Applied Strength of Materials

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Preface

This book is written primarily for students in four-year engineering technology programs and architectural schools to provide a clear, practical, and easy to understand textbook for a course in Applied Strength of Materials. A workable knowledge of algebra, geometry, and trigonometry is expected of the students. Calculus is used in a few sections for formula derivations and in only one section (beam deflection by the double integration method) for problem solutions, but a lack of background in calculus will not cause a major problem in using the book. Students are assumed to have completed a course in statics. The brief review of statics in Chapter 1 will refresh their memory on the subject.

Both U.S. customary units and SI units are used side by side throughout the book. The U.S. customary units are slightly favored in design topics because most design code, section property tables, and design aids are available only in U.S. customary units.

Basic concepts and fundamental principles are emphasized throughout the book. Topics are presented in a logically organized sequence, generally with increasing complexity. Each topic is carefully developed and clearly explained. An ample amount of example problems with detailed solutions are provided to illustrate each particular phase of the topic under consideration. Extra care has been taken to make the logic of the solution process easy for students to follow.

The book contains an extensive and well-developed coverage of design topics. These topics are designed to familiarize students with the general procedure involved in the design process and to provide them with some perception of the design work performed by engineers. The design of members is introduced as early as Chapter 2 and is scattered throughout the book. Since design is so closely related to analysis, it is logical to discuss the two types of problems at the same time. Furthermore, the early introduction of design problems gives students a greater incentive to study the subject.

A large number of problems of various levels of difficulty are provided at the end of each section within the chapter. In this way students immediately relate the problems to the section covered. The problems in each group are graded according to increasing difficulty, beginning with relatively simple, uncomplicated problems to help students gain confidence and develop technique. In many instances the given data are carefully arranged in order to simplify the numerical solution so that students can concentrate more on the logic and procedure of the solution. The last few problems in the group are usually more involved than the others. These problems provide students with enough challenge to maintain their interest. Answers to two-thirds of the problems are given at the end of the book.

A solutions manual, which provides detailed solutions to all the problems, is available to instructors.

Computer program assignments are included at the ends of Chapters 8, 11, and 12, where computer programming can be used advantageously to handle general problems in beam deflections, transformation of plane stress, and column buckling. These programs can be assigned to students as projects. Some instructors may prefer to load the FORTRAN programs listed in the solutions manual into the school computer and let the students input data and run the programs.

The book starts with a review of the fundamentals in Chapter 1, in which systems of units, differential and integral calculus, and statics are reviewed; followed by discussions on simple stresses caused by simple loading conditions in Chapter 2 and the relationship between stress and strain in Chapter 3. Shaft and beam topics are covered in the subsequent chapters. Before the shear force and bending moment diagrams are discussed in Chapter 6, axial force diagrams and torque diagrams are introduced in Chapters 2 and 5, respectively. The author believes that this arrangement helps students understand better the meaning and significance of the shear and moment diagrams.

All the material pertaining to statically indeterminate members is treated collectively in Chapter 9. This is done for two reasons: First, because of the similarity in the method of solution of all statically indeterminate problems, the solutions to one type of problem will help students to understand the solutions to the other type of problem. Second, most students find statically indeterminate problems more difficult. Therefore, the author feels strongly that none of the statically indeterminate problems should be discussed in the first few chapters.

The subject of combined stresses is discussed in Chapter 10. This chapter can be regarded as an overall review of the material studied previously. Transformation of plane stress and Mohr's circle are introduced in Chapter 11. The geometry of Mohr's circle is used for the derivation of the formulas for principal stresses; thereby more involved mathematics is avoided. The buckling of columns is discussed in Chapter 12. This discussion is mainly based on the Euler formula for long columns and the J. B. Johnson formula for intermediate columns. Finally, structural connections, including riveted connections, high-strength-bolt connections, and welded connections are covered in Chapter 13.

The book contains more material than can be covered in the first course in Applied Strength of Materials. The extra material is included to provide flexibility in the selection of topics for instructors and to serve as a valuable reference book for students. Topics identified with an asterisk on the section title can be omitted without affecting the continuity of the text.

The author is confident that this book will prove to be an effective textbook for its intended purpose. The initial lecture notes on which this book is based have been field-tested for many years and have been extremely well received by students.

To the many reviewers whose valuable suggestions made this book a better work, the author expresses deep appreciation. The author wants also to thank his wife, Rosa, and his two sons, Lincoln and Lindsay, for their loving support.

Fa-Hwa Cheng

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CHAPTER 1

Review of the Fundamentals

1–1 INTRODUCTION

Strength of materials deals with the internal forces in a body and the changes of shape and size of the body, particularly in the relationship of the internal force to the external forces that act on the body. The body is usually a structural or machine member, such as a shaft, a beam, or a column. The external forces acting on a body consist of loads and reactions. The body reacts to the external forces by developing internal resisting forces. The intensities of the internal resisting forces are called *stresses*. The changes in the dimensions of the body are called *deformations*.

The subject of strength of materials involves analytical methods for determining the *strength* (load-carrying capacity based on stresses inside a member), *stiffness* (deformation characteristics), and *stability* (the ability of a thin or slender member to maintain its initial configuration without buckling while being subjected to compressive loading). The sizes of all structural or machine members must be properly designed according to the requirements for strength, stiffness, and/or stability. For example, the wall of a pressure vessel must be of adequate strength to withstand the internal pressure for which the vessel is designed. On the other hand, if a thin-walled vessel is subjected to partial vacuum that causes compressive stress in the wall, then the safe level of vacuum at which the stability of the thin wall can be maintained must be determined. The floor of a building must be strong enough to carry the design load, while being stiff or rigid enough so that it will not deflect excessively under the applied load.

Strength of materials is one of the most fundamental subjects in the engineering curriculum. Its methods are needed by structural engineers in the design of bridges, buildings, and aircraft; by mechanical engineers in the design of machines, tools, and pressure vessels; and by mining engineers, chemical engineers, and electrical engineers in those phases of their jobs that involve the analysis and design of structural or machine members.

Keep in mind that in relating internal resisting forces to external forces, the methods developed in statics still apply because the body or part of the body under consideration is only slightly deformed and the small deformations have a negligible effect on equilibrium conditions. Therefore, free-body diagrams and application of the static equilibrium equations are essential to the determination of both the external reactions and the internal resisting forces in a body.

Statics is reviewed briefly in Section 1–7. Differential and integral calculus are discussed briefly in Section 1–8.

1–2 SYSTEMS OF UNITS

Currently, there are two systems of units used in engineering practice in the United States. They are the U.S. customary system of units and the International System of units, or SI units (from the French "Système International d'Unités"). The SI units have now been widely adopted throughout the world. In industrial and commercial applications in the United States, U.S. customary units are gradually being replaced by SI units. During the transition years, engineers in this country must be familiar with both systems. For this reason, both systems of units are presented in this book. The U.S. customary system is slightly favored in design problems because most design codes, section property tables, and design aids are available only in U.S. customary units.

1–3 U.S. CUSTOMARY UNITS

The U.S. Customary system of units is commonly used in engineering practice in the United States, especially in civil, architectural, and mechanical engineering. The base units in this system are

length: foot (ft)
force: pound (lb)
time: second (s)

Because the base unit for force, pound, is dependent on the gravitational attraction of the earth, this system is referred to as the *gravitational system* of units.

The unit of mass in this system is the slug, which is a derived unit. Newton's second law states that

$$\text{force} = \text{mass} \times \text{acceleration}$$

or

$$F = ma \tag{1-1}$$

Thus

$$m = \frac{F}{a} = \frac{\text{lb}}{\text{ft/s}^2} = \text{lb}-\text{s}^2/\text{ft} = \text{slug}$$

The unit "slug" is rarely used in strength of materials.

Other U.S. customary units frequently encountered in mechanics are

$$\text{mile (mi)} = 5280 \text{ ft}$$
$$\text{yard (yd)} = 3 \text{ ft}$$
$$\text{inch (in.)} = \tfrac{1}{12} \text{ ft}$$
$$\text{kilopound (kip)} = 1000 \text{ lb}$$
$$\text{U.S. ton (ton)} = 2000 \text{ lb}$$
$$\text{minute (min)} = 60 \text{ s}$$
$$\text{hour (h)} = 60 \text{ min} = 3600 \text{ s}$$

1–4 SI UNITS

The three base SI units are

length: meter (m)

mass: kilogram (kg)

time: second (s)

The SI units are called an *absolute system* of units, since the three base units chosen are independent of the location where the measurement is made.

The unit of force, called the newton (N), is a derived unit expressed in terms of the three base units. One newton is defined as the force that produces an acceleration of 1 m/s^2 (read "meters per second squared" or "meters per second per second") when applied to a mass of 1 kg. From Eq. (1–1),

$$F = ma$$

or

$$1 \text{ N} = (1 \text{ kg})(1 \text{ m/s}^2) = 1 \text{ kg} \cdot \text{m/s}^2$$

Thus the newton is equivalent to kg · m/s^2.

The acceleration of a freely falling body under the action of its own weight (which is the force exerted on the mass by gravity) is approximately 9.81 m/s^2 on the surface of the earth. This quantity is usually denoted by g and is called the *gravitational acceleration*. From Eq. (1–1), for a freely falling body on the surface of the earth, we have

$$W = mg = (1 \text{ kg})(9.81 \text{ m/s}^2) = 9.81 \text{ kg} \cdot \text{m/s}^2 = 9.81 \text{ N}$$

which means that the weight of 1-kg mass is 9.81 N on the surface of the earth.

Multiples of the SI units are abbreviated by use of the prefixes shown in Table 1–1.

TABLE 1–1 Recommended SI Prefixes

	Exponential Form	*Prefix*	*SI Symbol*
1 000 000 000*	10^9	giga	G
1 000 000	10^6	mega	M
1 000	10^3	kilo	k
0.001	10^{-3}	milli	m
0.000 001	10^{-6}	micro	μ

*A space rather than a comma is used to separate numbers in groups of three, counting from the decimal point in both directions. Space may be omitted for four-digit numbers.

The following are typical examples of the use of prefixes:

$$10^6 \text{ g} = 10^3 \text{ kg} = 1 \text{ Mg}$$
$$10^3 \text{ m} = 1 \text{ km}$$
$$10^3 \text{ N} = 1 \text{ kN}$$
$$10^{-3} \text{ kg} = 1 \text{ g}$$
$$10^{-3} \text{ m} = 1 \text{ mm}$$

1–5 CONVERSION OF UNITS

In this book, problems are solved in the system of units used in the data given. There is no need to convert units from one system to the other. In actual engineering applications, however, there are many occasions when it is necessary to convert units. For this purpose, the following unit conversion factors are useful:

$$1 \text{ ft} = 0.3048 \text{ m}$$
$$1 \text{ slug} = 14.59 \text{ kg}$$
$$1 \text{ lb} = 4.448 \text{ N}$$

The following examples illustrate the conversion of units.

EXAMPLE 1–1

Convert a moment of 1 lb-ft into equivalent value in N · m.

SOLUTION

$$\text{moment} = 1 \text{ lb-ft} = (1 \not{\text{lb}}\text{-}\not{\text{ft}})\left(\frac{4.448 \text{ N}}{1 \not{\text{lb}}}\right)\left(\frac{0.3048 \text{ m}}{1 \not{\text{ft}}}\right) = 1.356 \text{ N} \cdot \text{m}$$

The two conversion factors (4.448 N/1 lb) and (0.3048 m/1 ft) are each equal to unity. The value of a quantity is not changed when it is multiplied by factors of unity. ■

TABLE 1–2 U.S. Customary Units and SI Equivalents

Quantity	*U.S. Customary Unit*	*SI Equivalent*
Length	ft	0.3048 m
	in.	25.40 mm
	mi	1.609 km
Force	lb	4.448 N
	kip	4.448 kN
Mass	slug	14.59 kg
Area	ft^2	0.092 90 m^2
	$in.^2$	645.2 mm^2
	mi^2	2.590 km^2
Volume	ft^3	0.028 32 m^3
Velocity	ft/s (fps)	0.3048 m/s
	mi/h (mph)	1.609 km/h
Acceleration	ft/s^2	0.3048 m/s^2
Stress	lb/ft^2 (psf)	47.88 Pa (pascal or N/m^2)
(or pressure)	$lb/in.^2$ (psi)	6.895 kPa (kN/m^2)
	$kip/in.^2$ (ksi)	6.895 MPa (MN/m^2)
Moment	lb-ft	1.356 N · m
(of a force)	lb-in.	0.1130 N · m
Area moment of inertia	$in.^4$	0.4162×10^{-6} m^4
Work	ft-lb	1.356 J (joule or N · m)
Power	ft-lb/s	1.356 W (watt or N · m/s)
	hp (1 hp = 550 ft-lb/s)	745.7 W

EXAMPLE 1–2

Convert a stress (a quantity derived as force per unit area) of 1 psf (lb/ft^2) into equivalent value in Pa (pascal or N/m^2).

SOLUTION

$$\text{stress} = 1 \text{ psf} = \left(1\ \frac{\cancel{lb}}{\cancel{ft^2}}\right)\left(\frac{4.448\ N}{1\ \cancel{lb}}\right)\left(\frac{1\ \cancel{ft^2}}{0.0348^2\ m^2}\right) = 47.88\ N/m^2$$
$$= 47.88\ Pa$$

The U.S. customary units and the SI equivalents that are used most frequently in mechanics are listed in Table 1–2.

1–6 REMARKS ON NUMERICAL ACCURACY

The accuracy of the solution of a problem depends on two factors:

1. The accuracy of the data given.
2. The accuracy of the computations performed.

The accuracy of computations made by using an electronic calculator is always greater than the accuracy of the physical data given. Therefore, the accuracy of a solution is always limited by the accuracy of the known physical data.

A practical rule of rounding off figures in the computations involved in engineering analysis and design is to retain four significant figures for numbers beginning with the figure "1" and to retain three significant figures for numbers beginning with any figures from "2" through "9." Thus the value 182.35 is rounded off to 182.4, and the value 2934 is rounded off to 2930.

PROBLEMS*

1–1 Convert the following SI units to the SI units indicated.
- **(a)** 6.38 Gg to kg
- **(b)** 900 km to m
- **(c)** 3.76×10^7 g to Mg
- **(d)** 70 mm to m
- **(e)** 23 400 N to kN

1–2 The specific weight (weight per unit volume) of concrete is 150 lb/ft^3. What is its equivalent value in kN/m^3?

1–3 Use the conversion factors listed in Table 1–2 to convert the following units.
- **(a)** 200 lb-ft to N · m
- **(b)** 60 mph to km/h
- **(c)** 100 hp to kW
- **(d)** 9.81 m/s^2 to ft/s^2
- **(e)** 100 MN/m^2 to ksi ($kips/in.^2$)
- **(f)** 10 m/s to mph

1–7 BRIEF REVIEW OF STATICS

Some fundamental definitions, principles, laws, or theorems in statics are listed below.

1. Forces are vector quantities. Two concurrent forces can be added by the *parallelogram law*.
2. As far as the external effect of a force is concerned, the force can be considered to act at any point along its line of action. This is known as the *principle of transmissibility*.
3. The *moment of a force* about a point is defined as the product of the magnitude of the force and the perpendicular distance from the point to the line of action of the force. The moment is also equal to the sum of the moments produced by the components of the force about the same point. This is known as the *theorem of moments*.
4. The action and reaction forces between interactive bodies always occur in equal and opposite pairs. This is known as *Newton's third law*.
5. A body is in static equilibrium when the resultant of all the forces acting on it is zero. For a body to be in equilibrium under the action of coplanar

* Answers to two-thirds of the problems are given at the end of the book.

force system, the following equilibrium equations must be satisfied:

$$\Sigma F_x = 0 \qquad \Sigma F_y = 0 \qquad \Sigma M_A = 0 \qquad (1\text{–}2)$$

where A is an arbitrary point in the plane of the forces.

6. Instead of Eqs. (1–2), either one of the following sets of equilibrium equations can be used for solving static equilibrium problems.

$$\Sigma F_x = 0 \qquad \Sigma M_A = 0 \qquad \Sigma M_B = 0 \qquad (1\text{–}3)$$

where A and B are arbitrary points, except that line AB is not along the y-direction; or

$$\Sigma M_A = 0 \qquad \Sigma M_B = 0 \qquad \Sigma M_C = 0 \qquad (1\text{–}4)$$

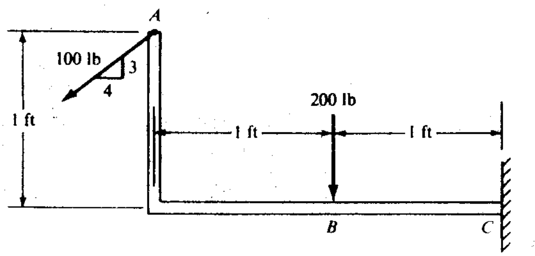
where A, B, and C are arbitrary points not along the same straight line.

7. A free-body diagram is a sketch of an isolated body with all the external forces acting on the body shown. To solve an equilibrium problem, a free-body diagram must be drawn first.
8. A two-force body is a body acted upon by only two forces. For a two-force body to be in equilibrium, the two forces must be equal, opposite, and collinear.
9. A three-force body is a body acted upon by three coplanar nonparallel forces. For a three-force body to be in equilibrium, the three forces must pass through a common point.

For detailed information on the items listed above, the student should refer to a statics text.

EXAMPLE 1–3

The bracket shown is supported by a fixed support at C. Determine the reactions at C due to the given loads.



SOLUTION

The free-body diagram of the bracket is shown in the following figure. The 100-lb force is replaced by its horizontal and vertical components. At the fixed support C, three unknown reaction components, R_x, R_y, and M, are shown.