THE MODERN ENGINEERING COMPANIONS: A SYSTEMS APPROACH COLLECTION

Christopher H. Jenkins, *Editor*

An Engineering Companion to the Mechanics of Materials

A Systems Approach

Christopher H. Jenkins
Sanjeev K. Khanna

MOMENTUM PRESS
ENGINEERING

An Engineering Companion to the Mechanics of Materials

An Engineering Companion to the Mechanics of Materials

A Systems Approach

Dr. Christopher H. Jenkins
Mechanical & Industrial Engineering Department
Montana State University

Dr. Sanjeev K. Khanna
Mechanical & Aerospace Engineering Department
University of Missouri

MOMENTUM PRESS
ENGINEERING

An Engineering Companion to the Mechanics of Materials: A Systems Approach

First published in 2016
by Momentum Press®, LLC
222 East 46th Street, New York, NY 10017
www.momentumpress.net

ISBN-13: 978-1-606-50661-5 (print)
ISBN-13: 978-1-606-50662-2 (e-book)

Momentum Press The Modern Engineering Companions: A Systems Approach to the Study of Engineering Collection

DOI: 10.5643/9781606506622

Cover and interior design by S4Carlisle Publishing Services Private Ltd., Chennai, India

10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

Dedication

Author Jenkins would like to thank his wife Mo for her support and guidance throughout writing this book. Many thanks also to Joel Stein at Momentum Press for continuing to believe in our projects.

Author Khanna would like to express his gratitude to his wife Vinita for her support and their children for their patience during the writing of this book. He also thanks his past students for their inquisitiveness.

Abstract

An Engineering Companion to Mechanics of Materials is the first volume in the Momentum Press collection *The Modern Engineering Companions: A Systems Approach to the Study of Engineering.* In *Mechanics of Materials*, we apply the intuitive "systems approach" to learning, the advantages of which are several. The student first gets a broad overview of the entire subject rather than the narrow piecemeal vision afforded by the traditional "component approach" common to most engineering texts. *Mechanics of Materials* comes with additional features to improve student learning, including Common Confusing Concepts (C^3) noted and clarified, indication of key concepts, side bar discussions, worked examples, and exercises for developing engineering intuition. The *Companions* are intended as a supplementary resource to help both undergraduate, graduate, and post-graduate students better learn and understand engineering concepts.

Keywords

mechanics of materials, solid mechanics, structures, strength of materials, supplemental learning materials, study guide

CONTENTS

Preface

An Engineering Companion to Mechanics of Materials is the first volume in the Momentum Press collection *The Modern Engineering Companions: A Systems Approach to the Study of Engineering.* Mechanics of materials is a fundamental engineering topic concerned with the response of structures to loads. It is a typical course of study in most engineering curriculums, often taken in the second year along with associated courses in statics and dynamics.

In *Mechanics of Materials*, we apply the intuitive "systems approach" to learning to the study of mechanics of materials. The advantages of the systems approach are several. The student first gets a broad overview of the entire subject rather than the narrow piecemeal vision afforded by the traditional "component approach" common to most engineering texts. Crucial, core topics can be reached early to provide motivation for student learning. Rather than studying a component and then leaving it behind, never to be considered again, the systems approach continually passes through components, reviewing and refreshing, then adding layers of increasing complexity.

Mechanics of Materials comes with additional features to improve student learning, including indication of key concepts, side bar discussions, worked examples, and exercises for developing engineering intuition. It is suitable as a text for a first undergraduate course, or as a companion for the advanced undergraduate, beginning graduate student, and the practicing professional in engineering.

The sole purpose of the *Engineering Companions* collection is to dramatically improve the learning of STEM (science, technology, engineering, and mathematics) topics for students of engineering. The *Companions* are intended as a supplementary resource to help both undergraduate and graduate students better learn and understand engineering concepts. They will also be found useful to the engineering post graduate looking to brush up on a topic long since forgotten. In all cases, it is assumed that *Companion* readers have a textbook, homework assignments, problem solutions, etc., either from a current course or a course previously taken. Unfortunately, what they also have is confusion and limited understanding of one or more crucial concepts in the subject.

Mechanics of Materials is of modest length with the intent of giving the reader an effective and efficient enhancement of important underlying concepts and applications, rather than trying to provide an expansive or comprehensive treatment of the foundational fields. *Mechanics of Materials* is an Engineering Fundamentals volume, which covers basic engineering topics most common among the various disciplines.

Books in this collection will appeal to college instructors as texts in fundamental and advanced topics courses, to students as a learning resource, and to practitioners in the field at all levels. The books will also be appealing to the technically savvy reader who wants a quick, but effective, orientation to collection topics though their background might be in a different technical field.

Navigating the *Mechanics of Materials Companion*

Nearly every mechanics of materials text has the chapters arranged by components (topics) of the subject. After an introductory chapter, there appear chapters on stress and strain, axial structures, torsion structures, beams, combined loading, etc. This is a perfectly reasonable approach for a <u>reference handbook</u>, typically consulted <u>after</u> one has learnt the subject. But it is non-optimal to support primary learning for the reasons already discussed here and the *Engineering Companion Preface*.

This *Companion* approaches achieving the learning objectives by *expanding circles of increasing complexity*. After an introductory chapter on fundamentals (Level 0 or Chapter 1), the next "circle" -- Level 1 (Chapter 2) considers configuration, equilibrium, deformation, and constitution for all three "strength design" structures (rod, shaft, beam). Level 2 adds complexity to what has come before, e.g., introducing the simpler combined flexure-torsion loading. Finally, Level 3 adds still more complexity, such as full tension-torsion-flexure combined loading.

A word about figure numbering is in order. There are four uses of figures in this *Companion*: introduction/motivation (I), representative problems (RP), examples (E), and general text. Thus a figure labeled Figure I1.2 is the second introductory/motivational figure in Chapter 1, Figure E3.4b is the second figure in the fourth worked example in Chapter 3, and so on. A figure label without an I, RP, or E is a figure in the general text.

Other Features

The *Engineering Companions* incorporate many additional features to aid in learning:

- Consistent nomenclature from volume to volume
- Chapter learning objectives and their practical importance
- Sidebars highlighting key concepts
- Common Confusing Concepts (C^3) noted and clarified
- Summary of key concepts
- Worked examples that demonstrate concepts
- Exercises to build engineering intuition

How to Use a *Companion*

The best way to use the *Companion* for your subject is start at the beginning and work your way through to the end. The *Companion* will lead you through the subject in an ever expanding pattern of increasing knowledge and complexity, while not losing the big picture of where you're going. However, should you want, say, as a refresher to follow the traditional path along a component, a traditional Component Index is there to guide you.

The ultimate success of any *Engineering Companion* will be measured by the extent to which confusing concepts are made clear (or at least clearer). That is our mission: to make clear the unclear. We wish the reader the best in their search for clarity.

—Chris Jenkins Bozeman, MT
Sanjeev Khanna Columbia, MO
March 2015

CHAPTER 1

Fundamentals

Learning Objectives: This chapter will provide the student with a systematic introduction to fundamental concepts in the study of mechanics of materials. Along the way, we will clear up several common confusing concepts (C^3s).

Clarifications: Studying this chapter will help clarify several C^3s, including definitions, physical concepts, methods of analysis, and where to go for help.

Importance: The design of structures crosses many disciplines and has a long history. Some of the earliest structures were civil structures, mostly habitats like tents and huts. Simple mechanical structures also were in early use, such as levers, and supports for processing and cooking game. Later, marine structures such as rafts and canoes came into existence. Other structures followed, including carts, construction equipment, and weapons. Roads, aquaducts, and bridges were built. Much later, early aerospace structures, such as balloons and parachutes, appeared.

Today, the fields of aerospace, civil, marine, and mechanical engineering are all involved in structural design. On a cursory level, we can define a *structure* as any physical body that must carry loads (other than its own weight), and hence develops stresses and strains. Often times these stresses and strains are trivial, and the body can be considered a *secondary structure*. However, in many cases, inadequate design for carrying loads can lead to significant, even catastrophic, failure in *primary structures*, those structures that have a primary function to carry loads. Unfortunately, examples of such failure are readily found, including the Tacoma Narrows Bridge disaster, the Kansas City Hyatt

> **C^3**
>
> 1.1 The word “structure” is used differently here than in my chemistry class. Why?
> *(Answer: Section 1.6)*

Regency skywalk collapse, and the space shuttle Challenger explosion. Adequate structural design is critically important!

1.0 Representative Problems

The following is an example problem that exhibits some fundamental concepts from mechanic

RP1.1. Equilibrium

Consider an equilateral truss loaded as shown in Figure RP1.1a. Determine the internal forces in the truss.

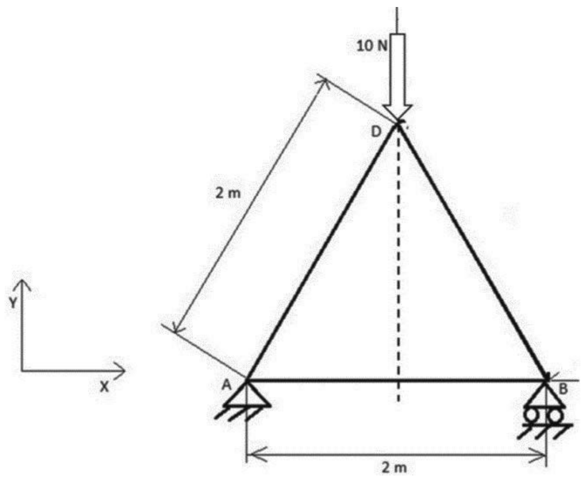

Figure RP1.1.

1.1 Mechanics and materials

> **C³**
>
> 1.2 My mechanics of materials course and text have very little in it about "materials". Does it matter? *(Answer: Section 1.6)*

Applied mechanics and materials science are broad fields of human endeavor with long histories. *Mechanics* deals with the theoretical and experimental analysis of forces on material bodies, and the resultant motions and deformations that follow. *Materials science* is concerned with the atomistic structure of material and the properties resulting therefrom. For our purposes here, a working, albeit over-simplified, definition is taken to be: mechanics is *physics*, materials science is *chemistry*.

Today, examples abound which show the need for engineers and scientists who have an integrated, interdisciplinary background that bridges mechanics and materials science. Consider, for example, the important and active area of high-performance composite materials.

Here, an intimate knowledge of structure-property relations is demanded for technological advancement. Bulk response can be predicted in an averaged sense using a mechanics approach, which is necessary to design a real composite structure; but only knowledge of the fine-scale (micro- to nano-scale) structure-property relations and interactions among the constituents can lead to an optimal "engineering" of these materials for an intended application.

Other topics of current interest include: computational modeling of materials with evolving microstructures; advanced manufacturing and processing challenges to mechanics and materials; mechanics and statistical physics of particulate materials; mechanics and materials science of contact; and processing and mechanics of nanoscale, multilayered materials. We will show in what follows that *every* structural design should be an integration of mechanics and materials technology.

1.2 Loads and Structures

1.2.1 Structural Loads

In structural design, we use the term "loads" to mean forces and moments applied to the structure, either externally on the surface (*surface loads*), or developed within the structure (*body loads*). (Recall that moments are forces acting through a "moment arm" so as to produce torsion or flexure.)

Loads are further considered to be either static or dynamic. Static loads are loads that do not depend on time, i.e., they are of constant magnitude, direction, and location. Although it might seem that certain structures are static, for example, on a civil structure such as a building, this is rarely the case. "Live loads" from occupant activity, wind loads, seismic (earthquake) loads, thermal cycling, etc., all may give rise to a dynamic load environment. However, if the loads vary slowly with time, they are often considered *quasi-static*, and taken as static loads. (*Slowly* usually means that structure inertia force due to accelerations may be neglected with respect to the difference of the externally applied forces and the internal resistance forces.)

Dynamic loads are divided into two main categories:

1. *Steady-state* loads are loads that maintain the same character (frequency, amplitude, etc.) over the long-term.
2. *Transient* loads are loads that change their character (for example, they may *decay*) with time.

Common structural loads are summarized in Table 1.1.

Table 1.1. Summary of common structural loads.

Surface Loads (Common name)	Units SI (US)	Body Loads	Units SI (US)
Concentrated force ("Point load")	N (lb)	Gravitational force ("Gravity load" or "weight")	N (lb)
Distributed force ("Line load") ("Pressure")	N/m (lb/in) N/m^2 (psi)	Thermal stress ("Thermal load")	N/m^2 (psi)
Moment or couple ("Bending moment" "Torsion moment")	N-m (lb-in)		

The *orientation* of the load on a structural member is also important. Although this issue will be discussed in more detail in latter chapters, a brief summary is given in Figure 1.1.

C^3

1.3 Can a "line" load or a "point" load really exist?
(Answer: Section 1.6)

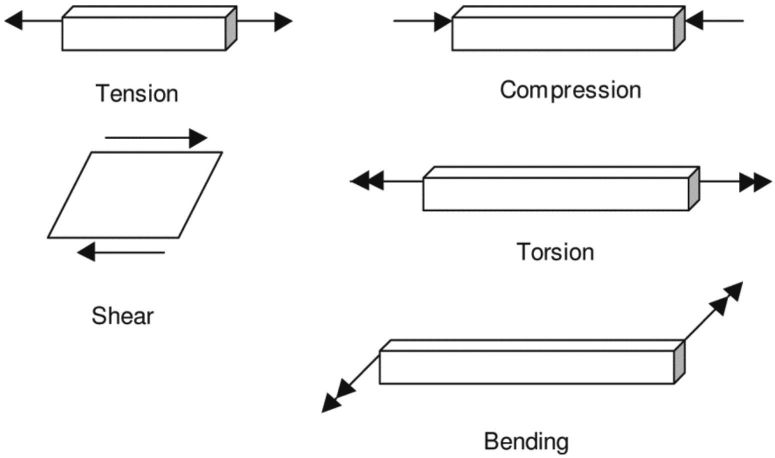

Figure 1.1. Simple load orientations. Single headed arrows are forces, double headed arrows are moments (and follow the right hand rule).

1.2.2 A Taxonomy of Structures

Humans have always tried to understand complex systems by "decomposing" them into a number of simpler, more manageable parts. The hope is that when this compartmentalized knowledge is "summed up" (*synthesized*), an accurate representation of the whole system results. While this approach has worked well in countless human enterprises, it is based on the *linear* assumption of *superposition*, which fails as systems become *nonlinear* and more complex.

Forewarned by this knowledge, we will attempt here a *taxonomy* (classification) of structures (complex systems) by decomposing them into their structural elements (simpler parts). Most real structures are comprised of a number of different types of structural elements, any one of which may assume a variety of different roles. The primary characteristic used to classify a structural element is: <u>how does it carry loads?</u>

Carrying loads is the primary *function* of a structure, and it is this characteristic that largely determines the *form* of the structural elements. Loads carried include: tensile and compressive axial loads; shear loads; torsion moment loads; bending moment loads; distributed loads; gravity loads; and thermal loads.