MECHANICAL ENGINEERING DESIGN

THIRD EDITION

SI VERSION

ANSEL C. UGURAL

CRC Press
Taylor & Francis Group

Mechanical Engineering Design

Third Edition

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

Cover image: Continuous Variable Transmission (or CVR)/Shutterstock

SI Version of third edition published 2022
by CRC Press
6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742

and by CRC Press
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

First edition published by McGraw-Hill 2004
Second edition published by CRC Press 2015
Third edition published by CRC Press 2021

CRC Press is an imprint of Taylor & Francis Group, LLC

ISBN: 978-1-032-17004-6 (hbk)
ISBN: 978-1-032-17006-0 (pbk)
ISBN: 978-1-003-25137-8 (ebk)

DOI: 10.1201/9781003251378-2

Typeset in Times
by codeMantra

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Preface

INTRODUCTION

This book was developed from classroom notes prepared in connection with junior–senior undergraduate courses in mechanical design, machine design, mechanical engineering design, and engineering design and analysis. The scope of this book is wider than any other book on the subject. In addition to its applicability to *mechanical engineering*, and to some extent, aerospace, agricultural, and nuclear engineering, and applied engineering mechanics curricula, I have endeavored to make this book useful to *practicing engineers* as well. This book offers a simple, comprehensive, and methodical presentation of the fundamental concepts and principles in the design and analysis of machine components and basic structural members. This coverage presumes knowledge of the mechanics of materials and material properties. However, topics that are particularly significant to understanding the subject are reviewed as they are taken up. Special effort has been made to present a book that is as self-explanatory as possible, thereby reducing the work of the instructor.

The presentation of the material in this book strikes a balance between the theory necessary to gain insight into mechanics and the design methods. I, therefore, attempt to stress those aspects of theory and application that prepare a student for more advanced study or professional practice in design. Above all, I have made an effort to provide a visual interpretation of equations and present the material in a form useful to a diverse audience. The analysis presented should facilitate the use of computers and programmable calculators. The commonality of the analytical methods needed to design a wide variety of elements and the use of computer-aided engineering as an approach to design are emphasized.

Mechanical Engineering Design provides unlimited opportunities for the use of computer graphics. Computer solutions are usually preferred because the evaluation of design changes and "what-if" analyses require only a few keystrokes. Hence, many examples, case studies, and problems in this book are discussed with the aid of a computer. Generally, solid modeling serves as a design tool that can be used to create finite element (FE) models for analysis and dynamic simulation. Instructors may use a simple PC-based FE program to give students exposure to the method applied to stress concentration and axisymmetrically loaded and plane stress problems. The website for this book (see Optional Media Supplements, page xxii) allows the user to treat problems more realistically and demonstrates the elements of good computational practice. This book is *independent* of any software package.

Traditional analysis in design, based on the methods of mechanics of materials, is given full treatment. In some instances, the methods of the applied theory of elasticity are employed. The role of the theory of elasticity in this book is threefold: it places limitations on the application of the mechanics of materials theory; it is used as the basis of FE formulation; and it provides exact solutions when configurations of loading and component shape are simple. Plates and basic structural members are discussed to enable the reader to solve real-life problems and understand interactive case studies. Website addresses of component and equipment manufacturers and open-ended web problems are given in many chapters to provide the reader access to additional information on those topics. Also presented is finite element analysis (FEA) in computer-aided design. The foregoing unified methods of analysis give the reader the opportunity to expand his or her ability to perform the design process in a more realistic setting. This book attempts to fill what I believe to be a void in the world of textbooks on mechanical design and machine design.

This book is divided into three sections. The basics of loading, stress, strain, materials, deflection, stiffness, and stability are treated first. Then fracture mechanics, failure criteria, fatigue phenomena, and surface damage of components are dealt with. These are followed by applications to machine and miscellaneous mechanical and structural components. All the sections attempt to provide an integrated approach that links together a variety of topics by means of case studies. Some chapters and sections in this book are also carefully integrated through cross-referencing. Throughout this book, most case studies provide numerous component projects. They present different aspects of the same design or analysis problem in successive chapters. Case studies in the preliminary design of two machines are taken up in the last chapter.

Attention is given to the presentation of the fundamentals and necessary empirical information required to formulate design problems. Important principles and applications are illustrated with numerical examples, and a broad range of practical problems are provided to be solved by students. This book offers numerous worked-out examples and case studies, aspects of which are presented in several sections of this book; many problem sets, most of which are drawn from engineering practice; and a multitude of formulas and tabulations from which design calculations can be made. Most problems can be readily modified for in-class tests. Answers to Selected Problems and References (identified in *square brackets*) are given at the end of this book.

A sign convention consistent with vector mechanics is used throughout for loads, internal forces (with the exception of the shear in beams), and stresses. This convention has been carefully chosen to conform to that used in most classical mechanics of materials, elasticity, and engineering design texts, as well as to that most often employed in the numerical analysis of complex machines and structures. Both the international system of units (SI) and the US customary system of units are introduced; however, all examples and problems in this book are provided using SI units.

TEXT ARRANGEMENT

A glance at the table of contents shows the topics covered and the way in which they are organized. Because of the extensive subdivision into a variety of topics and the use of alternative design and analysis methods, this book should provide flexibility in the choice of assignments to cover courses of varying length and content. A discussion of the design process and an overview of the material included in this book are given in Sections 1.1 through 1.4. Most chapters are substantially self-contained. Hence, the order of presentation can be smoothly altered to meet an instructor's preference. It is suggested, however, that Chapters 1 and 2 be studied first. The sections of this book marked with an asterisk (*) deal with special or advanced topics. These are optional for a basic course in design and can be skipped without disturbing the continuity of this book.

This book attempts to provide synthesis and analysis that cut through the clutter and save the reader's time. Every effort has been made to eliminate errors. I hope I have maintained a clarity of presentation, as much simplicity as the subject permits, unpretentious depth, an effort to encourage intuitive understanding, and a shunning of the irrelevant. In this context, emphasis is placed on the use of fundamentals to build students' understanding and ability to solve more complex problems throughout.

FEATURES

The following overview highlights key features of this innovative machine design book.

Large Variety of Interesting and Engaging Worked Examples and Homework Problems

Providing fresh, practically based problem content, the text offers *680 homework problems*, *185 worked examples*, and *14 case studies*.

Consistent Problem-Solving Approach

To provide students a consistent framework for organizing their work, worked examples and case studies use a standard problem-solving format:

1. Problem statement (given).
2. Find.

3. Assumptions.
4. Solution.
5. Comments.

Unique Case Studies

Fourteen text cases provide additional applications of the use of design processes. Two major case studies—the *crane with winch study* and the *high-speed cutting machine study*—concern system design, allowing students to see how the stress and displacement of any one member may be invariably affected by the related parts. These also add to the skill sets they need as practicing engineers. The cases are interesting and relevant with special emphasis on industry uses, material selection, safety considerations, and cost factors.

Three Aspects of Solid Mechanics Emphasized

Equilibrium, material behavior, and geometry of deformation. This book reinforces the importance of these *basic principles of analysis*.

Strong Visual Approach

This book includes about 540 figures and 35 photographs, many with multiple parts, to aid students' comprehension of the concepts. All regular figures include explanatory captions.

Introduction

The author provides solid pedagogical tools and objectives for each chapter, including an excellent summary at the beginning.

Additional Features

Free-body diagrams, review of key stress analysis concepts, material properties and applications, rational design procedure, role of analysis, and FEA in design.

This Edition's Promise

Text Accuracy

The author, a proofreader, and a production editor checked all final pages for accuracy.

Solution Accuracy

Fully worked-out solutions written and class-tested by the author. An accuracy checker independently checked all final solutions.

Reliability

Over the last three decades, Ansel C. Ugural has written best-selling books on advanced mechanics of materials, elasticity, mechanics of materials, beams, plates and shells, mechanical design, and mechanical engineering design.

Time-Saving Support Material

Available on the companion site at http://www.physicalpropertiesofmaterials.com/book/?isbn=9781439866511.

Meeting ABET Criteria

This book addresses the following ABET criteria:

1. An ability to apply knowledge of mathematics, science, and engineering.
2. An ability to design and conduct experiments, as well as to analyze and interpret data.

3. An ability to design a system, a component, or a process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.
4. An ability to identify, formulate, and solve engineering problems.
5. An understanding of professional and ethical responsibilities.
6. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

SUPPLEMENTS

This book is accompanied by a comprehensive ***Instructor's Solutions Manual***. Written and class tested by the author, it features complete solutions to all problems in the text. Answers to Selected Problems are given at the end of this book. The password-protected *Instructor's Solutions Manual* is available for adopters through the publisher.

Optional Material is also available from the CRC Website https://www.routledge.com/Mechanical-Engineering-Design/Ugural/p/book/9781032170046. This book, however, is *independent* of any *software* package.

Acknowledgments

To acknowledge everyone who contributed to this book in some manner is clearly impossible. However, the author is especially thankful to the following reviewers, who offered constructive suggestions and made detailed comments: D. Beale, Auburn University; D. M. McStravick, Rice University; T. R. Grimm, Michigan Technological University; R. E. Dippery, Kettering University; Y.-C. Yong, California Polytechnic University-San Luis Obispo; A. Shih, North Carolina State University; J. D. Gibson, Rose-Hulman Institute of Technology; R. Paasch, Oregon State University; J. P. H. Steele, Colorado School of Mines; C. Nuckolls, the University of Central Florida; D. Logan, the University of Wisconsin-Platteville; E. Conley, New Mexico State University; L. Dabaghian, California State University-Sacramento; E. R. Mijares, California State University-Long Beach; T. Kozik, Texas A&M University; C. Crane, the University of Florida; B. Bahram, North Carolina State University; A. Mishra, Auburn University; S. Yurgartis, Clarkson University; M. Corley, Louisiana Tech. University; R. Rowlands, the University of Wisconsin; B. Hyman, the University of Washington; G. H. McDonald, the University of Tennessee; J. D. Leland, the University of Nevada; O. Safadi, the University of Southern California; Y. Zhu, North Carolina State University; B. Sepahpour, Trenton College of New Jersey; S. G. Hall, Louisiana State University; A. Almqvist, Lulea University of Technology, Sweden; J. Svenninggaard, VIA University College, Horshens, Denmark; G. S. Tarrant, University of Montana; J. A. Hanks, University of Nebraska, Lincoln; T. D. Coburn, California State Polytechnic University, Pomona; A. Bazar, CSU Fullerton; and G. R. Pennock, Purdue University. P. Brackin, Rose-Hulman Institute of Technology, checked the accuracy of the text. R. Sodhi, New Jersey Institute of Technology, offered valuable perspectives on some case studies based on student design projects. I am pleased to express my gratitude to all of these colleagues for their invaluable advice.

Production was managed and handled efficiently by the staff of CRC Press and CodeMantra. I thank them for their professional help. Accuracy checking of the problems, typing of solutions manual and proofreading were done by my former student, Dr. Youngjin Chung. In addition, contributing to this volume with computer work and typing new inserts was Errol A. Ugural. Their work is much appreciated. Finally, I deeply appreciate the encouragement of my wife Nora, daughter Aileen, and son Errol during the preparation of this text.

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Dr. Ugural earned his MS in mechanical engineering and PhD in engineering mechanics from the University of Wisconsin–Madison. Professor Ugural has been a member of the American Society of Mechanical Engineers and the American Society of Engineering Education. He is also listed in *Who's Who in Engineering*.

Professor Ugural is the author of several books, including *Mechanical Design: An Integrated Approach* (McGraw-Hill, 2004); *Mechanical Design of Machine Components* (CRC Press, 2nd ed., 2016); *Mechanical Engineering Design* (CRC Press, 3rd ed., 2021); *Stresses in Plates and Shells* (McGraw-Hill, 1999); *Plates and Shells: Theory and Analysis* (CRC Press, 4th ed., 2018); *Mechanics of Materials* (McGraw-Hill, 1990); and *Mechanics of Materials* (Wiley, 2008). Some of these books have been translated into Korean, Chinese, and Portuguese. Dr. Ugural is also the coauthor (with S. K. Fenster) of *Advanced Mechanics of Materials and Applied Elasticity* (Pearson, 6th ed., 2020). In addition, he has published numerous articles in trade and professional journals.

Symbols

See Sections 11.2, 11.4, 11.9, 11.11, 12.3, 12.5, 12.6, 12.8, and 12.9 for some gearing symbols.

ROMAN LETTERS

A	Amplitude ratio, area, coefficient, cross-sectional area
A_e	Effective area of clamped parts, projected area
A_f	Final cross-sectional area
A_o	Original cross-sectional area
A_t	Tensile stress area, tensile stress area of the thread
a	Acceleration, crack depth, distance, radius, radius of the contact area of two spheres
B	Coefficient
b	Distance, width of beam, band, or belt; radius
C	Basic dynamic load rating, bolted-joint constant, centroid, constant, heat coefficient, specific heat, spring index transfer
C_c	Limiting value of column slenderness ratio
C_f	Surface finish factor
C_r	Reliability factor, contact ratio
C_s	Basic static load rating, size factor
c	Distance from neutral axis to the extreme fiber, radial clearance, center distance
D	Diameter, mean coil diameter, plate flexural rigidity $[Et^3/12(1-v^2)]$
D	Diameter, distance, pitch diameter, wire diameter
d_{avg}	Average diameter
d_c	Collar (or bearing) diameter
d_m	Mean diameter
d_p	Pitch diameter
d_r	Root diameter
E	Modulus of elasticity
E_b	Modulus of elasticity for the bolt
E_k	Kinetic energy
E_p	Modulus of elasticity for clamped parts, potential energy
e	Dilatation, distance, eccentricity, efficiency
F	Force, tension
F_a	Axial force, actuating force
F_b	Bolt axial force
F_c	Centrifugal force
F_d	Dynamic load
F_i	Initial tensile force or preload
F_n	Normal force
F_p	Clamping force for the parts, proof load
F_r	Radial force
F_t	Tangential force
F_u	Ultimate force
f	Coefficient of friction, frequency
f_c	Collar (or bearing) coefficient of friction
f_n	Natural frequency
G	Modulus of rigidity
g	Acceleration due to gravity

H	Time rate of heat dissipation, power
H_B	Brinell hardness number (Bhn)
H_V	Vickers hardness number
h	Cone height, distance, section depth, height of fall, weld size, film thickness
h_f	Final length, free length
h_0	Minimum film thickness
h_s	Solid height
I	Moment of inertia
I_e	Equivalent moment of inertia of the spring coil
J	Polar moment of inertia, factor
K	Bulk modulus of elasticity, constant, impact factor, stress intensity factor, system stiffness
K_c	Fracture toughness
K_f	Fatigue stress-concentration factor
K_r	Life adjustment factor
K_s	Service factor, shock factor, direct shear factor for the helical spring
K_t	Theoretical or geometric stress concentration factor
K_w	Wahl factor
k	Buckling load factor for the plate, constant, element stiffness, spring index or stiffness
k_b	Stiffness for the bolt
k_p	Stiffness for the clamped parts
L	Grip, length, lead
L_e	Equivalent length of the column
L_f	Final length
L_0	Original length
L_5	Rating life for reliability greater than 90%
L_{10}	Rating life
l	Direction cosine, length
M	Moment
M_a	Alternating moment
M_f	Moment of friction forces
M_m	Mean moment
M_n	Moment of normal forces
m	Direction cosine, mass, module, mass
N	Normal force, number of friction planes, number of teeth, fatigue life or cycles to failure
N_a	Number of active spring coils
N_{cr}	Critical load of the plate
N_t	Total number of spring coils
N_θ	Hoop force
N_ϕ	Meridional force
n	Constant, direction cosine, factor of safety, modular ratio, number, number of threads, rotational speed
n_{cr}	Critical rotational speed
P	Force, concentrated load, axial load, equivalent radial load for a roller bearing, radial load per unit projected area
P_a	Alternating load
P_{all}	Allowable load
P_{cr}	Critical load of the column or helical spring
P_m	Mean load
p	Pitch, pressure, probability
p_{all}	Allowable pressure
p_i	Internal pressure

p_{max} Maximum pressure
p_{min} Minimum pressure
p_o Outside or external pressure
p_0 Maximum contact pressure
$p(x)$ Probability or frequency function
Q First moment of area, imaginary force, volume, flow rate
Q_s Side leakage rate
q Notch sensitivity factor, shear flow
R Radius, reaction force, reliability, stress ratio
R_b Rockwell hardness in B scale
R_c Rockwell hardness in C scale
r Aspect ratio of the plate, radial distance, radius, radius of gyration
r_{avg} Average radius
r_i Inner radius
r_o Outer radius
S Section modulus, Saybolt viscometer measurement in seconds, Sommerfeld number, strength
S_e Endurance limit of mechanical part
S'_e Endurance limit of specimen
S_{es} Endurance limit in shear
S_f Fracture strength
S_n Endurance strength of mechanical part
S'_n Endurance strength of specimen
S_p Proof strength, proportional limit strength
S_u Ultimate strength in tension
S_{uc} Ultimate strength in compression
S_{us} Ultimate strength in shear
S_y Yield strength in tension
S_{ys} Yield strength in shear
s Distance, sample standard deviation
T Temperature, tension, torque
T_a Alternating torque
T_d Torque to lower the load
T_f Friction torque
T_m Mean torque
T_o Torque of overhauling
T_t Transition temperature
T_u Torque to lift the load
T Temperature, distance, thickness, time
t_a Temperature of surrounding air
t_o Average oil film temperature
U Strain energy, journal surface velocity
u_0 Strain energy density
U_{od} Distortional strain energy density
U_{ov} Dilatational strain energy density
U_r Modulus of resilience
U_t Modulus of toughness
U^* Complementary energy
U^*_o Complementary energy density
u Radial displacement, fluid flow velocity
V Linear velocity, a rotational factor, shear force, volume

V_s Sliding velocity
υ Displacement, linear velocity
W Work, load, weight
w Distance, unit load, deflection, displacement
X A radial factor
y Lewis form factor based on diametral pitch or module, a thrust factor
y Distance from the neutral axis, Lewis form factor based on circular pitch, quantity
$\bar{y}$ Distance locating the neutral axis
z Number of standard deviations

GREEK LETTERS

α Angle, angular acceleration, coefficient, coefficient of thermal expansion, cone angle, form factor for shear, thread angle
α_n Thread angle measured in the normal plane
β Angle, coefficient, half-included angle of the V belt
γ Included angle of the disk clutch or brake, pitch angle of the sprocket, shear strain, weight per unit volume; y_{xy}, y_{yz}, and y_{xz} are shear strains in the xy, yz, and xz planes
$\gamma_{\max}$ Maximum shear strain
Δ Gap, material parameter in computing contact stress
δ Deflection, displacement, elongation, radial interference or shrinking allowance, a virtual infinitesimally small quantity
$\delta_{\max}$ Maximum or dynamic deflection
δ_s Solid deflection
δ_{st} Static deflection
δ_w Working deflection
ϵ Eccentricity ratio
ε Normal strain; ε_x, ε_y, and ε_z are normal strains in the x, y, and z directions
ε_f Normal strain at fracture
ε_t True normal strain
ε_u Ultimate strain
η Absolute viscosity or viscosity
θ Angle, angular displacement, slope
θ_p Angle to a principal plane or to a principal axis
θ_s Angle to a plane of maximum shear
λ Lead angle, helix angle, material constant
μ Population mean
ν Kinematic viscosity, Poisson's ratio
ρ Mass density
σ Normal stress; σ_x, σ_y, and σ_z are normal stresses in the x, y, and z planes, standard deviation
σ_a Alternating stress
σ_{all} Allowable stress
σ_{cr} Critical stress
σ_e Equivalent stress
σ_{ea} Equivalent alternating stress
σ_{em} Equivalent mean stress
$\sigma_{\max}$ Maximum normal stress
$\sigma_{\min}$ Minimum normal stress
σ_{nom} Nominal stress
σ_{oct} Octahedral normal stress
σ_{res} Residual stress

τ	Shear stress; τ_{xy}, τ_{yz}, and τ_{xz} are shear stresses perpendicular to the *x*, *y*, and *z* axes and parallel to the *y*, *z*, and *x* axes; direct shear stress; torsional shear stress
τ_{avg}	Average shear stress
τ_{all}	Allowable shear stress
τ_{oct}	Octahedral shear stress
τ_{max}	Maximum shear stress
τ_{min}	Minimum shear stress
τ_{nom}	Nominal shear stress
ϕ	Angle, angle giving the position of minimum film thickness, pressure angle, angle of twist, angle of wrap
ϕ_{max}	Position of maximum film pressure
ψ	Helix angle, spiral angle
ω	Angular velocity, angular frequency ($\omega = 2\pi f$)
ω_n	Natural angular frequency

Abbreviations

all	Allowable
avg	Average
Bhn	Brinell hardness number
CCW	Counterclockwise
CD	Cold drawn
cr	Critical
CW	Clockwise
fpm	Foot per minute
ft	Foot, feet
h	Hour
HD	Hard drawn
hp	Horsepower
HT	Heat treated
Hz	Hertz (cycles per second)
ID	Inside diameter
in.	Inch, inches
ipm	Inch per minute
ips	Inch per second
J	Joule
kg	Kilogram(s)
kip	Kilopound (1000 lb)
kips	Kilopounds
ksi	Kips per square inch (10^3 psi)
kW	Kilowatt
lb	Pound(s)
ln	Napierian natural logarithm
log	Common logarithm (base 10)
m	Meter
max	Maximum
min	Minimum
mph	Miles per hour
m/s	Meter per second
N	Newton
NA	Neutral axis
OD	Outside diameter
OQ&T	Oil quenched and tempered
OT	Oil tempered
Pa	Pascal
psi	Pounds per square inch
Q&T	Quenched and tempered
rad	Radian
req	Required
res	Residual
rpm	Revolutions per minute
rps	Revolutions per second
s	Second

SI	System of international units
st	Static
SUS	Saybolt universal seconds
SUV	Saybolt universal viscosity
VI	Viscosity index
W	Watt
WQ&T	Water quenched and tempered

Section I

Fundamentals

A bolt cutter suited for professional users (www.ridgit.com). We will examine such a tool in Case Studies 1.1, 3.1, and 4.1. Section I is devoted to the analysis of load, material properties, stress, strain, deflection, and elastic stability of variously loaded machine and structural components.

DOI: 10.1201/9781003251378-1

1 Introduction

1.1 SCOPE OF THIS BOOK

As an applied science, engineering uses scientific knowledge to achieve a specific objective. The mechanism by which a requirement is converted to a meaningful and functional plan is called a *design*. The design is an innovative, iterative, decision-making process. This book deals with the analysis and design of *machine elements or components* and the basic *structural members* that compose the system or assembly. Typical truss, frame, and plate structures are also considered. The purpose and scope of this text may be summarized as follows: it presents a body of knowledge that will be useful in component design for performance, strength, and durability; provides treatments of *design to meet strength requirements* of members and other aspects of design involving prediction of the displacement and buckling of a given component under prescribed loading; presents classical and numerical methods amenable to use in electronic digital computers for the analysis and design of members and structural assemblies; and presents many examples, case studies, and problems of various types to provide an opportunity for the reader to develop competence and confidence in applying the available design formulas and deriving new equations as required.

The text consists of three sections. Section I focuses on fundamental principles and methods, a synthesis of stress analysis, and materials engineering, which forms the cornerstone of the subject and has to be studied carefully. We begin with a discussion of basic concepts in design and analysis and definitions relating to properties of a variety of engineering materials. Detailed equilibrium and energy methods of analysis for determining stresses and deformations in variously loaded members, designs of bars and beams, buckling, failure criteria, and reliability are presented in Section II. A thorough grasp of these topics will prove of great value in attacking new and complex problems. Section III is devoted mostly to the design of machine components. The fundamentals are applied to specific elements such as shafts, bearings, gears, belts, chains, clutches, brakes, and springs and typical design situations that arise in the selection and application of these items and others. Power screws; threaded fasteners; bolted, riveted, and welded connections; adhesive bonding; and axisymmetrically loaded components are also considered in some detail. In conclusion, introductory finite element analysis (FEA) and case studies in design are covered.

A full understanding of terminology in both statics and principles of mechanics is an essential prerequisite for the analysis and design of machines and structures. Design methods for members are founded on the methods of mechanics of materials; and the theory of applied elasticity is used or referred to in the design of certain elements. The objective of this chapter is to provide the reader with the basic definitions and process of the design, load analysis, and the concepts of solid mechanics in a condensed form. Selected references provide readily available sources where additional analysis and design information can be obtained.

1.2 MECHANICAL ENGINEERING DESIGN

Design is the formulation of a plan to satisfy a particular need, real or imaginary. Fundamentally, design represents the process of problem solving. *Engineering design* can be defined as the process of applying science and engineering methods to prescribe a component or a system in sufficient detail to permit its realization. A system constitutes several different elements arranged to work together as a whole. Design is thus the essence, art, and intent of engineering. *Design function* refers to the process in which mathematics, computers, and graphics are used to produce a plan. Engineers with more scientific insight are able to devise better solutions to practical problems. Interestingly,

DOI: 10.1201/9781003251378-2

there is a similarity between the engineer and the physician. Although they are not scientists, both use scientific evidence complemented by empirical data and professional judgment in dealing with demanding problems.

Mechanical design means the design of components and systems of a mechanical nature—machines, structures, devices, and instruments. For the most part, mechanical design utilizes stress analysis methods and materials engineering and energy concepts. That is, it applies them to the design of mechanical systems or components where structures, motion, and energy or heat transfer can be involved. A *machine* is an apparatus consisting of interrelated elements or a device that modifies force motion or energy (see Section 1.9). *Machine design* is the art of planning or devising new or improved machines to accomplish a specific purpose. The field of machine design is a subset of mechanical design in which focus is on the structures and motion *only*.

Mechanical engineering design deals with the conception, design, development, and application of machines and mechanical apparatus of all types. It involves *all* the disciplines of mechanical engineering. Although *structural design* is most directly associated with civil engineering, it interacts with any engineering field that requires a structural system or member. As noted earlier, the topic of machine design is the main focus of this text.

The ultimate goal in a mechanical design process is to size and shape the elements and choose appropriate materials and manufacturing processes so that the resulting system can be expected to perform its intended function without failure. An *optimum design* is the best solution to a design problem within prescribed constraints. Of course, such a design depends on a seemingly limitless number of variables. When faced with many possible choices, a designer may make various design decisions based on experience, reducing the problem to that, with one or few variables.

Generally, it is assumed that a good design meets performance, safety, reliability, aesthetics, and cost goals. Another attribute of a good design is robustness, a resistance to quality loss, or deviation from desired performance. Knowledge from the entire engineering curricula goes into formulating a good design. Communication is as significant as technology. Basically, the means of communication are written, oral, and graphical forms. The first fundamental canon in the *Code of Ethics for Engineers* [1] states that "Engineers shall hold paramount the safety, health, and welfare of the public in the performance of their professional duties." Therefore, engineers must design products that are safe during their intended use for the life of the products. Product safety implies that the product will protect humans from injury, prevent property damage, and prevent harm to the environment.

A plan for satisfying a need often includes preparation of individual preliminary design. A *preliminary design*, sometimes also referred to as a conceptual design, is mainly concerned with analysis, synthesis, evaluation, and comparison of proposed machine components or machines. Each preliminary design involves a thorough consideration of the loads and actions that the structure or machine has to support. For each case, a mechanical analysis is necessary. *Design decisions*, or choosing the reasonable values of the factors, are important in the design process. As a designer gains more experience, decisions are reached more readily. Both individual talent and creativeness are needed in engineering design.

1.2.1 ABET Definition of Design

The Accreditation Board for Engineering and Technology (ABET) defines engineering design as the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which basic science, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.

The engineering design component of a curriculum must include most of the following features: development of student creativity, use of open-ended problems, development and use of modern design theory and methodology, formulation of design problem statements and specifications, consideration of alternative solutions, feasibility considerations, production processes, concurrent engineering design, and detailed system description. Further, it is essential to include a variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics, and social impact. The ABET criteria (Preface) for accreditation emphasize the use of teams in solving problems and creating designs.

1.3 DESIGN PROCESS

The *process* of *design* is basically an exercise in creativity. The complete process may be outlined by design flow diagrams with feedback loops. Figure 1.1 shows some aspects of such a diagram. In this section, we discuss the *phases of design* common to all disciplines in the field of engineering design. Most engineering designs involve safety, ecological, and societal considerations. It is a challenge to the engineer to recognize all of these in proper proportion. Fundamental actions proposed for the design process are establishing a need as a design problem to be solved, understanding the problem, generating and evaluating possible solutions, and deciding on the best solution.

1.3.1 Phases of Design

The design process is independent of the product and is based on the concept of a product life cycle. The content of each engineering design problem is unique, but the methodology for solving these problems is universal and can be described in a specific way. To understand fully all that must be considered in the process of design, here we explain the characteristics of each phase of Figure 1.1. The process is neither exhaustive nor rigid and will probably be modified to suit individual problems. A number of authorities on the methodology of design have presented similar descriptions of the process.

1.3.1.1 Identification of Need

The design process begins with a recognition of a *need*, real or imagined, and a *decision* to do something about it. For example, present equipment may require improvements to its durability, efficiency, weight, speed, or cost. New equipment may be needed to perform an automated function, such as computation, assembly, or servicing. The identification aspect of design can have its origin in any number of sources. Customer reports on the product's function and quality may force

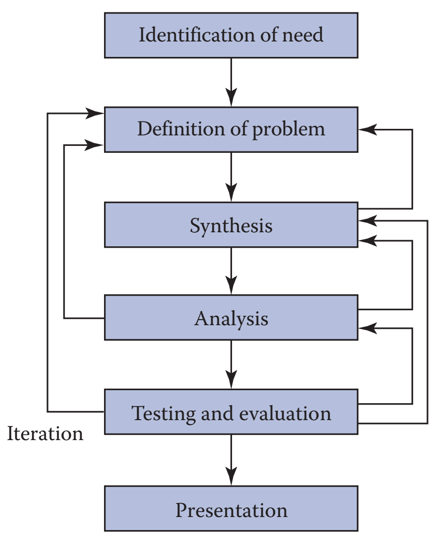

FIGURE 1.1 Design process.

a redesign. Business and industrial competition constantly force the need for new or improved apparatus, processes, and machinery designs. Numerous other sources of needs give rise to contemporary design problems.

1.3.1.2 Definition of the Problem

This phase in design conceives the mechanisms and arrangements that will perform the needed function. For this, a broad knowledge of members is desirable, because new equipment ordinarily consists of new members, perhaps with changes in size and material. *Specification* is a form of input and output quantities. A number of decisions must be made to establish the *specification set*, which is a collection of drawings, text, bills of materials, and detailed directions. All specifications must be carefully spelled out. Often, this area is also labeled *design and performance requirements*. The specifications also include the definitions of the member to be manufactured, the cost, the range of the operating temperature, expected life, and the reliability.

A *standard* is a set of specifications for parts, materials, or processes intended to achieve uniformity, efficiency, and a specified quality. A *code* is a set of specifications for the analysis, design, manufacture, and construction of something. The purpose of a code is to achieve a specified degree of safety, efficiency, and performance or quality. All organizations and technical societies (listed in Section 1.6) have established specifications for standards and safety or design codes.

Once the specifications have been prepared, relevant design information is collected to make a *feasibility study*. The purpose of this study is to verify the possible success or failure of a proposal both from the technical and economic standpoints. Frequently, as a result of this study, changes are made in the specifications and requirements of the project. The designer often considers the engineering feasibility of various alternative proposals. When some idea as to the amount of space needed or available for a project has been determined, to-scale layout drawings may be started.

1.3.1.3 Synthesis

The synthesis (putting together) of the solution represents perhaps the most challenging and interesting part of the design. Frequently termed the *ideation and invention phase*, it is where the largest possible number of creative solutions is originated. The philosophy, functionality, and uniqueness of the product are determined during synthesis. In this step, the designer combines separate parts to form a complex whole of various new and old ideas and concepts to produce an overall new idea or concept.

1.3.1.4 Analysis

Synthesis and analysis are the main stages that constitute the design process. Analysis has as its objective satisfactory performance, as well as durability with minimum weight and competitive cost. Synthesis cannot take place without both analysis or resolution and optimization, because the product under design must be analyzed to determine whether the performance complies with the specifications. If the design fails, the synthesis procedure must begin again. After synthesizing several components of a system, we analyze what effect this has on the remaining parts of the system. It is now necessary to draw the layouts, providing details, and make the supporting calculations that will ultimately result in a prototype design. The designer must specify the dimensions, select the components and materials, and consider the manufacturing, cost, reliability, serviceability, and safety.

1.3.1.5 Testing and Evaluation

At this juncture, the working design is first fabricated as a *prototype*. Product evaluation is the final proof of a successful design and usually involves testing a prototype in a laboratory or on a computer that provides the analysis database. More often, computer prototypes are utilized because they are less expensive and faster to generate. By evaluation, we discover whether the design really satisfies the need and other desirable features. Subsequent to many *iterations* (i.e., repetitions or returns to a previous state), the process ends with the vital step of communicating the design to others.

1.3.1.6 Presentation

The designer must be able to understand the need and describe a design graphically, verbally, and in writing. This is the presentation of the plans for satisfying the need. A successful presentation is of utmost importance as the final step in the design process. Drawings are utilized to produce blueprints to be passed to the manufacturing process.

It is interesting to note that individual parts should be designed to be easily fabricated, assembled, and constructed. The goal of the *manufacturing process* is to construct the designed component or system. Manufacturability plays an important role in the success of commercial products. Individual parts should be designed to be easily fabricated, assembled, and constructed. The process planning attempts to determine the most effective sequence to produce the component. The produced parts are inspected and must pass certain quality control or assurance requirements. Components surviving inspection are assembled, packaged, labeled, and shipped to customers.

The features of a product that attract consumers and how the product is presented to the marketplace are significant functions in the success of a product. Marketing is a crucial last stage of the manufacturing process. Market feedback is very important in enhancing products. These feedback loops are usually incorporated into the first stage of a design process. Many disciplines are involved in product development. Therefore, design engineers need to be familiar with other disciplines, at least from a communication standpoint, to integrate them into the design process.

1.3.2 Design Considerations

Usually engineering designs involve quite a number of considerations that must be properly recognized by the engineer. *Traditional considerations* for a mechanical component, or perhaps the entire system, include strength, deflection, weight, size and shape, material properties, operating conditions, processing, cost, availability, usability, utility, and life. Examples of *modern considerations* are safety, quality of life, and the environment. *Miscellaneous considerations* include reliability, maintainability, ergonomics, and esthetics.

We shall consider some of the foregoing factors throughout this text. Frequently, fundamentals will be applied to resolve a problem based on the design decisions. A final point to be noted is that often a variety of design considerations may be incompatible until the engineer puts together a sufficiently imaginative and ingenious solution. The design of the winch crane (see Figure 18.1) provides a simple example. Here, achieving a desired aesthetic appearance is almost incompatible with cost limitations.

In concluding this section, we note that a degree of caution is necessary when employing formulas for which there is uncertainty in applicability and restriction of use. The relatively simple form of many formulas usually results from idealizations made in their derivations. These assumptions include simplified boundary conditions and loading on a member, and approximation of shape or material properties. Designers and stress analysts must be aware of such constraints.

1.4 DESIGN ANALYSIS

The objective of the design analysis is, of course, to attempt to predict the stress or deformation in the component so that it may safely carry the loads that will be imposed on it. The analysis begins with an attempt to put the conceptual design in the context of the abstracted engineering sciences to evaluate the performance of the expected product. This constitutes design modeling and simulation.

1.4.1 Engineering Modeling

Geometric modeling is the method of choice for obtaining the data necessary for failure analysis early in the design process. Creating a useful engineering model of a design is probably the most difficult and challenging part of the whole process. It is the responsibility of the designer to ensure the adequacy of a chosen geometric model for a particular design. If the structure is simple enough, theoretical solutions for basic configurations may be adequate for obtaining the stresses involved. For more complicated structures, finite element models can not only estimate the stresses, but also utilize them to evaluate the failure criteria for each element in a member.

We note that the geometric model chosen and subsequent calculations made merely approximate reality. Assumptions and limitations, such as linearity and material homogeneity, are used in developing the model. The choice of a geometric model depends directly on the kind of analysis to be performed. Design testing and evaluation may require changing the geometric model before finalizing it. When the final design is achieved, the drafting and detailing of the models start, followed by the documentation and production of final drawings.

1.4.2 Rational Design Procedure

The rational design procedure to meet the *strength requirements* of a load-carrying member attempts to take the results of fundamental tests, such as tension, compression, and fatigue, and apply them to all complicated and involved situations encountered in present-day structures and machines. However, not all topics in design have a firm analytical base from which to work. In those cases, we must depend on a semi-rational or empirical approach to solving a problem or selecting a design component.

In addition, details related to actual service loads and various factors, discussed in Section 7.7, have a marked influence on the strength and useful life of a component. The static design of axially loaded members, beams, and torsion bars are treated by the rational procedure in Chapters 3 and 9. Suffice it to say that complete design solutions are not unique and often trial and error is required to find the best solution.

1.4.3 Methods of Analysis

Design methods are based on the mechanics of materials theory generally used in this text. Axisymmetrically loaded mechanical components are analyzed by methods of the elasticity theory in Chapter 16. The former approach employs assumptions based on experimental evidence along with engineering experience to make a reasonable solution for the practical problem possible. The latter approach concerns itself largely with more mathematical analysis of the *exact* stress distribution on a loaded body [2, 3]. The difference between the two methods of analysis is further discussed at the end of Section 3.17.

Note that solutions based on the mechanics of materials give average stresses at a cross-section. Since, at concentrated forces and abrupt changes in a cross-section, irregular local stresses (and strains) arise, only at a distance about equal to the depth of the member from such disturbances are the stresses in agreement with the mechanics of materials. This is due to **Saint-Venant's Principle**: the stress of a member at points away from points of load application may be obtained on the basis of a statically equivalent loading system; that is, the manner of a force's application on stresses is significant only in the vicinity of the region where the force is applied. This is also valid for the disturbances caused by the changes in the cross-section. The mechanics of materials approach is therefore best suited for relatively slender members.

The complete analysis of a given component subjected to prescribed loads by the method of equilibrium requires consideration of three conditions. These *basic principles of analysis* can be summarized as follows:

1. *Statics*. The equations of equilibrium must be satisfied.
2. *Deformations*. Stress–strain or force deformation relations (e.g., Hooke's law) must apply to the behavior of the material.
3. *Geometry*. The conditions of compatibility of deformations must be satisfied; that is, each deformed part of the member must fit together with adjacent parts.

Solutions based on these requirements must satisfy the boundary conditions. Note that it is not always necessary to execute the analysis in this exact order. Applications of the foregoing procedure are illustrated in the problems involving mechanical components as the subject unfolds. Alternatively, stress and deformation can also be analyzed using the energy methods. The roles of both methods are twofold. They can provide solutions of acceptable accuracy, where the configurations of loading and member are regular, and they can be employed as a basis of the numerical methods for more complex problems.

1.5 PROBLEM FORMULATION AND COMPUTATION

The discussion in Section 1.3 shows that synthesis and analysis are the *two faces* of the design. They are opposites, but symbiotic. These are the phases of the mechanical design process addressed in this book. Most examples, case studies, and problems are set up so the identification of need, specifications, and feasibility phases already have been defined. As noted previously, this text is concerned with the fundamentals involved, and mostly with the application to specific mechanical components. The machine and structural members chosen are widely used and will be somewhat familiar to the reader. The emphasis in treating these components is on the methods and procedures used.

1.5.1 Solving Mechanical Component Problems

Ever-increasing industrial demand for more sophisticated machines and structures calls for a good grasp of the concepts of analysis and design and a notable degree of ingenuity. Fundamentally, design is the process of problem solving. It is very important to formulate a mechanical element problem and its solution accurately. This requires consideration of the physical item and its related mathematical situations. The reader may find the following format helpful in problem formulation and solution:

1. **Given**: define the problem and known quantities.
2. **Find**: state consistently what is to be determined.
3. **Assumptions**: list simplifying idealizations to be made.
4. **Solution**: apply the appropriate equations to determine the unknowns.
5. **Comments**: discuss the results briefly.

We illustrate most of these steps in the solution of the sample problems throughout the text.

Assumptions expand on the given information to further constrain the problem. For example, one might take the effects of friction to be negligible, or the weight of the member can be ignored in a particular case. The student needs to understand what assumptions are made in solving a problem. Comments present the key aspects of the solution and discuss how better results might be obtained by making different analysis decisions, relaxing the assumptions, and so on.

This book provides the student with the ideas and information necessary for understanding mechanical analysis and design and encourages the creative process based on that understanding. It is important that the reader visualizes the nature of the quantities being computed. Complete, carefully drawn, free-body diagrams (FBDs) facilitate visualizations, and we provide these, knowing that the subject matter can be mastered best by solving practical problems. It should also be pointed out that the relatively simple form of many equations usually results from simplifying assumptions made with respect to the deformation and load patterns in their derivation. Designers and analysts must be aware of such restrictions.

1.5.1.1 Significant Digits

In practical engineering problems, the data are seldom known with an accuracy of greater than 0.2%; answers to such problems should not exceed this accuracy. Note that when calculations are performed by electronic calculators and computers (usually carrying eight or nine digits), the possibility exists that the numerical result will be reported to an accuracy that has no physical meaning. Consistently throughout this text, we shall generally follow a common engineering rule to report the final results of calculations:

- Numbers beginning with "1" are recorded to four significant digits.
- All other numbers (that begin with "2" through "9") are recorded to three significant digits.

Hence, a force of 15 N, for example, should read 15.00 N, and a force of 32 N should read 32.0 N. Intermediate results, if recorded for further calculations, are recorded to several additional digits to preserve the numerical accuracy. We note that the values of π and trigonometric functions are calculated to many significant digits (10 or more) within the calculator or computer.

1.5.2 Computational Tools for Design Problems

A wide variety of computational tools can be used to perform design calculations with success. A high-quality scientific calculator may be the best tool for solving most of the problems in this book. General purpose analysis tools such as spreadsheets and equation solvers have particular merit for certain computational tasks. These mathematical software packages include MATLAB®, TK Solver, and MathCAD. The tools have the advantage of allowing the user to document and save completed work in a detailed form. Computer-aided design (CAD) software may be used throughout the design process, but it supports the analysis stages of the design more than the conceptual phases.

In addition, there is proprietary software developed by a number of organizations to implement the preliminary design and proposal presentation stage. This is particularly true for cases in which existing product lines needed to be revised to meet new specifications or codes.

The computer-aided drafting software packages can produce realistic 3D representations of a member or solid models. The CAD software allows the designer to visualize without costly models, iterations, or prototypes. Most CAD systems provide an interface to one or more FEA or boundary element analysis (BEA) programs. They permit direct transfer of the model's geometry to an FEA or BEA package for analysis of stress and vibration, as well as fluid and thermal analysis. However, usually, these analyses of design problems require the use of special purpose programs. The FEA techniques are briefly discussed in Chapter 17.

The computer-based software may be used as a tool to assist students with design projects and lengthy homework assignments. However, computer output providing analysis results must not be accepted on faith alone; the designer must always check computer solutions. It is necessary that fundamentals of analysis and design be thoroughly understood.

1.5.3 The Best Time to Solve Problems

Daily planning can help us make the best of our time. A tentative schedule [4] for the *morning person* who prefers to wake up early and go to sleep early is presented in Table 1.1. It is interesting to note that the so-called evening person works late and wakes up late. Most people may shift times from one to another, and others combine some characteristics of both.

We point out that creativity refers to the state or quality of being creative and serves well for open-ended thinking. Rejuvenation is a phenomenon of vitality and freshness being restored and achieved by renewing the mind with activities like reading, artwork, and puzzle solving. During times suitable for problem solving, concentration is at the highest for doing analysis. Work involving concentration is unsuitable when the body's biological clock changes.

TABLE 1.1
Optimum Time to Do Everything

Time	Activity
6:00 a.m.	Wake
6:00–6:30 a.m.	Unsuitable for concentration
6:30–8:30 a.m.	Suitable for creativity
8:30 a.m.–12:00 noon	Suitable for problem solving
12:00–2:30 p.m.	Unsuitable for concentration
2:30–4:30 p.m.	Suitable for problem solving
4:30–8:00 p.m.	Rejuvenation
8:00–10:00 p.m.	Unsuitable for problem solving
10:00 (or 11:00) p.m.–6:00 a.m.	Sleep

1.6 FACTOR OF SAFETY AND DESIGN CODES

It is sometimes difficult to determine accurately the various factors involved in the phases of design of machines and structures. An important area of uncertainty is related to the assumptions made in the stress and deformation analysis. An equally significant item is the nature of failure. If failure is caused by ductile yielding, the consequences are likely to be less severe than if caused by brittle fracture. In addition, a design must take into account such matters as the following: types of service loads, variations in the properties of the material, whether failure is gradual or sudden, the consequences of failure (minor damage or catastrophe), human safety, and economics.

1.6.1 Definitions

Engineers employ a safety factor to ensure against the foregoing unknown uncertainties involving strength and loading. This factor is used to provide assurance that the load applied to a member does not exceed the largest load it can carry. The factor of safety, n, is the ratio of the maximum load that produces failure of the member to the load allowed under service conditions:

$$n = \frac{\text{Failure load}}{\text{Allowable load}} \tag{1.1}$$

The allowable load is also referred to as the *service load* or *working load*. The preceding represents the basic definition of the factor of safety. This ratio must always be greater than unity, $n > 1$. Since the allowable service load is a known quantity, the usual design procedure is to multiply this by the safety factor to obtain the failure load. Then, the member is designed so that it can just sustain the maximum load at failure.

A common method of design is to use a safety factor with respect to the strength of the member. In most situations, a linear relationship exists between the load and the stress produced by the load. Then, the factor of safety may also be defined as:

$$n = \frac{\text{Material strength}}{\text{Allowable stress}} \tag{1.2}$$

In this equation, the materials strength represents either static or dynamic properties. Obviously, if loading is static, the material strength is either the yield strength or the ultimate strength. For fatigue loading, the material strength is based on the endurance limit, discussed in Chapter 7.

The allowable stress is also called the *applied stress*, *working stress*, or *design stress*. It represents the required strength.

The foregoing definitions of the factor of safety are used for all types of member and loading conditions (e.g., axial, bending, shear). Inasmuch as there may be more than one potential mode of failure for any component, we can have more than one value for the factor of safety. The smallest value of n for any member is of the greatest concern, because this predicts the most likely mode of failure.

1.6.2 Selection of a Factor of Safety

Modern engineering design gives a rational accounting for all factors possible, leaving relatively few items of uncertainty to be covered by a factor of safety. The following numerical values of factor of safety are presented as a guide. They are abstracted from a list by Vidosic [5]. These safety factors are based on the yield strength S_y or endurance limit S_e of a *ductile material*. When they are used with a *brittle material* and the ultimate strength S_u, the factors must be approximately doubled:

1. $n = 1.25$–1.5 is for exceptionally reliable materials used under controllable conditions and subjected to loads and stresses that can be determined with certainty. It is used almost invariably where low weight is a particularly important consideration.
2. $n = 1.5$–2 is for well-known materials under reasonably constant environmental conditions, subjected to loads and stresses that can be determined readily.
3. $n = 2$–2.5 is for average materials operated in ordinary environments and subjected to loads and stresses that can be determined.
4. $n = 2.5$–4 is for less-tried (or 3–4 for untried) materials under average conditions of environment, load, and stress.
5. $n = 3$–4 is also for better-known materials used in uncertain environments or subjected to uncertain stresses.

Where higher factors of safety might appear desirable, a more thorough analysis of the problem should be undertaken before deciding on their use.

In the field of aeronautical engineering, in which it is necessary to reduce the weight of the structures as much as possible, the term factor of safety is replaced by the term *margin of safety*:

$$n = \frac{\text{Ultimate load}}{\text{Design load}} - 1 \tag{a}$$

In the nuclear reactor industries, the safety factor is of prime importance in the face of many unknown effects, and hence, the factor of safety may be as high as five. The value of factor of safety is selected by the designer on the basis of experience and judgment.

The simplicity of Equations (1.1) and (1.2) sometimes masks their importance. A large number of problems requiring their use occur in practice. The employment of a factor of safety in a design is a reliable, time-proven approach. When properly applied, sound and safe designs are obtained. We note that the factor of safety method to safe design is based on rules of thumb, experience, and testing. In this approach, the strengths used are always the *minimum* expected values.

A concept closely related to safety factor is termed *reliability*. It is the statistical measure of the probability that a member will not fail in use. In the reliability method of design, the goal is to achieve a reasonable likelihood of survival under the loading conditions during the intended design life. For this purpose, mean strength and load distributions are determined, and then, these two are related to achieve an acceptable safety margin. Reliability is discussed in Chapter 6.

1.6.3 Design and Safety Codes

Numerous engineering societies and organizations publish standards and codes for specific areas of engineering design. Most are merely recommendations, but some have the force of law. For the majority of applications, the relevant factors of safety are found in various construction and manufacturing codes, for instance, the American Society of Mechanical Engineers (ASME) Pressure Vessel Codes. Factors of safety are usually embedded into computer programs for the design of specific members. Building codes are legislated throughout this country and often deal with publicly accessible structures (e.g., elevators and escalators). Underwriters Laboratories (UL) has developed its standards for testing consumer products. When a product passes their tests, it may be labeled *listed UL*. States and local towns have codes as well, relating mostly to fire prevention and building standards.

It is clear that, where human safety is involved, high values of safety factors are justified. However, members should not be overdesigned to the point of making them unnecessarily costly, heavy, bulky, or wasteful of resources. The designer and stress analyst must be aware of the codes and standards, lest their work lead to inadequacies.

The following is a partial list of societies and organizations* that have established specifications for standards and safety or design codes:

AA	Aluminum Association
AFBMA	Anti-Friction Bearing Manufacturing Association
AGMA	American Gear Manufacturing Association
AIAA	American Institute of Aeronautics and Astronautics
AISC	American Institute of Steel Construction
AISI	American Iron and Steel Institute
ANSI	American National Standards Institute
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
ASLE	American Society of Lubrication Engineers
ASM	American Society of Metals
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AWS	American Welding Society
IFI	Industrial Fasteners Institute
ISO	International Standards Organization
NASA	National Aeronautics and Space Administration
NIST	National Institute for Standards and Technology
SAE	Society of Automotive Engineers
SEM	Society for Experimental Mechanics
SESA	Society for Experimental Stress Analysis
SPE	Society of Plastic Engineers

1.7 UNITS AND CONVERSION

The units of the physical quantities employed in engineering calculations are of major significance. The most recent universal system is the International System of Units (SI). The US customary units have long been used by engineers in this country. While both systems of units are reviewed briefly here, this text primarily uses SI units. Some of the fundamental quantities in SI and the US customary systems of units are listed in Table 1.2. For further details, see, for example, Reference [6].

* The addresses and data on their publications can be obtained in any technical library or from a designated website; for example, for specific titles of ANSI standards, see www.ansi.org.

We observe from the table that, in SI, force F is a derived quantity (obtained by multiplying the mass m by the acceleration a, in accordance with Newton's Second Law, $F = ma$). However, in the US customary system, the situation is reversed, with mass being the derived quantity. It is found from Newton's Second Law, as lb · s²/ft, sometimes called the *slug*.

Temperature is expressed in SI by a unit termed kelvin (K), but for common purposes, the degree Celsius (°C) is used (as shown in Table 1.2). The relationship between the two units: temperature in Celsius = temperature in kelvins − 273.15. The temperature is expressed in US units by the degree Fahrenheit (°F). Conversion formulas between the temperature scales are given by

$$t_c = \frac{5}{9}\left(t_f - 32\right) \tag{1.3}$$

and

$$t_k = \left(t_f - 32\right) + 273.15 \tag{1.4}$$

where t is the temperature. Subscripts c, f, and k denote the Celsius, Fahrenheit, and kelvin, respectively.

It is sufficiently accurate to assume that the acceleration of gravity, denoted by g, near Earth's surface equals

$$g = 9.81\ \text{m/s}^2 \qquad \left(\text{or } 32.2\ \text{ft/s}^2\right)$$

From Newton's second law, it follows that, in SI, the weight W of a body of mass 1 kg is $W = mg =$ (1 kg) (9.81 m/s^2) = 9.81 N. In the US customary system, the weight is expressed in pounds (lb). The unit of force is of particular importance in engineering analysis and design, because it is involved in calculations of the force, moment, torque, stress (or pressure), work (or energy), power, and elastic modulus. Interestingly, in SI units, a newton is approximately the weight of (or earth's gravitational force on) an average apple.

Tables A.1 and A.2 furnish conversion factors and SI prefixes in common usage. The use of prefixes avoids unusually large or small numbers. Note that a dot is to be used to separate units that are multiplied together. Thus, for instance, a newton meter is written N · m and must not be confused with mN, which stands for millinewtons. The reader is cautioned always to check the units in any equation written for a problem solution. If properly written, an equation should cancel all units across the equals sign.

TABLE 1.2
Basic Units

	SI Unit		US Unit	
Quantity	**Name**	**Symbol**	**Name**	**Symbol**
Length	Meter	m	Foot	ft
Force[3]	Newton	N[a]	Pound force	lb
Time	Second	s	Second	s
Mass	Kilogram	kg	Slug	lb · s²/ft
Temperature	Degree Celsius	°C	Degree Fahrenheit	°F

[a] Derived unit (kg · m/s²).

1.8 LOADING CLASSES AND EQUILIBRIUM

External forces, or loads acting on a structure or member, may be classified as surface forces and body forces. A surface force acts at a point or is distributed over a finite area. Body forces are distributed throughout the volume of a member. All forces acting on a body, including the reactive forces caused by supports and the body forces, are considered external forces. Internal forces are the forces holding together the particles forming the member.

Line loads and *concentrated forces* are considered to act along a line and at a single *point*, respectively. Both of these forces are thus idealizations. Nevertheless, they permit accurate analysis of a loaded member, except in the immediate vicinity of the loads. Loads and internal forces can be further classified with respect to location and method of application: normal, shear, bending, and torsion loads and combined loadings. There are a few types of loading that may commonly occur on machine or structural members.

A *static load* is applied slowly, gradually increasing from zero to its maximum value and thereafter remaining constant. Thus, a static load can be a stationary (i.e., unchanging in magnitude, point of application, and direction) force, torque, moment, or a combination of these acting on a member. In contrast, *dynamic loads* may be applied very suddenly, causing vibration of the structure, or they may change in magnitude with time. Note that, unless otherwise stated, we assume in this book that the *weight* of the body can be *neglected* and that the load is static. As observed earlier, in SI, force is expressed in newtons (N). But, because the newton is a small quantity, the kilonewton (kN) is often used in practice. The unit of force in the US customary system is pounds (lb) or kilopounds (kips).

1.8.1 Conditions of Equilibrium

When a system of forces acting on a body has zero resultant, the body is said to be in equilibrium. Consider the equilibrium of a body in space. The conditions of equilibrium require that the following *equations of statics* need be satisfied:

$$\begin{aligned} &\Sigma F_x = 0 \qquad \Sigma F_y = 0 \qquad \Sigma F_z = 0 \\ &\Sigma M_x = 0 \qquad \Sigma M_y = 0 \qquad \Sigma M_z = 0 \end{aligned} \tag{1.5}$$

If the forces act on a body in equilibrium in a single (xy) plane, a planar problem, the most common forms of the static equilibrium equations are:

$$\Sigma F_x = 0 \quad \Sigma F_y = 0 \quad \Sigma M_z = 0 \tag{1.6}$$

By replacing either or both force summations by equivalent moment summations in Equation (1.6), two *alternate* sets of equations can be obtained [3].

When bodies are accelerated, that is, the magnitude or direction of their velocity changes, it is necessary to use Newton's Second Law to relate the motion of the body with the forces acting on it. The *plane motion* of a body, symmetrical with respect to a plane (xy) and rotating about an axis (z), is defined by:

$$\Sigma F_x = ma_x \quad \Sigma F_y = ma_y \quad \Sigma M_z = I\alpha \tag{1.7}$$

in which

m represents the mass, and

I is the principal centroidal mass moment of inertia about the z axis.

The quantities a_x, a_y, and α represent the linear and angular accelerations of the mass center about the principal x, y, and z axes, respectively. The preceding relationships express that the system of external forces is equivalent to the system consisting of the inertia forces (ma_x and ma_y) attached at the mass center and the couple moment $I\alpha$. Equation (1.7) can be written for all the connected members in a 2D system and an entire set solved simultaneously for forces and moments.

A structure or system is said to be *statically determinate* if all forces on its members can be obtained by using only the equilibrium conditions; otherwise, the structure is referred to as *statically indeterminate*. The degree of static indeterminacy is equal to the difference between the number of unknown forces and the number of pertinent equilibrium equations. Since any reaction in excess of those that can be found by statics alone is called *redundant*, the number of redundants is the same as the degree of indeterminacy. To effectively study a structure, it is usually necessary to make simplifying idealizations of the structure or the nature of the loads acting on the structure. These permit the construction of an FBD, a sketch of the isolated body and all external forces acting on it. When internal forces are of concern, an imaginary cut through the body at the section of interest is displayed, as illustrated in the next section.

1.8.2 Internal Load Resultants

Distributed forces within a member can be represented by statically equivalent *internal forces*, so-called *stress-resultants*, or load resultants. Usually, they are exposed by an imaginary cutting plane containing the centroid C through the member and resolved into components normal and tangential to the cut section. This process of dividing the body into two parts is called the method of sections. Figure 1.2a shows only the isolated left part of a slender member. A bar whose least dimension is less than about 1/10 its length may usually be considered a *slender* member. Note that the sense of moments follows the right-hand screw rule and, for convenience, is often represented by double-headed vectors. In 3D problems, the four modes of load transmission are axial force P (also denoted F or N), shear forces V_y and V_z, torque or twisting moment T, and bending moments M_y and M_z.

In planar problems, we find only three components acting across a section: the axial force P, the shear force V, and the bending moment M (Figure 1.2b). The cross-sectional face, or *plane*, is defined as positive when its outward normal points in a positive coordinate direction and as negative when its *outward* normal points in the negative coordinate direction. According to Newton's Third Law, the forces and moments acting on the faces at a cut section are equal and opposite. The location in a plane where the largest internal force resultants develop and failure is most likely to occur is called the *critical section*.

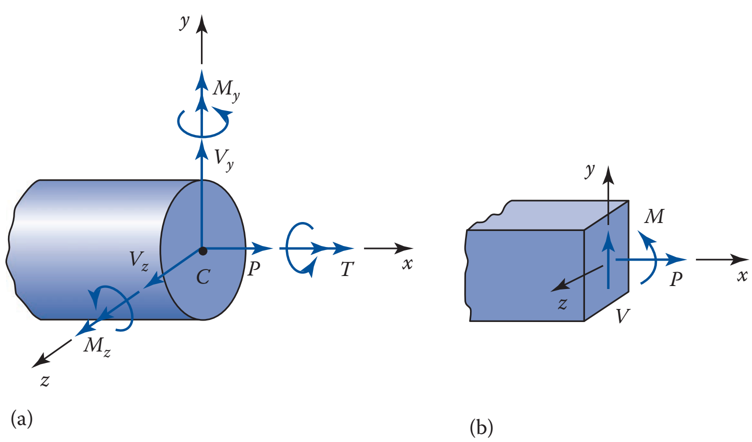

FIGURE 1.2 Internal forces and moments by the method of sections: (a) the general or three-dimensional (3D) case and (b) the two-dimensional (2D) case.

1.8.3 Sign Convention

When both the outer normal and the internal force or moment vector component point in a positive (or negative) coordinate direction, the force or moment is defined as positive. Therefore, Figure 1.2 depicts positive internal force and moment components. However, it is common practice for the direction shown in the figure to represent a negative internal shear force. In this text, we use a sign convention for *shear force* in a beam that is contrary to the definition given in Figure 1.2 (see Section 3.6). Note also that the sense of the *reaction* at a support of a structure is arbitrarily assumed; the positive (or negative) sign of the answer obtained by the equations of statics will indicate that the assumption is correct (or incorrect).

1.9 FREE-BODY DIAGRAMS AND LOAD ANALYSIS

Application of equilibrium conditions requires a complete specification of all loads and reactions that act on a structure or machine. So, the first step in the solution of an equilibrium problem should consist of drawing a *free-body diagram* (FBD) of the body under consideration. An FBD is simply a sketch of a body, with all of the appropriate forces, both known and unknown, acting on it. This may be of an entire structure or a substructure of a larger structure. The general procedure in drawing a complete FBD includes the following steps:

1. Select the free body to be used.
2. Detach this body from its supports and separate from any other bodies. (If internal force resultants are to be determined, use the method of sections.)
3. Show on the sketch all of the external forces acting on the body. Location, magnitude, and direction of each force should be marked on the sketch.
4. Label significant points and include dimensions. Any other detail, however, should be omitted.

Clearly, the prudent selection of the free body to be used (see Step 1) is of primary significance. The reader is strongly urged to adopt the habit of drawing clear and complete FBDs in the solution of problems concerning equilibrium. Example 1.1 and Case Study 1.1 will illustrate the construction of the FBDs and the use of equations of statics.

A *structure* is a unit composed of interconnected members supported in a manner capable of resisting applied forces in static equilibrium. The constituents of such units or systems are bars, beams, plates, and shells, or their combinations. An extensive variety of structures are used in many fields of engineering. Structures can be considered in four broad categories: frames, trusses, machines, and thin-walled structures. Adoption of thin-walled structure behavior allows certain simplifying assumptions to be made in the structural analysis [2]. The American Society of Civil Engineers (ASCE) lists design loads for buildings and other common structures [7].

Here, we consider load analysis dealing with the assemblies or structures made of several connected members. A *frame* is a structure that always contains at least one multiforce member, that is, a member acted on by three or more forces, which generally are not directed along the member. A *truss* is a special case of a frame, in which all forces are directed along the axis of a member. Machines are similar to frames in that at least one of the elements may be multiforce members. However, as noted earlier, a *machine* is designed to transmit and modify forces (or energy) and always contains moving parts.

Usually, the whole machine requires a *base* (a frame, housing) into or upon which all subassemblies are mounted. For this purpose, a variety of structural types may be used. A *baseplate* represents the simplest kind of machine frame. A machine room floor consists of a number of spaced cross-beams forming a grid pattern. Basically, components of machines and their bases are designed on similar principles. In both cases, recognition must be given to growing necessity for integration of manufacturing, assembly, and inspection requirements into the design process at an early stage (Section 1.3).

The approach used in the load analysis of a pin-jointed structure may be summarized as follows. First, consider the entire structure as a free body, and write the equations of static equilibrium. Then, dismember the structure, and identify the various members as either two-force (axially loaded) members or multiforce members. Pins are taken to form an integral part of one of the members they connect. Draw the FBD of each member. Clearly, when two-force members are connected to the same member, they are acted on by that member with equal and opposite forces of unknown magnitude, but known direction. Finally, the equilibrium equations obtained from the FBDs of the members may be solved to yield various internal forces.

Example 1.1: Load Resultants at a Section of a Piping

An L-shaped pipe assembly of two perpendicular parts *AB* and *BC* is connected by an elbow at *B* and bolted to a rigid frame at *C*. The assembly carries a vertical load P_A, a torque T_A at *A*, as well as its own weight (Figure 1.3a). Each pipe is made of steel of unit weight *w* and nominal diameter *d*.

Find

What are the axial force, shear forces, and moments acting on the cross-section at point *O*?

Given

$a = 0.6$ m, $b = 0.48$ m, $d = 63.5$ mm (2.5 in.), $P_A = 100$ N, $T_A = 25$ N · m, $w = 5.79$ lb/ft (see Table A.4)

Assumption

The weight of the pipe assembly is uniformly distributed over its entire length.

Solution

See Figure 1.3 and Equation (1.5).

Using the conversion factor from Table A.1, $w = 5.79$ (N/m)/(0.0685) = 84.53 N/m. Thus, the weights of the pipes *AB* and *BO* are equal to

$$W_{AB} = (84.53)(0.6) = 50.72 \text{ N}, \quad W_{BO} = (84.53)(0.48) = 40.57 \text{ N}$$

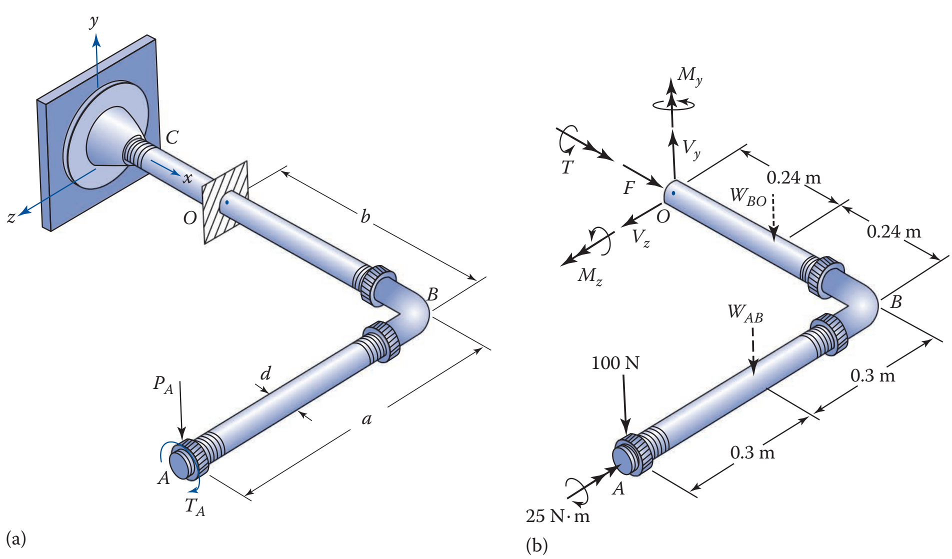

FIGURE 1.3 Example 1.1. (a) Pipe assembly and (b) FBD of part *ABO*.

Free body: Part ABO. We have six equations of equilibrium for the 3D force system of six unknowns (Figure 1.3b). The first three from Equation (1.5) results in the internal forces on the pipe at point O as follows:

$$\Sigma F_x = 0: \quad F = 0$$

$$\Sigma F_y = 0: \quad V_y - 50.72 - 40.57 - 100 = 0: \quad V_y = 191.3 \text{ N}$$

$$\Sigma F_z = 0: \quad V_z = 0$$

Applying the last three from Equation (1.5), the moments about point O are found to be

$$\Sigma M_x = 0: \quad T + (50.72)(0.3) + 100(0.6) = 0, \quad T = -75.2 \text{ N} \cdot \text{m}$$

$$\Sigma M_y = 0: \quad M_y = 0$$

$$\Sigma M_z = 0: \quad M_z - 25 - 100(0.48) - (50.72)(0.48) - (40.57)(0.24) = 0,$$

$$M_z = 107.1 \text{ N} \cdot \text{m}$$

Comment: The negative value calculated for T means that the torque vector is directed opposite to that indicated in Figure 1.3b.

1.10 CASE STUDIES IN ENGINEERING

An engineering case is an account of an engineering activity, event, or problem. Good case studies are taken from real-life situations and include sufficient data for the reader to treat the problem. They may come in the following varieties: the history of an engineering activity, illustration of some form of engineering process, an exercise (such as stress and deformation analysis), a proposal of problems to be solved, or a preliminary design project. Design analysis has its objective satisfactory performance as well as durability with minimum weight and competitive cost. Through case studies, we can create a bridge between systems theory and actual design plans.

The basic geometry and loading on a member must be given to the engineer before any analysis can be done. The stress that would result, for example, in a bar subjected to a load would depend on whether the loading gives rise to tension, transverse shear, direct shear, torsion, bending, or contact stresses. In this case, *uniform stress* patterns may be more efficient at carrying the load than others. Therefore, making a careful study of the types of loads and stress patterns that can arise in structures or machines, considerable insight can be gained into improved shapes and orientations of components. This type of study allows the designer and analyst in choosing the shape or volume (weight) of members that will optimize the use of the material provided under the conditions of applied loads.

Case studies presented in select chapters of this text involve situations found in engineering practice. Among these are various preliminary design projects: the assemblies containing a variety of elements such as links under combined axial and bending loads, ductile–brittle transition of steel, shafts subjected to bending and torsion simultaneously, gear sets and bearings subject to steady and fluctuating loads, compression springs, connections, a floor crane with electric winch, and a high-speed cutting machine. Next, Case Study 1.1 involving a bolt cutter demonstrates the simplest form of force determination.

Case Study 1.1 Bolt Cutter Loading Analysis

Many components, such as bicycle levers, automotive scissors jacks, bolt cutting tools, various types of pliers, and pin-connected symmetrical assemblies, may be treated by applying Equation (1.5), similar to that which will be illustrated here. We note that a mechanical linkage

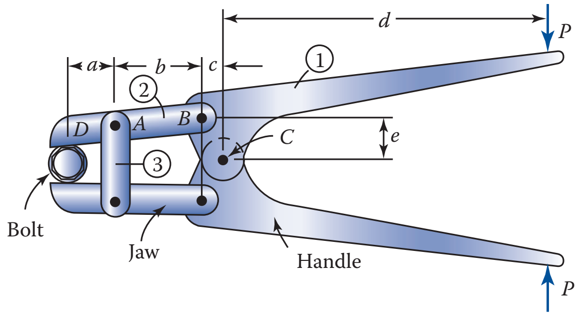

FIGURE 1.4 Sketch of a bolt cutter.

system is designed to transform a given input force and movement into a desired output force and movement. In this case, accelerations on moving bars require that a dynamic analysis be done through the use of Equation (1.7). *Bolt cutters* can be used for cutting rods (see Section I section opener page), wire mesh, and bolts. Often, a bolt cutter's slim cutting head permits cutting close to surfaces and incorporates one-step internal cam mechanism to maintain precise *jaw* or *blade* alignment. *Handle* design and handle grips lend to controlled cutting action. Jaws are manufactured from heat-treated, hardened alloy steel.

Figure 1.4 depicts schematic drawing of a bolt cutter, a pin-connected tool in the closed position in the process of gripping its jaws into a bolt. The user provides the input loads between the handles, indicated as the reaction pairs *P*. Determine the force exerted on the bolt and the pins at joints *A*, *B*, and *C*.

Given

The geometry is known. The data are

$$P = 9 \text{ N}, \quad a = 25 \text{ mm}, \quad b = 75 \text{ mm}, \quad c = 12.5 \text{ mm}, \quad d = 200 \text{ mm}, \quad e = 25 \text{ mm}$$

Assumptions

Friction forces in the pin joints are omitted. All forces are coplanar, 2D, and static. The weights of members are neglected as being insignificant compared to the applied forces.

Solution

The equilibrium conditions are fulfilled by the entire cutter. Let the force between the bolt and the jaw be *Q*, whose direction is taken to be normal to the surface at contact (point *D*). Due to the symmetry, only two FBDs shown in Figure 1.5 need to be considered. Inasmuch as link 3 is a two-force member, the orientation of force F_A is known. Note also that the force components on the two elements at joint *B* must be equal and opposite, as shown on the diagrams.

Conditions of equilibrium are applied to Figure 1.5a to give $F_{Bx} = 0$ and

$$\Sigma F_y = Q - F_A + F_{By} = 0 \quad F_A = Q + F_{By}$$

$$\Sigma M_B = Q(100) - F_A(75) = 0 \quad F_A = \frac{4Q}{3}$$

from which $Q = 3F_{By}$. In a like manner, referring to Figure 1.5b, we obtain