chapter starts with a section called *The Big Picture*. Here the basic concepts developed in the chapter are identified and students are asked to think about examples from their own experience where these concepts are used. Sometimes they are asked to explore new things on their own to discover how a product works or how it can fail. They are coached to make observations about the behavior of common mechanical devices, vehicles, industrial machinery, consumer products, and structures. Educational philosophy indicates that students learn better and retain more when such methods are employed.

**Activity-Based Learning.** Activity-based learning activities are integrated into the popular Big Picture section, a successful feature in all previous editions. The activity can be used independently by the students, by the instructor as a classroom demonstration, or a combination of these approaches. These activities allow the instructor and the students to extend the Big Picture dialog into hands-on experiences that give an enhanced appreciation and greater physical feel for the phenomena involved. Activities can help students from different disciplines work together and learn from each other. The activities are generally simple and can be completed in a short amount of time with inexpensive materials and quick setups. The emphasis is on qualitative appreciation of the physical phenomena with a modest amount of measurement involved. Educational research has shown that students learn better when they are personally involved in activities as opposed to listening to lectures. Furthermore, retention of abilities learned is improved along with greater ability to transfer learning to new and different applications.

**Problem-Solving Techniques.** Students must be able to solve real problems, complete the necessary calculations, manipulate units in equations, seek appropriate data, and make good design decisions. The example problems in this book are designed to help students master these processes. In addition, students must learn to communicate the results of their work to others in the field. One important means of communication is the presentation of the problem solutions in an orderly, well-documented manner using established methods. Example problems are set off with a distinctive graphic design and type font. Readers are guided in the process of formulating an approach to problem solving that includes:

- a. Statement of the objective of the problem
- b. Summary of the given information
- c. Definition of the analysis technique to be used
- d. Detailed development of the results with all of the equations used and unit manipulations
- e. At times, comments on the solution to remind the reader of the important concepts involved and to judge the appropriateness of the solution
- f. At times, comments present alternate approaches or improvements to the machine element or structural member being analyzed or designed

The reader's thought process is carried beyond the requested answer into a critical review of the result. With this process, designers gain good habits of organization when solving their own problems.

**Design Approaches.** This text provides extensive information about guidelines for design of mechanical devices and structural members than in most books on this subject. The design approaches are based on another book of mine, *Machine Elements in Mechanical Design*, Fourth Edition, 2004, from Prentice Hall. Learning about design in addition to analysis increases the usefulness of the book to students and professional users. There are some students who will not go on to a following course that emphasizes design. They should get some introduction to the principles of design in the introductory course in strength of materials. For those who do proceed to a design course, they should enter that course with a higher level of capability.

**Design Properties of Materials.** Chapter 2 includes extensive information and discussion on the proper application of engineering materials of many types, both metallic and nonmetallic. There is an extensive introduction to the nature of composite materials given along with commentary throughout the book on the application of composites to various kinds of load-carrying members. Information about the advantages of composites relative to traditional structural materials such as metals, wood, concrete, and plastics are given. The reader is encouraged to seek more education and experience to learn the unique analysis and design techniques required for the proper application of composite materials. Such materials are, in fact, tailored to a specific application, and general tables of material properties are not readily available.

Chapter 2 also includes a new section on materials selection based on the landmark publication *Materials Selection in Mechanical Design*, 3rd ed., by Michael F. Ashby, published by Elsevier-Butterworth-Heinemann (2005).

**End-of-Chapter Problems.** There is an extensive set of problems for student practice at the end of each chapter. The problems are typically organized around the main topics in the chapter. In general, they are presented in a graded manner with simpler problems followed by more comprehensive problems. There are many additional problems at the end of most chapters for practice, review, and design.

**Extensive Appendix.** To complement the use of design approaches, the Appendix provides additional information on material properties, geometry of common areas and commercially available structural shapes, stress concentration factors, formulas for beam deflection, conversion factors, and many others. This allows for a wider variety of problems in the book and for creating tests and projects. It adds to the realism of the book and gives the student practice in looking for the necessary information to solve a problem or to complete a design.

This edition includes a significant amount of additional Appendix data in SI metric units. All commercially available section property data for structural shapes include separate tables of SI data in addition to the formerly included U.S. Customary unit data. The SI data are taken from the latest versions of publications by the American Institute of Steel Construction (AISC). The SI data tables and the U.S. data tables are coordinated so students and instructors can quickly compare the designations and specific data from the two systems. Problems stated in SI metric data should be solved using the SI property data; instructors can develop their own quiz and exam problems completely in the SI system.

An entirely new table has been added on property data for mechanical tubing to supplement the standard pipe data from AISC and to offer designers of mechanical devices or manufacturing applications a wider variety of sizes of hollow circular sections, particularly on the smaller part of the size spectrum.



## Adjustments to Format from Previous Edition

Users of previous editions of this book will find a significant amount of reordering of the coverage of some topics. Guided by intensive feedback from users, the revised arrangement is more streamlined. Some highlights of these changes are:

- Chapter 1, Basic Concepts in Strength of Materials, has been reduced in size to focus on the most cogent introductory material. Several sections on material properties, stress, and strain were relocated into Chapters 2 and 3.
- The coverage of deformation due to axial stresses has been integrated into Chapter 3 on Direct Stresses instead of being in a separate chapter.
- All topics on combined stresses have been consolidated into a single chapter (Chapter 10).
- The discussions of continuous beams and the theorem of three moments have been included with the chapter on Shearing Forces and Bending Moments in Beams (Chapter 5). Other topics related to statically indeterminate beams have been integrated into Chapter 9, Deflection of Beams.
- The introduction of the area property of section modulus has been included in the chapter on Centroids and Moments of Inertia of Areas (Chapter 6). This topic is expanded upon in Chapter 7, Stress Due to Bending.

**Enhanced Visual Attractiveness.** The addition of a second color makes the book more visually appealing; illustrations, graphs, and tables are easier to use and interpret. Many illustrations have been improved by the addition of three-dimensional graphics, greater realism, and more effective use of shading as well as the introduction of color.

## Acknowledgments

I appreciate the feedback provided by both students and instructors who have used the earlier editions of this book. I am also grateful to my colleagues at the University of Dayton. I would like to thank the participants of a focus group that provided input for the revision of this book: Janice Chambers, Portland Community College; Janak Dave, University of Cincinnati; David Dvorak, University of Maine; Frank Gourley, West Virginia University Institute of Technology; and Jack Zecher, Indiana University–Purdue University at Indianapolis (IUPUI). I would also like to thank the reviewers of this edition: Joana Finegan, Central Michigan University; Robert Michael, Pennsylvania State University, Erie; and Thomas Roberts, Milwaukee Area Technical College for their helpful suggestions for improvement. I hope this edition has implemented those suggestions in a manner consistent with the overall approach of the book.

**Robert L. Mott**  
**University of Dayton**

# Contents

Preface xi

## **1 Basic Concepts in Strength of Materials 1**

The Big Picture 2

1-1 Objective of This Book—To Ensure Safety 5

1-2 Objectives of This Chapter 14

1-3 Problem-Solving Procedure 14

1-4 Basic Unit Systems 15

1-5 Relationship among Mass, Force, and Weight 16

1-6 The Concept of Stress 18

1-7 Direct Normal Stress 20

1-8 Stress Elements for Direct Normal Stresses 23

1-9 The Concept of Strain 24

1-10 Direct Shear Stress 24

1-11 Stress Elements for Shear Stresses 30

1-12 Preferred Sizes and Standard Shapes 30

1-13 Experimental and Computational Stress Analysis 38

## **2 Design Properties of Materials 53**

The Big Picture 54

2-1 Objectives of This Chapter 55

2-2 Design Properties of Materials 55

2-3 Steel 71

2-4 Cast Iron 77

2-5 Aluminum 78

2-6 Copper, Brass, and Bronze 80

2-7 Zinc, Magnesium, Titanium, and Nickel-Based Alloys 80

2-8 Nonmetals in Engineering Design 82

2-9	Wood	82
2-10	Concrete	83
2-11	Plastics	86
2-12	Composites	88
2-13	Materials Selection	103
<b>3</b>	<b>Direct Stress, Deformation, and Design</b>	<b>111</b>
	The Big Picture and Activity	112
3-1	Objectives of This Chapter	114
3-2	Design of Members under Direct Tension or Compression	115
3-3	Design Normal Stresses	115
3-4	Design Factor	116
3-5	Design Approaches and Guidelines for Design Factors	118
3-6	Methods of Computing Design Stress	122
3-7	Elastic Deformation in Tension and Compression Members	127
3-8	Deformation Due to Temperature Changes	133
3-9	Thermal Stress	137
3-10	Members Made of More Than One Material	140
3-11	Stress Concentration Factors for Direct Axial Stresses	143
3-12	Bearing Stress	147
3-13	Design Bearing Stress	151
3-14	Design Shear Stress	157
<b>4</b>	<b>Torsional Shear Stress and Torsional Deformation</b>	<b>185</b>
	The Big Picture and Activity	186
4-1	Objectives of This Chapter	190
4-2	Torque, Power, and Rotational Speed	190
4-3	Torsional Shear Stress in Members with Circular Cross Sections	194
4-4	Development of the Torsional Shear Stress Formula	197
4-5	Polar Moment of Inertia for Solid Circular Bars	198
4-6	Torsional Shear Stress and Polar Moment of Inertia for Hollow Circular Bars	199
4-7	Design of Circular Members under Torsion	201
4-8	Comparison of Solid and Hollow Circular Members	205
4-9	Stress Concentrations in Torsionally Loaded Members	208
4-10	Twisting—Elastic Torsional Deformation	215
4-11	Torsion in Noncircular Sections	226
<b>5</b>	<b>Shearing Forces and Bending Moments in Beams</b>	<b>239</b>
	The Big Picture and Activity	240
5-1	Objectives of This Chapter	245
5-2	Beam Loading, Supports, and Types of Beams	246

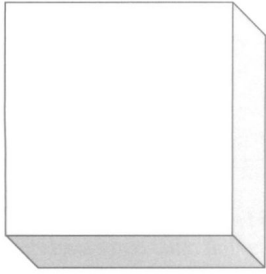
5-3	Reactions at Supports	254
5-4	Shearing Forces and Bending Moments for Concentrated Loads	258
5-5	Guidelines for Drawing Beam Diagrams for Concentrated Loads	263
5-6	Shearing Forces and Bending Moments for Distributed Loads	270
5-7	General Shapes Found in Bending Moment Diagrams	276
5-8	Shearing Forces and Bending Moments for Cantilever Beams	277
5-9	Beams with Linearly Varying Distributed Loads	279
5-10	Free-Body Diagrams of Parts of Structures	281
5-11	Mathematical Analysis of Beam Diagrams	285
5-12	Continuous Beams—Theorem of Three Moments	296
<b>6</b>	<b>Centroids and Moments of Inertia of Areas</b>	<b>314</b>
	The Big Picture and Activity	315
6-1	Objectives of This Chapter	317
6-2	The Concept of Centroid—Simple Shapes	317
6-3	Centroid of Complex Shapes	318
6-4	The Concept of Moment of Inertia of an Area	322
6-5	Moment of Inertia of Composite Shapes Whose Parts Have the Same Centroidal Axis	325
6-6	Moment of Inertia for Composite Shapes—General Case—Use of the Parallel Axis Theorem	327
6-7	Mathematical Definition of Moment of Inertia	330
6-8	Composite Sections Made from Commercially Available Shapes	331
6-9	Moment of Inertia for Shapes with All Rectangular Parts	335
6-10	Radius of Gyration	336
6-11	Section Modulus	340
<b>7</b>	<b>Stress Due to Bending</b>	<b>352</b>
	The Big Picture and Activity	353
7-1	Objectives of This Chapter	355
7-2	The Flexure Formula	356
7-3	Conditions on the Use of the Flexure Formula	359
7-4	Stress Distribution on a Cross Section of a Beam	361
7-5	Derivation of the Flexure Formula	362
7-6	Applications—Beam Analysis	364
7-7	Applications—Beam Design and Design Stresses	367
7-8	Section Modulus and Design Procedures	369
7-9	Stress Concentrations	376
7-10	Flexural Center or Shear Center	382
7-11	Preferred Shapes for Beam Cross Sections	385
7-12	Design of Beams to Be Made from Composite Materials	389

<b>8</b>	<b>Shearing Stresses in Beams</b>	<b>413</b>
	The Big Picture and Activity	414
8-1	Objectives of This Chapter	415
8-2	Importance of Shearing Stresses in Beams	417
8-3	The General Shear Formula	418
8-4	Distribution of Shearing Stress in Beams	424
8-5	Development of the General Shear Formula	431
8-6	Special Shear Formulas	433
8-7	Design for Shear	437
8-8	Shear Flow	439
<b>9</b>	<b>Deflection of Beams</b>	<b>452</b>
	The Big Picture and Activity	453
9-1	Objectives of This Chapter	458
9-2	The Need for Considering Beam Deflections	458
9-3	General Principles and Definitions of Terms	460
9-4	Beam Deflections Using the Formula Method	463
9-5	Comparison of the Manner of Support for Beams	469
9-6	Superposition Using Deflection Formulas	475
9-7	Successive Integration Method	484
9-8	Moment-Area Method	495
<b>10</b>	<b>Combined Stresses</b>	<b>525</b>
	The Big Picture and Activity	526
10-1	Objectives of This Chapter	528
10-2	The Stress Element	529
10-3	Stress Distribution Created by Basic Stresses	530
10-4	Creating the Initial Stress Element	536
10-5	Combined Normal Stresses	538
10-6	Combined Normal and Shear Stresses	546
10-7	Equations for Stresses in Any Direction	551
10-8	Maximum Stresses	554
10-9	Mohr's Circle for Stress	557
10-10	Stress Condition on Selected Planes	572
10-11	Special Case in Which Both Principal Stresses Have the Same Sign	575
10-12	Use of Strain-Gage Rosettes to Determine Principal Stresses	579
<b>11</b>	<b>Columns</b>	<b>600</b>
	The Big Picture and Activity	601
11-1	Objectives of This Chapter	604
11-2	Slenderness Ratio	604

11-3	Transition Slenderness Ratio	609
11-4	The Euler Formula for Long Columns	611
11-5	The J. B. Johnson Formula for Short Columns	611
11-6	Summary—Buckling Formulas	611
11-7	Design Factors for Columns and Allowable Load	614
11-8	Summary—Method of Analyzing Columns	614
11-9	Column Analysis Spreadsheet	618
11-10	Efficient Shapes for Column Cross Sections	620
11-11	Specifications of the AISC	621
11-12	Specifications of the Aluminum Association	623
11-13	Non-Centrally Loaded Columns	624
<b>12</b>	<b>Pressure Vessels</b>	<b>637</b>
	The Big Picture and Activity	638
12-1	Objectives of This Chapter	640
12-2	Distinction between Thin-Walled and Thick-Walled Pressure Vessels	640
12-3	Thin-Walled Spheres	642
12-4	Thin-Walled Cylinders	644
12-5	Thick-Walled Cylinders and Spheres	647
12-6	Analysis and Design Procedures for Pressure Vessels	649
12-7	Spreadsheet Aid for Analyzing Thick-Walled Spheres and Cylinders	655
12-8	Shearing Stress in Cylinders and Spheres	656
12-9	Other Design Considerations for Pressure Vessels	659
12-10	Composite Pressure Vessels	662
<b>13</b>	<b>Connections</b>	<b>667</b>
	The Big Picture and Activity	668
13-1	Objectives of This Chapter	669
13-2	Modes of Failure for Bolted Joints	671
13-3	Design of Bolted Connections	672
13-4	Riveted Joints	675
13-5	Eccentrically Loaded Riveted and Bolted Joints	677
13-6	Welded Joints with Concentric Loads	680
	<b>Appendix</b>	<b>689</b>
	<b>Answers to Selected Problems</b>	<b>755</b>
	<b>Index</b>	<b>771</b>

NOTE: Every effort has been made to provide accurate and current Internet information in this book. However, the Internet and information posted on it are constantly changing, and it is inevitable that some of the Internet addresses listed in this textbook will change.





# 1

## Basic Concepts in Strength of Materials

### The Big Picture

- 1-1 Objective of This Book—To Ensure Safety
- 1-2 Objectives of This Chapter
- 1-3 Problem-Solving Procedure
- 1-4 Basic Unit Systems
- 1-5 Relationship among Mass, Force, and Weight
- 1-6 The Concept of Stress
- 1-7 Direct Normal Stress
- 1-8 Stress Elements for Direct Normal Stresses
- 1-9 The Concept of Strain
- 1-10 Direct Shear Stress
- 1-11 Stress Elements for Shear Stresses
- 1-12 Preferred Sizes and Standard Shapes
- 1-13 Experimental and Computational Stress Analysis



## Basic Concepts in Strength of Materials

### Discussion Map

- |  |  |
|--|--|
| <ul style="list-style-type: none"> <li><input type="checkbox"/> Products, machines, and structures must be designed to be safe and to provide satisfactory performance during the intended use.</li> <li><input type="checkbox"/> Safety is paramount. The load-carrying components must not fracture during use.</li> <li><input type="checkbox"/> Excessive deformation is another form of failure.</li> <li><input type="checkbox"/> Buckling, occurring when the shape of a load-carrying member becomes unstable, must be avoided.</li> <li><input type="checkbox"/> You will learn about the basic nature of stresses and strains in this course.</li> <li><input type="checkbox"/> You will be able to recognize several types of stresses created by different loading and support situations.</li> <li><input type="checkbox"/> You will analyze situations where more than one kind of stress is experienced by a load-carrying member at the same time.</li> <li><input type="checkbox"/> Design requires that you determine the shape and size of a load-carrying member and specify the material from which it is to be made.</li> <li><input type="checkbox"/> You will learn how to design safe load-carrying components of machines and structures.</li> </ul> | <p><b>Discover</b></p> <p><i>Think about products, machines, and structures that you are familiar with that contain components that must carry loads safely. For each device that you think of, write down the following information:</i></p> <p><i>The basic function or purpose of the device.</i></p> <p><i>The description and sketches of its primary components, particularly those that are subjected to significant forces.</i></p> <p><i>The material from which each component is made. Is it a metal or plastic? What kind of metal? What kind of plastic? Is it some other material?</i></p> <p><i>How is each component supported within the product, machine, or structure?</i></p> <p><i>How are forces applied to the component?</i></p> <p><i>What would be the consequence if the component broke?</i></p> <p><i>How much deformation would cause the component to be incapable of performing its desired function?</i></p> <p><i>Consider products around your home; parts of your bicycle, car, or motorcycle; buildings; toys; amusement park rides; aircraft and space vehicles; ships; manufacturing machinery; construction equipment; agricultural machinery; and others.</i></p> <p><i>Discuss these products and systems with your colleagues and with your course instructor or facilitator.</i></p> |
|--|--|

Here are some examples of mechanical and structural systems and how they relate to the material you will study in this book.

1. In your home, the floors must be strong and stiff to support the loads due to people, furniture, and appliances [Figure 1–1(a)]. A typical floor is comprised of a series of joists that are supported on walls or beams, a subfloor on top of the joists, and the finished floor. These elements act together to provide a rigid support system. Pitched roofs employ trusses to span long distances between support walls and to provide the support for the roof sheathing and shingles while remaining fairly lightweight and using materials efficiently. Chairs and tables must be designed to support people and other materials safely and stably. Even in the refrigerator, the shelves must be designed to support heavy milk and juice jugs while being lightweight and allowing the free movement of cooled air over the food. In the garage, you might have a stepladder, a garage door opener, a lawn mower, and shovels, all of which carry forces when they are used. What other examples can you find around the home?