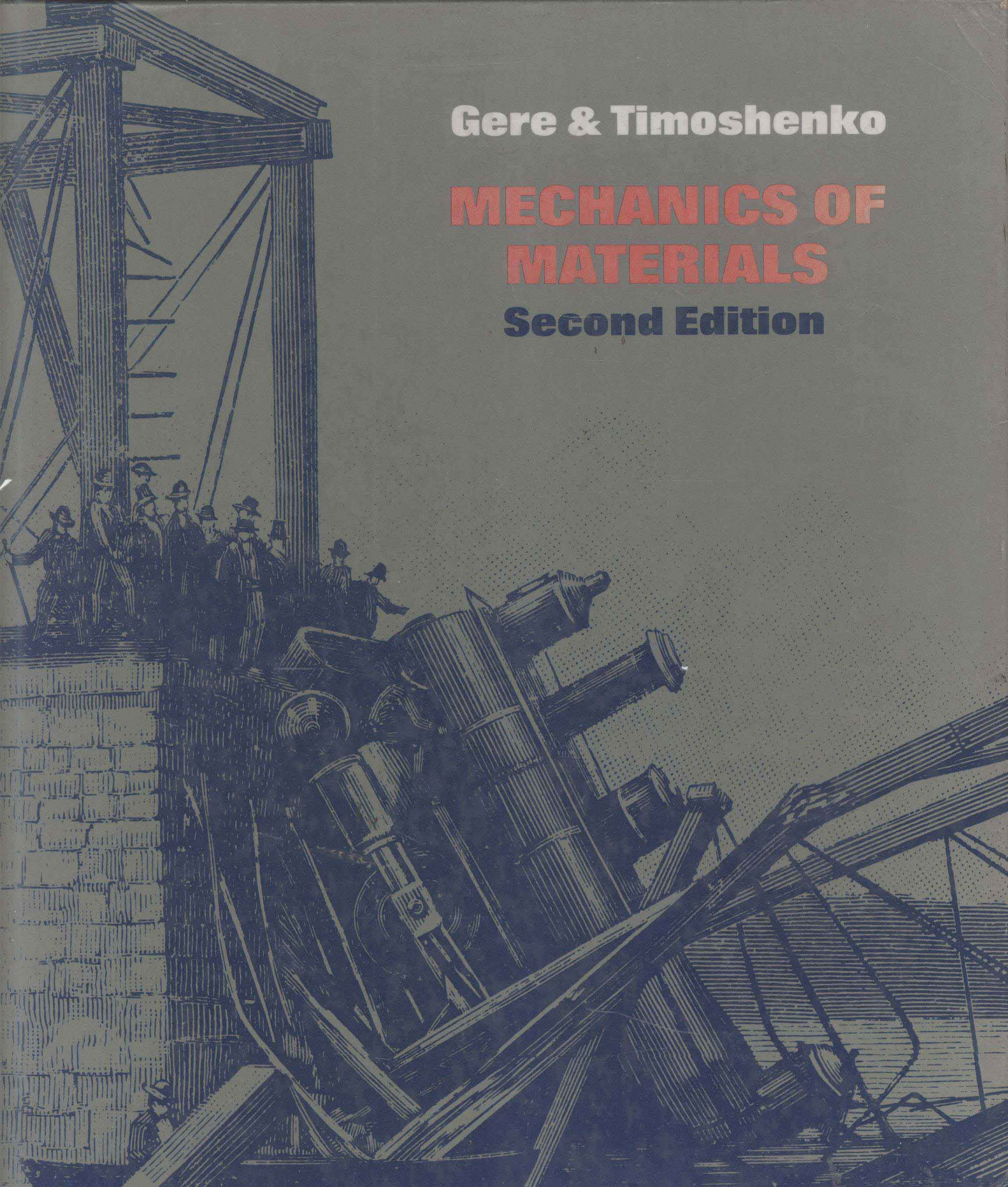
Gere & Timoshenko

MECHANICS OF MATERIALS

Second Edition



Mechanics of Materials

SECOND EDITION

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Brooks/Cole Engineering Division Monterey, California

Brooks/Cole Engineering Division
A Division of Wadsworth, Inc.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Library of Congress Cataloging in Publication Data

Timoshenko, Stephen, 1878–1972.
Mechanics of materials.

Author's names in reverse order on original ed.
Bibliography: p.
Includes indexes.
1. Strength of materials. I. Gere, James M.
II. Title.
TA405.T493 1984 620.1'1 83-24308
ISBN 0-534-03099-8

Sponsoring Editor: Ray Kingman
Production Services Coordinator: Bill Murdock
Production: Mary Forkner, Publication Alternatives
Manuscript Editor: Patricia Cain
Cover Design: Jamie Sue Brooks
Art Direction: Pat Rogondino
Artists: Mary Burkhardt, Carol Johnston, Georg Klatt, Judith McCarty, Pat Rogondino
Typesetting: Syntax International
Printing and Binding: R. R. Donnelley & Sons

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Preface

A course in mechanics of materials provides an opportunity to accomplish two things: first, to teach students a basic engineering subject and, second, to develop their analytical and problem-solving abilities. While preparing this extensive revision, I have kept both of these goals in mind. The facts, theories, and methodologies are presented in a teachable and easy-to-learn manner, with ample discussions and numerous illustrative examples, so that undergraduate students can readily master the subject matter. At the same time, emphasis is placed on fundamental concepts and on how to analyze mechanical and structural systems. Many examples and problems require that students do some original thinking.

This book covers all the standard topics of mechanics of materials and presents them at a level suitable for sophomore and junior engineering students. In addition, much material of a more advanced and specialized nature is included. Thus, this book can serve both as a text and as a permanent reference.

A glance at the table of contents shows the topics covered and the way in which they are organized. The topics include the analysis and design of structural members subjected to axial loads, torsion, and bending, as well as such fundamental concepts as stress, strain, elastic and inelastic behavior, and strain energy. Other topics of general interest are the transformations of stress and strain, deflections of beams, behavior of columns, and energy methods. More specialized topics are thermal and prestrain effects, pressure vessels, nonprismatic members, unsymmetric bending, shear center, inelastic bending, and discontinuity functions.

Much more material than can be covered in a single course is included in the book, hence teachers have the opportunity to select the topics that they feel are the most fundamental and relevant. Teachers will also appreciate the hundreds of new problems (over 1,000 problems total) that are available for homework assignments and classroom discussions.

Both the International System of Units (SI) and the U.S. Customary System (USCS) are used in the numerical examples and problems. Discussions of both systems and a table of conversion factors are given in the appendix.

References and historical notes are collected at the back of the book. They include the original sources of the subject matter and biographical notes about the pioneering engineers, scientists, and mathematicians who created the subject.

This book is new in the sense that it is a completely new presentation of mechanics of materials; yet in another sense it is old because it evolved from earlier books of Professor Stephen P. Timoshenko (1878–1972). Timoshenko's first book on mechanics of materials was published in Russia in 1908. His first American book on the subject was published in two volumes in 1930 by D. Van Nostrand Company under the title *Strength of Materials;* second editions were published in 1940 and 1941 and third editions in 1955 and 1956. The first edition of *Mechanics of Materials,* written by the present author but drawing upon the earlier books, was published in 1972.

This second edition has been completely rewritten with expanded and easier-to-read discussions, many more examples and problems, and several new topics (including pressure vessels, discontinuity functions, and inelastic buckling). Every effort has been made to eliminate errors, but no doubt some are inevitable. If you find any, please jot them down and mail them to the author (Department of Civil Engineering, Stanford University, Stanford, CA 94305); then we can correct them immediately in the next printing of the book.

To acknowledge everyone who contributed to this book in some manner is clearly impossible, but a major debt is owed my former Stanford teachers (those giants of mechanics, including Timoshenko himself, Wilhelm Flügge, James Norman Goodier, Miklós Hetényi, Nicholas J. Hoff, and Donovan H. Young) from whom I learned so much and my current Stanford colleagues (especially Ed Kavazanjian, Tom Kane, Anne Kiremidjian, Helmut Krawinkler, Jean Mayers, Cedric Richards, Haresh Shah, and Bill Weaver) who made suggestions for the book and provided cooperation during its writing. Several reviewers and friends (including Jim Harp, Ian Johnston, Hugh Keedy, and Aron Zaslavsky) provided valuable comments, and conscientious graduate students (Thalia Anagnos, João Azevedo, Fouad Bendimerad, and Hassan Hadidi-Tamjed) checked the proofs. The manuscript was carefully typed by Susan Gere Durham, Janice Gere, Lu Ann Hall, and Laurie Yadon. Editing and production were handled with great skill and a cooperative spirit by Ray Kingman of Brooks/Cole and Mary Forkner of Publication Alternatives, Palo Alto. My wife, Janice, offered encouragement and exercised patience throughout this project. So also did other family members—Susan and DeWitt Durham, Bill Gere, and David Gere. To all of these wonderful people I am pleased to express my gratitude.

James M. Gere

List of Symbols

A	area, action (force or couple), constant
a, b, c	dimensions, distances, constants
C	centroid, constant of integration, compressive force
c	distance from neutral axis to outer surface of a beam
D	displacement (translation or rotation)
d	diameter, dimension, distance
E	modulus of elasticity, elliptic integral of the second kind
E_r	reduced modulus of elasticity
E_t	tangent modulus of elasticity
e	eccentricity, dimension, distance, unit volume change (dilatation, volumetric strain)
F	force, discontinuity function, elliptic integral of the first kind, flexibility
f	shear flow, shape factor for plastic bending, flexibility, frequency (Hz)
f_s	form factor for shear
G	modulus of elasticity in shear
g	acceleration of gravity
H	distance, force, reaction, horsepower
h	height, dimension
I	moment of inertia (or second moment) of a plane area
I_x, I_y, I_z	moments of inertia with respect to x, y, and z axes
I_{xy}	product of inertia with respect to the x and y axes
I_p	polar moment of inertia
I_1, I_2	principal moments of inertia
J	torsion constant
K	bulk modulus of elasticity, effective length factor for a column
k	spring constant, stiffness, symbol for $\sqrt{P/EI}$
L	length, distance, span length
L_e	effective length of a column
M	bending moment, couple, mass
M_p	plastic moment for a beam
M_y	yield moment for a beam
m	moment per unit length, mass per unit length

N	axial force
n	factor of safety, number, ratio, integer, revolutions per minute (rpm)
O	origin of coordinates
O'	center of curvature
P	force, concentrated load, axial force, power
P_{allow}	allowable load (or working load)
P_{cr}	critical load for a column
P_r	reduced-modulus load for a column
P_t	tangent-modulus load for a column
P_u	ultimate load
P_y	yield load
p	pressure
Q	force, concentrated load, first moment (or static moment) of a plane area
q	intensity of distributed load (load per unit distance), intensity of distributed torque (torque per unit distance)
q_u	ultimate load intensity
q_y	yield load intensity
R	reaction, radius, force
r	radius, distance, radius of gyration ($r = \sqrt{I/A}$)
S	section modulus of the cross section of a beam, shear center, stiffness, force
s	distance, length along a curved line
T	twisting couple or torque, temperature, tensile force
T_u	ultimate torque
T_y	yield torque
t	thickness, time
U	strain energy
u	strain energy density (strain energy per unit volume)
u_r	modulus of resilience
u_t	modulus of toughness
$U^\star$	complementary energy
$u^\star$	complementary energy density (complementary energy per unit volume)
V	shear force, volume
v	deflection of a beam, velocity
v', v'', etc.	dv/dx, d^2v/dx^2, etc.
W	weight, work
$W^\star$	complementary work
X	statical redundant
x, y, z	rectangular coordinates, distances
$\bar{x}$, $\bar{y}$, $\bar{z}$	coordinates of centroid
Z	plastic modulus of the cross section of a beam

α	angle, coefficient of thermal expansion, nondimensional ratio, spring constant, stiffness
α_s	shear coefficient
β	angle, nondimensional ratio, spring constant, stiffness
γ	shear strain, specific weight (weight per unit volume)
$\gamma_{xy}, \gamma_{yz}, \gamma_{zx}$	shear strains in the xy, yz, and zx planes
γ_θ	shear strain for inclined axes
$\gamma_{x_1y_1}$	shear strain in the x_1y_1 plane
δ, Δ	deflection, displacement, elongation
ϵ	normal strain
$\epsilon_x, \epsilon_y, \epsilon_z$	normal strains in the x, y, and z directions
ϵ_θ	normal strain for inclined axes
$\epsilon_{x_1}, \epsilon_{y_1}$	normal strains in the x_1 and y_1 directions
$\epsilon_1, \epsilon_2, \epsilon_3$	principal normal strains
ϵ_y	yield strain
θ	angle, angle of twist per unit length, angle of rotation of beam axis
θ_p	angle to a principal plane or to a principal axis
θ_s	angle to a plane of maximum shear stress
κ	curvature ($\kappa = 1/\rho$)
κ_y	yield curvature
λ	distance
ρ	radius, radius of curvature, radial distance in polar coordinates, mass density (mass per unit volume, specific mass)
ν	Poisson's ratio
σ	normal stress
$\sigma_x, \sigma_y, \sigma_z$	normal stresses on planes perpendicular to the x, y, and z axes
σ_θ	normal stress on inclined plane
$\sigma_{x_1}, \sigma_{y_1}$	normal stresses on planes perpendicular to the rotated x_1y_1 axes
$\sigma_1, \sigma_2, \sigma_3$	principal stresses
σ_{allow}	allowable stress (or working stress)
σ_{cr}	critical stress for a column ($\sigma_{cr} = P_{cr}/A$)
σ_{pl}	proportional limit stress
σ_r	residual stress
σ_u	ultimate stress
σ_y	yield stress
τ	shear stress
$\tau_{xy}, \tau_{yz}, \tau_{zx}$	shear stresses on planes perpendicular to the x, y, and z axes and parallel to the y, z, and x axes
τ_θ	shear stress on inclined plane
$\tau_{x_1y_1}$	shear stress on plane perpendicular to the rotated x_1 axis and parallel to the y_1 axis

τ_{allow}	allowable stress (or working stress) in shear
τ_u	ultimate stress in shear
τ_y	yield stress in shear
ϕ	angle, angle of twist
ψ	nondimensional ratio
ω	angular velocity, angular frequency ($\omega = 2\pi f$)

*An asterisk denotes a difficult or advanced section, example, or problem.

Greek Alphabet

Α	α	Alpha	Ν	ν	Nu
Β	β	Beta	Ξ	ξ	Xi
Γ	γ	Gamma	Ο	o	Omicron
Δ	δ	Delta	Π	π	Pi
Ε	ϵ	Epsilon	Ρ	ρ	Rho
Ζ	ζ	Zeta	Σ	σ	Sigma
Η	η	Eta	Τ	τ	Tau
Θ	θ	Theta	Υ	υ	Upsilon
Ι	ι	Iota	Φ	ϕ	Phi
Κ	κ	Kappa	Χ	χ	Chi
Λ	λ	Lambda	Ψ	ψ	Psi
Μ	μ	Mu	Ω	ω	Omega

Contents

CHAPTER 3

Torsion

CHAPTER 4

Shear Force and Bending Moment

CHAPTER 5

Stresses in Beams

*An asterisk denotes a difficult or advanced section, example, or problem.

CHAPTER 8

Statically Indeterminate Beams 429

CHAPTER 9

Unsymmetric Bending 469

CHAPTER 10

Inelastic Bending 515

CHAPTER 11

Columns 551

CHAPTER 12

Energy Methods 597

CHAPTER 1

Tension, Compression, and Shear

1.1 INTRODUCTION

Mechanics of materials is a branch of applied mechanics that deals with the behavior of solid bodies subjected to various types of loading. This field of study is known by several names, including "strength of materials" and "mechanics of deformable bodies." The solid bodies considered in this book include axially loaded members, shafts in torsion, thin shells, beams, and columns, as well as structures that are assemblies of these components. Usually the objectives of our analysis will be the determination of the stresses, strains, and deflections produced by the loads. If these quantities can be found for all values of load up to the failure load, then we will have a complete picture of the mechanical behavior of the body.

A thorough understanding of mechanical behavior is essential for the safe design of all structures, whether buildings and bridges, machines and motors, submarines and ships, or airplanes and antennas. Hence, mechanics of materials is a basic subject in many engineering fields. Of course, statics and dynamics are also essential, but they deal primarily with the forces and motions associated with particles and rigid bodies. In mechanics of materials, we go one step further by examining the stresses and strains that occur inside real bodies that deform under loads. We use the physical properties of the materials (obtained from experiments) as well as numerous theoretical laws and concepts, which are explained in succeeding sections of this book.

Theoretical analyses and experimental results have equally important roles in the study of mechanics of materials. On many occasions, we will make logical derivations to obtain formulas and equations for predicting mechanical behavior, but we must recognize that these formulas cannot be used in a realistic way unless certain properties of the materials are known. These properties are available to us only after suitable