Statics and Strength of Materials

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Preface

This book is designed to provide a clear, practical, and easy to understand text for use in engineering technology programs. The materials are presented in such a manner that the book can also be used as a reference for practicing structural engineers, mechanical engineers, and architects. Applications of the underlying principles in the subject matter—Statics and Strength of Materials—are emphasized, while using a level of mathematics that does not include calculus. A working knowledge of algebra, geometry, and trigonometry, however, is essential. A review of trigonometry is included in Chapter 1.

Each topic in this book is carefully developed and clearly explained. Many example problems with detailed solutions are provided to illustrate each particular phase of the topic under consideration. In the Statics part, the coverage of the concepts of force systems is systematic and thorough. These concepts are very important in the basic training in mechanics and all too often are covered too briefly. In the Strength of Materials part, the book contains an extensive and well-developed coverage of design topics. These topics are intended 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 practicing technologists and designers. Furthermore, this book includes the following features.

1. Topics are presented in a logically organized sequence aimed at enhancing the learning process. Topics appear in a sequence of increasing difficulty to provide students with a reasonable challenge and to maintain their interest as they progress.

2. Many problems of various levels of difficulty are provided with each new topic. 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 teachers who have adopted this book for classroom use. The problems in each group are arranged in order of increasing difficulty, beginning with relatively simple, uncomplicated problems to help students gain confidence in the topic. The last few problems in the group are usually more involved than the others. These more difficult problems could be assigned to students who prefer more challenging assignments. The author believes that with this arrangement the book can be used for classes of varying ability.

3. A good understanding of the basic principles and their applications is emphasized, so that the students can utilize the far-reaching applicability of a few basic principles and methods and apply these to a variety of problems.

4. Both U.S. customary units and SI units (the international system of units)

are used throughout the book. These systems of units are introduced in Chapter 1. The author believes that this approach will help students to cope with both present practice and the anticipated increasing usage of SI units in engineering practice.

5. Students are expected to use a "scientific calculator." Instructions on proper and efficient use of the calculator for typical computations are included whenever they are encountered for the first time.

6. Computer program assignments are included at the ends of Chapters 15, 16, and 18, where computer programming can be used advantageously to handle the general problems in beam deflections, stress transformation, and column buckling. These programs may be assigned to students as projects or an instructor may choose to load the FORTRAN programs listed in the Solutions Manual into the school computer and let students input data and run the programs to get results.

7. Because free-body diagrams are the foundation of mechanics, they are discussed in great detail in Chapter 4 and their importance is emphasized throughout the book.

8. Three-dimensional problems are treated after completion of two-dimensional analysis. This approach will allow students to gain confidence in two-dimensional analysis before coping with the more involved three-dimensional problems. It also permits an instructor with limited time to have the option of omitting the three-dimensional problems altogether without affecting the continuity of the course.

9. Many topics, including graphical method of joints (Maxwell diagram), analysis of machines (frames with movable parts), square-threaded screws, belt friction, liquid pressure, flexible cables, stress concentrations, transformation of plane stress, Mohr's circle of stresses, axial stresses in members of two materials, thermal stresses, and statically indeterminate beams, which usually are not covered in other books of the same level, are included in this book. This is done for two reasons: First, it provides instructors with more freedom in their selection of topics; and second, even though some of these topics are not covered in class, the materials could be useful references for students in other course work or in engineering practice.

The author is confident that this work will prove to be an effective textbook for teaching the statics and strength of materials course in engineering technology programs. The initial lecture notes on which this book is based have been used successfully in the classroom for many years by the author and by his colleagues.

The author wants to thank Professor Hugh B. Phelps for his enthusiasm in field testing the manuscripts in the classrooms and for his many valuable suggestions. Thanks are also due to the following reviewers whose constructive suggestions have made this book a better work: Victor G. Forsnes, Ricks College; Ronald F. Amberger, Rochester Institute of Technology; David A. Pierce, Columbus Technical Institute; John O. Pautz, Middlesex County College; T. M. Brittain, The University of Akron; and John Keeley, Mt. Hood Community College. The author also acknowledges the contributions of Ms. Judy Green, Executive Editor, and Mrs. Elaine Wetterau, Production Supervisor, in the production of this book. Appreciation is due to the author's wife, Rosa, and his two sons, Lincoln and Lindsay, for their support and encouragement during the busy period when the manuscript of this book was being prepared.

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CHAPTER 1

Fundamental Concepts

1–1 INTRODUCTION

Mechanics deals with forces and with the effects of forces acting on bodies as to the state of rest or motion, as well as the internal resistances and deformations of the bodies. Mechanics is usually divided into three parts: statics, dynamics, and strength of materials. *Statics* concerns the balance of forces that act on bodies at rest or in unaccelerated motion. *Dynamics* deals with the motion of bodies and forces which cause that motion. *Strength of materials* deals with the relations between external forces applied to bodies and the resulting stresses (force per unit area within a body) and deformations (changes of shapes and/or sizes of bodies). It also involves the determination of proper sizes of various types of structural members to satisfy strength and deformation requirements.

In the study of statics and dynamics, all bodies are assumed to be rigid. A *rigid body* is a solid in which all the points in the body remain in fixed positions relative to each other. This is an idealized situation, since in reality deformations do occur in all bodies when they are subjected to forces. However, actual deformations are usually very small and they can be neglected in static and dynamic analyses without introducing appreciable error.

In the study of strength of materials, deformations of structural members become very important. Structural members are treated as elastic bodies and their small deformations due to externally applied forces will not be ignored. In some cases quantitative determination of deformation is necessary, such as calculations of beam deflections and the amount of twist in circular shafts. In other cases deflection conditions of structures are needed to determine the external support reactions in so-called "statically indeterminate" problems.

This book concentrates on two major topics. The first eight chapters deal with statics, and the remaining chapters deal with strength of materials. Dynamics is not covered in this book.

1–2 NATURE OF A FORCE

A *force* is any effect that may start, stop, or change the motion of a body. It represents the action and/or reaction of one body on another. The existence of forces can be observed by the effects that the forces produce. A body stands still or moves because of the action of forces.

Force is applied either by direct physical contact between bodies or by remote action. Gravitational and magnetic forces are applied through remote action. Most other forces are applied by direct contact.

The pulling forces exerted on a rope by hands and the forces between an engine and its supports are examples of forces applied by direct contact. Less obvious cases of contact forces occur when a solid body comes in contact with a liquid or a gas. Forces exist between water and the hull of a boat, and similarly, between air and airplane wings.

When a ball is thrown into the air, it falls to the ground. The pull of the earth's gravity, exerted through remote actions, causes the ball to fall. The attraction force of the earth acting on a body is usually referred to as the weight of the body. When a magnet attracts small pieces of iron through remote action, the magnetic force causes the iron to move.

A force is characterized by its magnitude, its direction, its line of action, and its point of application. A force is therefore a *vector quantity*. The characteristics of vector quantities are discussed in the next section.

1–3 SCALARS AND VECTORS

Quantities dealt with in mechanics can generally be classified as scalars and vectors. Scalar quantities can be totally specified by a magnitude. Examples of scalar quantities are length, area, volume, speed, mass, and time.

Vector quantities are described by magnitude, direction, line of action, and sometimes point of application. Furthermore, vector quantities obey a mathematical rule, called the "parallelogram law" for the addition of vectors. The parallelogram law is discussed in Chapter 2. Examples of vector quantities are force, moment, displacement, velocity, and acceleration.

1–4 NEWTON'S LAWS

In the latter part of the seventeenth century, Sir Isaac Newton (1642–1727) formulated three laws governing the equilibrium (a body subjected to balanced forces) and motion (a body subjected to unbalanced forces) of a particle. A particle is a point mass of negligible dimension. Newton's laws now form the foundation of what is known as Newtonian mechanics. Newton's three laws are

First Law. *A particle remains at rest or continues to move along a straight line with a constant velocity if the resultant force (vector sum of the forces) acting on it is zero.*

Second Law. *If the resultant force acting on a particle is not zero, the particle accelerates (changes velocity with respect to time) in the direction of the resultant, and the magnitude of the acceleration (the rate of change of velocity per unit time) is proportional to the magnitude of the resultant force.*

Third Law. *The force of action and reaction (applied and counterreacting forces) between interactive bodies are always along the same line of action and have the same magnitudes, but opposite directions.*

Newton's second law forms the basis for the study of dynamics. It may be written as a vector equation:

$$\Sigma \mathbf{F} = m\mathbf{a} \tag{1-1}$$

where boldface letters represent vector quantities and the symbol Σ (the Greek capital letter sigma) denotes a summation. The quantity $\Sigma \mathbf{F}$ stands for the resultant (vector sum) of external forces acting on a particle. The vector $\mathbf{a}$ is the acceleration of the particle caused by the resultant force, and the scalar m is the mass of the particle. Mass is a measure of the particle's inertia, its resistance to a change of motion. A particle of larger mass has greater resistance to a change of motion and hence will accelerate less under the action of a given force.

The first law can be considered as a special case of the second law, since if the resultant force acting on the particle is zero, then from Eq. (1–1) the acceleration ($\mathbf{a}$) must also be zero, and thus the particle undergoes no change of velocity.

The third law is important for applications in both statics and dynamics. It states that active and reactive forces between interactive bodies always occur in equal and opposite pairs. For example, the downward push exerted by an object resting on a table is accompanied by an upward push of the same magnitude exerted by the table on the object. Newton's third law applies equally well for gravitational and magnetic forces. For example, the gravitational force exerted by the earth on a flying airplane is equal to the force that the airplane exerts on the earth (of course, this force has a negligible effect on the earth because of the earth's enormous mass).

1–5 SYSTEMS OF UNITS

The quantities appearing in Eq. (1–1) involve measurements of length, time, mass, and force. The units of measurement of these four quantities cannot be chosen independently. Equation (1–1) is an equality, meaning that both numerical magnitudes and units must be the same on each side of the equation. We are free to choose the units of three of the four quantities, but the fourth must be derived in accordance with Eq. (1–1).

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.

1–6 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.

In this system, the unit for mass is derived from the three base units. From Eq. (1–1),

$$F = ma$$

where the unit for force is the pound and the unit for acceleration, a, is ft/s^2. Therefore, the derived unit for mass is

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

which is called the slug (i.e., slug = lb-s^2/ft). The slug is rarely used in statics or in strength of materials.

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

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

The conversion of units within the U.S. customary system requires use of these conversion factors. For example, to convert 60 mph (mi/h) into its equivalent value in ft/s, we write

$$v = \left(60\,\frac{\cancel{\text{mi}}}{\cancel{\text{h}}}\right)\left(\frac{5280\text{ ft}}{1\,\cancel{\text{mi}}}\right)\left(\frac{1\,\cancel{\text{h}}}{3600\text{ s}}\right) = 88\text{ ft/s}$$

Since it is known that 1 mi = 5280 ft and 1 h = 3600 s, the two conversion factors, 5280 ft/1 mi and 1 h/3600 s, are each equal to unity. The value of a quantity is not changed when it is multiplied by factors of unity.

1–7 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 $\text{kg} \cdot \text{m/s}^2$.

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:

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

The conversion of SI units can be effected simply by multiplying by proper multiples and making the corresponding change in prefixes:

$$4.58 \text{ km} = 4.58 \times 10^3 \text{ m}$$
$$2.73 \text{ Mg} = 2.73 \times 10^3 \text{ kg} = 2.73 \times 10^6 \text{ g}$$
$$83.4 \text{ mm} = 83.4 \times 10^{-3} \text{ m}$$

1–8 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 (a quantity derived as a force multiplied by a distance) of 1 lb-ft into equivalent value in N · m.

SOLUTION

$$\text{moment} = 1 \text{ lb-ft} = (1 \cancel{\text{lb-ft}})\left(\frac{4.448 \text{ N}}{1 \cancel{\text{lb}}}\right)\left(\frac{0.3048 \text{ m}}{1 \cancel{\text{ft}}}\right) = 1.356 \text{ N} \cdot \text{m}$$

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).