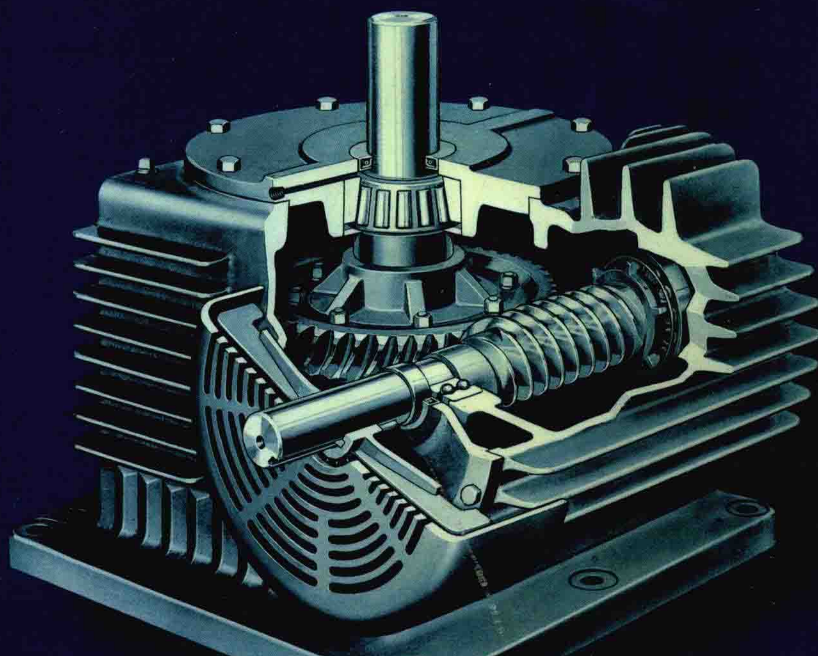
缩编国外精品教材

Mechanical Design

An Integrated Approach

机械设计

[美] Ansel C. Ugural 著　李良军 缩编



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缩编说明

本教材是美国新泽西技术学院(New Jersey Institute of Technology) Ansel C. Ugural 教授所著的"Mechanical Design: An Integrated Approach"教材的缩编版。根据我国机械设计课程教学的基本要求,原教材被缩编为9章,内容包括:设计概述,疲劳强度,轴及轴毂联接,轴承与润滑,直齿圆柱齿轮传动,斜齿圆柱齿轮传动、直齿锥齿轮传动、蜗杆传动,带传动、链传动,弹簧,螺旋传动、螺纹联接等。另有附录:英制与国际单位制换算表,常用材料性能数据,应力集中系数数据,原书著者序。

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李良军

2005年1月

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He is the author of several books, including *Stresses in Plates and Shells* (McGraw-Hill, 1999) and *Mechanics of Materials* (McGraw-Hill, 1991) with editions in Korean (1992) and Chinese (1994). Dr. Ugural is also the coauthor (with S. K. Fenster) of *Advanced Strength and Applied Elasticity* (Prentice Hall, 2003). In addition, he has published numerous articles in trade and professional journals.

Abbreviations

all	allowable
avg	average
Bhn	Brinell hardness number
CD	cold drawn
CCW	counterclockwise
cr	critical
CW	clockwise
ft	foot, feet
fpm	foot per minute
HD	hard drawn
hp	horsepower
hr	hour
H. T.	heat treated
Hz	hertz (cycles per second)
ID	inside diameter
in.	inch, inches
ipm	inch per minute
ips	inch per second
J	Joule
kip	kilopound (1000 lb)
kips	kilopounds
kg	kilogram(s)
ksi	kips per square inch (10^3 psi)
kW	kilowatt
log	common logarithm (base 10)
lb	pound(s)
ln	Naperian natural logarithm
max	maximum
m	meter
min	minimum
mph	miles per hour
m/s	meter per second
N	newton
N. A.	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
R_C	Rockwell hardness, C scale
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

Symbols

See Sections 5. 2, 5. 4, 5. 8, 5. 10, 6. 3, 6. 5, 6. 6, 6. 8, and 6. 9 for some gearing symbols.

ROMAN LETTERS

A amplitude ratio, area, coefficient, cross-sectional area
A_f final cross-sectional area
A_o original cross-sectional area
A_e effective area of clamped parts, projected area
A_t tensile stress area, tensile stress area of the thread
a acceleration, crack depth, distance, radius, radius of contact area of two spheres

B coeffcient
b distance, width of beam, band, or belt; radius

C basic dynamic load rating, bolted-joint constant, centroid, constant, heat transfer coefficient, specific heat, spring index
C_c limiting value of column slenderness ratio
C_f surface finish factor
C_r reliability factor
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 [$Et^3/12(l-v^2)$]
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_k kinetic energy
E_b modulus of elasticity for the bolt
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_f fatigue stress concentration factor
K_c fracture toughness
K_r a 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_o	original length
L_{10}	rating life
L_5	rating life for reliability greater than 90%
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	meridianal 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_o	outside or external pressure
p_0	maximum contact pressure
p_{max}	maximum pressure
p_{min}	minimum 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'_n	endurance strength of specimen
S_{es}	endurance limit in shear
S_n	endurance strength of mechanical part
S_f	fracture strength
S_p	proof strength, proportional limit strength
S_y	yield strength in tension
S_{ys}	yield strength in shear
S_u	ultimate strength in tension
S_{uc}	ultimate strength in compression
S_{us}	ultimate strength in shear
s	distance, sample standard deviation
T	temperature, tension, torque
T_a	alternating torque
T_d	torque to lower the load
T_m	mean torque
T_f	friction 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_o	strain energy density
U_{ov}	dilatational strain energy density
U_{od}	distortional 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
v	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 curved beam factor, section modulus
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 iin 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; γ_{xy}, γ_{yz}, and γ_{xz} are shear strains in the xy, yz, and xz planes
γ_{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
δ_{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

Π potential energy function

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
σ_{max} maximum normal stress
σ_{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
τ_{avg} average shear stress
τ_{all} allowable shear stress
τ_d direct shear stress
τ_{oct} octahedral shear stress
τ_{max} maximum shear stress
τ_{min} minimum shear stress
τ_{nom} nominal shear stress
τ_t torsional 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

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Chapter 1
INTRODUCTION TO DESIGN

1.1 SCOPE OF TREATMENT

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, and decision-making process. This book deals with the analysis and design of *machine elements* and basic *structural members* that compose the system or assembly. 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 displacements and buckling of a given component under prescribed loading; presents classical and numerical methods amenable to electronic digital computers for the analysis and design of members and structural assemblies; 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 is devoted mostly to mechanical component design. The fundamentals are applied to specific machine 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 members and others. Power screws; threaded fasteners; bolted, riveted, and welded connections are also considered in some detail.

The full understanding of both terminology in statics and principles of mechanics is an essential prerequisite to 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 elasticity is used or referred to in design of certain elements. The objective of this chapter is to provide the reader the basic definitions and process of the design, and the concepts of stress concentration factors, reliability, contact stress distributions in a condensed form.

1.2 ENGINEERING DESIGN

Design is the formulation of a plan to satisfy a particular need, real or imaginary. *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.

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 the stress analysis methods and materials engineering. A *machine* is an apparatus consisting of interrelated elements or a device that modifies force or motion. *Machine design* is the art of planning or devising new or improved machines to accomplish specific purpose. Although *structural design* is most directly associated with civil engineering, it interacts with any engineering discipline 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, 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. Communications is as significant as technology. Basically, the means of communication are in written, oral, and graphical forms. The first fundamental canon in the *Code of Ethics for Engineers* 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. 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 reasonable values of the factors, is important in the design process. As a designer gains more experience, decisions are reached more readily.

1.3 THE 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 need as a design problem to be solved, understanding the problem, generating and evaluating possible solutions, and deciding on the best solution.

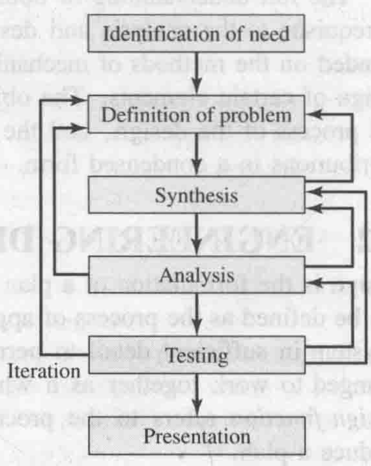

Figure 1.1 Design process.

PHASES OF DESIGN

The design process is independent of the product and is based on the concept of product life cycle. 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. Note that, the process is neither exhaustive nor rigid and will probably be modified to suit individual problems.

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 improving 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 origin in any number of sources. Customer reports on the product function and quality may force 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.

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. All specifications, that is, all forms of input and output quantities, 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.

Synthesis

The synthesis (putting together) of the solution represents perhaps the most challenging and interesting part of 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.

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.

Testing

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.

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. A number of references are available on the design process for those seeking a more-thorough discussion.

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. 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 communications standpoint, to integrate them into the design process.

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.

THE ENGINEERING MODELING

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

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 2.7, 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. Suffice it to say that complete design solutions are not unique, and often trial and error is required to find the best solution.

METHODS OF ANALYSIS

Design methods are based on the mechanics of materials theory generally used in this text. The approach employs assumptions based on experimental evidence along with engineering experience to make a reasonable solution of the practical problem possible.

Note that solutions based on the mechanics of materials give average stresses at a section. Since, at concentrated forces and abrupt changes in cross section, irregular local stresses (and strains) arise, only at 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 force 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 configurations of loading and member are regular, and they can be employed as a basis of the numerical methods, for more complex problems.