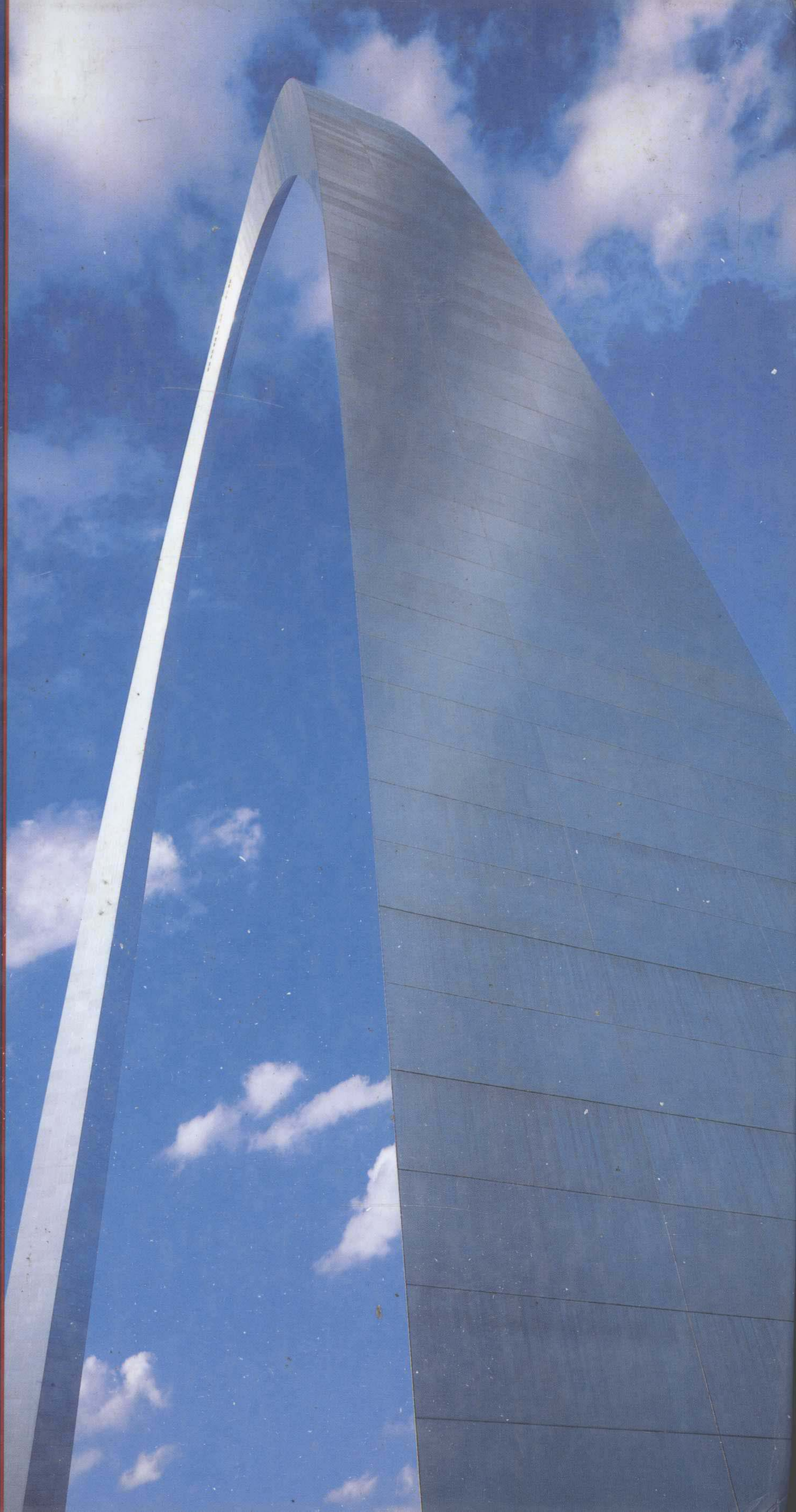
James M. Gere

Mechanics of Materials

FIFTH EDITION



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Preface

Mechanics of materials is a basic engineering subject that must be understood by anyone concerned with the strength and physical performance of structures, whether those structures are man-made or natural. The subject matter includes such fundamental concepts as stresses and strains, deformations and displacements, elasticity and inelasticity, strain energy, and load-carrying capacity. These are the concepts that underlie the design and analysis of a huge variety of mechanical and structural systems.

At the college level, mechanics of materials is usually taught during the sophomore and junior years. It is a required subject for most students majoring in mechanical, structural, civil, aeronautical, and aerospace engineering. Furthermore, many students from such diverse fields as materials science, industrial engineering, architecture, and agricultural engineering also find it worthwhile to study this subject.

About this Book

The main topics covered in this book are the analysis and design of structural members subjected to tension, compression, torsion, and bending, including the fundamental concepts mentioned in the first paragraph. Other topics of general interest are the transformations of stress and strain, combined loadings, stress concentrations, deflections of beams, and stability of columns.

Specialized topics include thermal effects, dynamic loading, nonprismatic members, beams of two materials, shear centers, pressure vessels, and statically indeterminate beams. For completeness and occasional reference, elementary topics such as shear forces, bending moments, centroids, and moments of inertia also are presented.

Much more material than can be taught in a single course is included in this text and, therefore, instructors have the opportunity to select the topics they wish to cover. As a guide, some of the more specialized topics are identified by asterisks.

This Fifth Edition of *Mechanics of Materials* has been thoroughly edited to make it even more readable than before. Problems have been revised and improved, and all of the figures have been carefully redrawn for increased clarity and accuracy. As instructors of mechanics know, the figures in a book of this kind have an essential role in making the subject matter understandable.

Considerable effort has been spent in checking and proofreading the text so as to eliminate errors, but if you happen to find one, no matter how minor, please notify me by e-mail (jgere@ce.Stanford.edu) or write to me in care of the publisher. (All correspondence will be answered.)

Examples

Numerous examples are presented in order to illustrate the theoretical concepts and show how those concepts may be used in practical situations. The examples vary in length from one to four pages, depending upon the complexity of the material to be illustrated. When the emphasis is on concepts, the examples are worked out in symbolic terms so as to better illustrate the ideas, and when the emphasis is on problem-solving, the examples are numerical in character.

Problems

In any mechanics course, solving problems is an important part of the learning process. This text offers more than 1,000 problems for homework assignments and classroom discussions. The problems are placed at the end of each chapter so that they are easy to find and don't break up the presentation of the subject matter. Also, an unusually difficult or lengthy problem is indicated by attaching one or more stars (depending upon the degree of difficulty) to the problem number, thus alerting students to the time necessary for solution. Answers to all problems are listed near the back of the book.

Units

Both the International System of Units (SI) and the U.S. Customary System (USCS) are used in the examples and problems. Discussions of both systems and a table of conversion factors are given in Appendix A. For problems involving numerical solutions, odd-numbered problems are in USCS units and even-numbered problems are in SI units. This convention makes it easy to know in advance which system of units is being used in any particular problem. (The only exceptions are problems involving the tabulated properties of structural-steel shapes, because the tables for these shapes are presented only in USCS units.)

References and Historical Notes

References and historical notes appear immediately after the last chapter in the book. They consist of original sources for the subject matter plus biographical notes about the pioneering scientists, engineers, and mathematicians who created the subject of mechanics of materials. A separate name index makes it easy to look up any of these historical figures.

S. P. Timoshenko (1878–1972)

Many readers of this book will recognize the name of Stephen P. Timoshenko—probably the most famous name in the field of mechanics. Timoshenko appeared as co-author on earlier editions of this book because the book began at his instigation. The first edition, published in 1972, was written by the present author at the suggestion of Professor Timoshenko. Although Timoshenko did not participate in the actual writing, he provided much of the book's contents because the first edition was based heavily upon his two earlier books titled *Strength of Materials*. The second edition, a major revision of the first, was published many years later (in 1984), and each subsequent edition (in 1990 and 1997) has incorporated many new changes and improvements.

Timoshenko is generally recognized as the most outstanding pioneer in applied mechanics. He contributed many new ideas and concepts and became famous for both his scholarship and his teaching. As a teacher and lecturer, he was well-known for his ability to bring the subject matter of his classes to life. He wrote 13 major textbooks on both elementary and advanced subjects in mechanics, and these books have gone through many editions and been translated into a dozen languages. Through these books he made a profound change in the teaching of mechanics not only in this country but wherever mechanics is taught. His methodology was to start from a scientific and mathematical base and then develop the subject in a logical and step-by-step manner. Consequently, he raised the level of instruction and broadened our understanding of applied mechanics. (You can find a brief biography of Timoshenko in the first reference at the back of the book.)

Acknowledgments

To acknowledge everyone who contributed to this book in some manner is clearly impossible, but I owe a major debt to my former Stanford teachers, including (besides Timoshenko) those other pioneers in mechanics, Wilhelm Flügge, James Norman Goodier, Miklós Hetényi, Nicholas J. Hoff, and Donovan H. Young. I am also indebted to my Stanford colleagues—especially Tom Kane, Anne Kiremidjian, Helmut Krawinkler, Kincho Law, Peter Pinsky, Haresh Shah, Sheri Sheppard, and the late Bill Weaver. They provided me with many hours of discussions about mechanics and educational philosophy. My thanks also to Wayne Hamilton of the University of Maine for his valuable insights concerning Mechanics of Materials and its presentation.

The following reviewers provided both general and specific comments for changes and improvements in the book: Fred K. Bogner, University of Dayton; George R. Buchanan, Tennessee Technological

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I was assisted in manuscript preparation and proofreading by Duc Wong, who worked with great care and accuracy. Many others helped with proofreading and the preparation of solutions for the problems. They include Mark Audigier, Kymberly Eliot, Mary Godfrey-Dickson, Racquel Hagen, Jerome Lynch, Gabriela Medina, Ricardo Medina, and Nuthaporn Nuttyasakul.

The editing and production aspects of the book were a source of great pleasure and satisfaction to me, because everyone I dealt with on the staff of the Brooks/Cole Publishing Company was extremely talented and knowledgeable. Furthermore, their goal was the same as mine—to produce the best possible book without stinting at any step of the way. The people with whom I had personal contact are Bill Stenquist, Publisher, who set the tone for excellence and provided both leadership and inspiration; Suzanne Jeans, Editor, who launched the book; Jamie Sue Brooks, Editorial Production Supervisor, who made sure that every phase of the work was handled to perfection; Jennifer Mackres, Art Editor, who handled the artwork with great skill; Vernon Boes, Art Director, who created the attractive design of the covers; Ellen Brownstein, Editorial Production Manager, who skillfully handled all phases of the work during the early stages; Shelley Gesicki, Editorial Coordinator, who monitored progress and kept us organized; and Rose Kernan of RPK Editorial Services, who supervised with great skill every aspect of the physical production of the book. To each of these individuals I express my heartfelt thanks not only for a job well done but also for the friendly and considerate way in which it was done.

Many other people who I did not meet personally also participated in the development of this book—for instance, the talented artists at Rolin Graphics, who prepared the figures and tolerated my nitpicking over details; and the typesetters at Better Graphics, who meticulously laid out every page of text. To each of these individuals, I also extend my sincere thanks for a job well done.

Finally, I appreciate the patience and encouragement provided by my family, especially my wife, Janice, throughout this project.

To all of these wonderful people, I am pleased to express my gratitude.

James M. Gere

Symbols

A	area
A_f, A_w	area of flange; area of web
a, b, c	dimensions, distances
C	centroid, compressive force, constant of integration
c	distance from neutral axis to outer surface of a beam
D	diameter
d	diameter, dimension, distance
E	modulus of elasticity
E_r, E_t	reduced modulus of elasticity; tangent modulus of elasticity
e	eccentricity, dimension, distance, unit volume change (dilatation)
F	force
f	shear flow, shape factor for plastic bending, flexibility, frequency (Hz)
f_T	torsional flexibility of a bar
G	modulus of elasticity in shear
g	acceleration of gravity
H	height, distance, horizontal force or 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_{x_1}, I_{y_1}	moments of inertia with respect to x_1 and y_1 axes (rotated axes)
I_{xy}	product of inertia with respect to xy axes
$I_{x_1y_1}$	product of inertia with respect to x_1y_1 axes (rotated axes)
I_P	polar moment of inertia
I_1, I_2	principal moments of inertia
J	torsion constant
K	stress-concentration factor, bulk modulus of elasticity, effective length factor for a column
k	spring constant, stiffness, symbol for $\sqrt{P/EI}$
k_T	torsional stiffness of a bar
L	length, distance

L_E	effective length of a column
ln, log	natural logarithm (base e); common logarithm (base 10)
M	bending moment, couple, mass
M_P, M_Y	plastic moment for a beam; yield moment for a beam
m	moment per unit length, mass per unit length
N	axial force
n	factor of safety, integer, revolutions per minute (rpm)
O	origin of coordinates
O'	center of curvature
P	force, concentrated load, power
P_{allow}	allowable load (or working load)
P_{cr}	critical load for a column
P_P	plastic load for a structure
P_r, P_t	reduced-modulus load and tangent-modulus load for a column
P_Y	yield load for a structure
p	pressure (force per unit area)
Q	force, concentrated load, first moment of a plane area
q	intensity of distributed load (force per unit distance)
R	reaction, radius
r	radius, radius of gyration ($r = \sqrt{I/A}$)
S	section modulus of the cross section of a beam, shear center
s	distance, distance along a curve
T	tensile force, twisting couple or torque, temperature
T_P, T_Y	plastic torque; yield torque
t	thickness, time, intensity of torque (torque per unit distance)
t_f, t_w	thickness of flange; thickness of web
U	strain energy
u	strain-energy density (strain energy per unit volume)
u_r, u_t	modulus of resistance; modulus of toughness
V	shear force, volume, vertical force or reaction
v	deflection of a beam, velocity
v', v'', etc.	dv/dx, d^2v/dx^2, etc.
W	force, weight, work
w	load per unit of area (force per unit area)
x, y, z	rectangular axes (origin at point O)
x_c, y_c, z_c	rectangular axes (origin at centroid C)
$\bar{x}$, $\bar{y}$, $\bar{z}$	coordinates of centroid
Z	plastic modulus of the cross section of a beam

α	angle, coefficient of thermal expansion, nondimensional ratio
β	angle, nondimensional ratio, spring constant, stiffness
β_R	rotational stiffness of a spring
γ	shear strain, weight density (weight per unit volume)
$\gamma_{xy}, \gamma_{yz}, \gamma_{zx}$	shear strains in xy, yz, and zx planes
$\gamma_{x_1y_1}$	shear strain with respect to x_1y_1 axes (rotated axes)
γ_θ	shear strain for inclined axes
δ	deflection of a beam, displacement, elongation of a bar or spring
ΔT	temperature differential
δ_P, δ_Y	plastic displacement; yield displacement
ϵ	normal strain
$\epsilon_x, \epsilon_y, \epsilon_z$	normal strains in x, y, and z directions
$\epsilon_{x_1}, \epsilon_{y_1}$	normal strains in x_1 and y_1 directions (rotated axes)
ϵ_θ	normal strain for inclined axes
$\epsilon_1, \epsilon_2, \epsilon_3$	principal normal strains
ϵ'	lateral strain in uniaxial stress
ϵ_T	thermal strain
ϵ_Y	yield strain
θ	angle, angle of rotation of beam axis, rate of twist of a bar in torsion (angle of twist per unit length)
θ_p	angle to a principal plane or to a principal axis
θ_s	angle to a plane of maximum shear stress
κ	curvature ($\kappa = 1/\rho$)
λ	distance, curvature shortening
ν	Poisson's ratio
ρ	radius, radius of curvature ($\rho = 1/\kappa$), radial distance in polar coordinates, mass density (mass per unit volume)
σ	normal stress
$\sigma_x, \sigma_y, \sigma_z$	normal stresses on planes perpendicular to x, y, and z axes
$\sigma_{x_1}, \sigma_{y_1}$	normal stresses on planes perpendicular to x_1y_1 axes (rotated axes)
σ_θ	normal stress on an inclined plane
$\sigma_1, \sigma_2, \sigma_3$	principal normal 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_T	thermal stress
σ_U, σ_Y	ultimate stress; yield stress

τ	shear stress
τ_{xy}, τ_{yz}, τ_{zx}	shear stresses on planes perpendicular to the x, y, and z axes and acting parallel to the y, z, and x axes
$\tau_{x_1y_1}$	shear stress on a plane perpendicular to the x_1 axis and acting parallel to the y_1 axis (rotated axes)
τ_θ	shear stress on an inclined plane
τ_{allow}	allowable stress (or working stress) in shear
τ_U, τ_Y	ultimate stress in shear; yield stress in shear
ϕ	angle, angle of twist of a bar in torsion
ψ	angle, angle of rotation
ω	angular velocity, angular frequency ($\omega = 2\pi f$)

★A star attached to a section number indicates a specialized or advanced topic. One or more stars attached to a problem number indicate the level of difficulty in the solution.

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

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★Stars denote specialized and advanced topics.

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1

Tension, Compression, and Shear

1.1 INTRODUCTION TO MECHANICS OF MATERIALS

Mechanics of materials is a branch of applied mechanics that deals with the behavior of solid bodies subjected to various types of loading. Other names for this field of study are *strength of materials* and *mechanics of deformable bodies*. The solid bodies considered in this book include bars with axial loads, shafts in torsion, beams in bending, and columns in compression.

The principal objective of mechanics of materials is to determine the stresses, strains, and displacements in structures and their components due to the loads acting on them. If we can find these quantities for all values of the loads up to the loads that cause failure, we will have a complete picture of the mechanical behavior of these structures.

An understanding of mechanical behavior is essential for the safe design of all types of structures, whether airplanes and antennas, buildings and bridges, machines and motors, or ships and spacecraft. That is why mechanics of materials is a basic subject in so many engineering fields. Statics and dynamics are also essential, but those subjects 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 inside real bodies, that is, bodies of finite dimensions that deform under loads. To determine the stresses and strains, we use the physical properties of the materials as well as numerous theoretical laws and concepts.

Theoretical analyses and experimental results have equally important roles in mechanics of materials. We use theories to derive formulas and equations for predicting mechanical behavior, but these expressions cannot be used in practical design unless the physical properties of the materials are known. Such properties are available only after careful experiments have been carried out in the laboratory. Furthermore, not all practical problems are amenable to theoretical analysis alone, and in such cases physical testing is a necessity.

The historical development of mechanics of materials is a fascinating blend of both theory and experiment—theory has pointed the way to useful results in some instances, and experiment has done so in others. Such famous persons as Leonardo da Vinci (1452–1519) and Galileo Galilei (1564–1642) performed experiments to determine the strength of wires, bars, and beams, although they did not develop adequate theories (by today's standards) to explain their test results. By contrast, the famous mathematician Leonhard Euler (1707–1783) developed the mathematical theory of columns and calculated the critical load of a column in 1744, long before any experimental evidence existed to show the significance of his results. Without appropriate tests to back up his theories, Euler's results remained unused for over a hundred years, although today they are the basis for the design and analysis of most columns.*

Problems

When studying mechanics of materials, you will find that your efforts are divided naturally into two parts: first, understanding the logical development of the concepts, and second, applying those concepts to practical situations. The former is accomplished by studying the derivations, discussions, and examples that appear in each chapter, and the latter is accomplished by solving the problems at the ends of the chapters. Some of the problems are numerical in character, and others are symbolic (or algebraic).

An advantage of *numerical problems* is that the magnitudes of all quantities are evident at every stage of the calculations, thus providing an opportunity to judge whether the values are reasonable or not. The principal advantage of *symbolic problems* is that they lead to general-purpose formulas. A formula displays the variables that affect the final results; for instance, a quantity may actually cancel out of the solution, a fact that would not be evident from a numerical solution. Also, an algebraic solution shows the manner in which each variable affects the results, as when one variable appears in the numerator and another appears in the denominator. Furthermore, a symbolic solution provides the opportunity to check the dimensions at every stage of the

*The history of mechanics of materials, beginning with Leonardo and Galileo, is given in Refs. 1-1, 1-2, and 1-3.