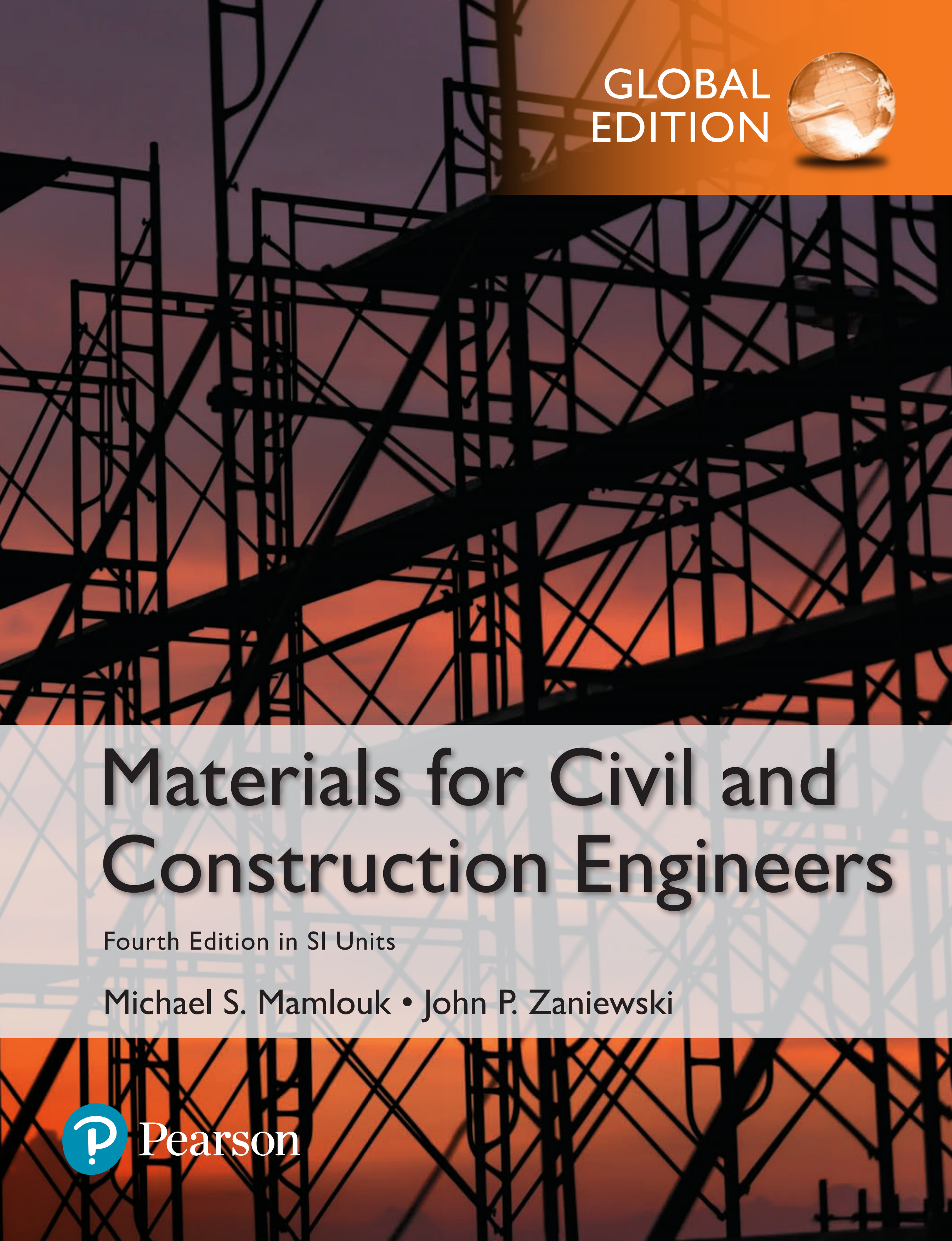
GLOBAL EDITION

Materials for Civil and Construction Engineers

Fourth Edition in SI Units

Michael S. Mamlouk • John P. Zaniewski

Pearson



MATERIALS FOR CIVIL AND CONSTRUCTION ENGINEERS

FOURTH EDITION IN SI UNITS

MICHAEL S. MAMLOUK

JOHN P. ZANIEWSKI

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PREFACE

A basic function of civil and construction engineering is to provide and maintain the infrastructure needs of society. The infrastructure includes buildings, water treatment and distribution systems, waste water removal and processing, dams, and highway and airport bridges and pavements. Although some civil and construction engineers are involved in the planning process, most are concerned with the design, construction, and maintenance of facilities. The common denominator among these responsibilities is the need to understand the behavior and performance of materials. Although not all civil and construction engineers need to be material specialists, a basic understanding of the material selection process, and the behavior of materials, is a fundamental requirement for all civil and construction engineers performing design, construction, and maintenance.

Material requirements in civil engineering and construction facilities are different from material requirements in other engineering disciplines. Frequently, civil engineering structures require tons of materials with relatively low replications of specific designs. Generally, the materials used in civil engineering have relatively low unit costs. In many cases, civil engineering structures are formed or fabricated in the field under adverse conditions. Finally, many civil engineering structures are directly exposed to detrimental effects of the environment.

The subject of engineering materials has advanced greatly in the past few decades. As a result, many of the conventional materials have either been replaced by more efficient materials or modified to improve their performance. Civil and construction engineers have to be aware of these advances and be able to select the most cost-effective material or use the appropriate modifier for the specific application at hand.

This text is organized into three parts: (1) introduction to materials engineering, (2) characteristics of materials used in civil and construction engineering, and (3) laboratory methods for the evaluation of materials.

The introduction to materials engineering includes information on the basic mechanistic properties of materials, environmental influences, and basic material classes. In addition, one of the responsibilities of civil and construction engineers is the inspection and quality control of materials in the construction process. This requires an understanding of material variability and testing procedures. The atomic structure of materials is covered in order to provide basic understanding of material behavior and to relate the molecular structure to the engineering response.

The second section, which represents a large portion of the book, presents the characteristics of the primary material types used in civil and construction engineering: steel, aluminum, concrete, masonry, asphalt, wood, and composites. Since the discussion of concrete and asphalt materials requires a basic knowledge of aggregates, there is a chapter on aggregates. Moreover, since composites are gaining wide acceptance among engineers and are replacing many of the conventional materials, there is a chapter introducing composites.

The discussion of each type of material includes information on the following:

- Basic structure of the materials
- Material production process
- Mechanistic behavior of the material and other properties
- Environmental influences
- Construction considerations
- Special topics related to the material discussed in each chapter

Finally, each chapter includes an overview of various test procedures to introduce the test methods used with each material. However, the detailed description of the test procedures is left to the appropriate standards organizations such as the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO). These ASTM and AASHTO standards are usually available in college libraries, and students are encouraged to use them. Also, there are sample problems in most chapters, as well as selected questions and problems at the end of each chapter. Answering these questions and problems will lead to a better understanding of the subject matter.

There are volumes of information available for each of these materials. It is not possible, or desirable, to cover these materials exhaustively in an introductory single text. Instead, this book limits the information to an introductory level, concentrates on current practices, and extracts information that is relevant to the general education of civil and construction engineers.

The content of the book is intended to be covered in one academic semester, although quarter system courses can definitely use it. The instructor of the course can also change the emphasis of some topics to match the specific curriculum of the department. Furthermore, since the course usually includes a laboratory portion, a number of laboratory test methods are described. The number of laboratory tests in the book is more than what is needed in a typical semester in order to provide more flexibility to the instructor to use the available equipment. Laboratory tests should be coordinated with the topics covered in the lectures so that the students get the most benefit from the laboratory experience.

The first edition of this textbook served the needs of many universities and colleges. Therefore, the second edition was more of a refinement and updating of the book, with some notable additions. Several edits were made to the steel chapter to improve the description of heat treatments, phase diagram, and the heat-treating effects of welding. Also, a section on stainless steel was added, and current information on the structural uses of steel was provided. The cement and concrete chapters have been augmented with sections on hydration-control admixtures, recycled wash water, silica fume, self-consolidating concrete, and flowable fill. When the first edition was published, the Superpave mix design method was just being introduced to the industry. Now Superpave is a well-established method that has been field tested and revised to better meet the needs of the paving community. This development required a complete revision to the asphalt chapter to accommodate the current methods and procedures for both Performance Grading of asphalt binders and the Superpave mix design method. The chapter on wood was revised to provide information on recent manufactured wood products that became available in the past several years. Also, since fiber-reinforced polymer composites have been more commonly used in retrofitting old and partially damaged structures, several examples were added in the chapter on composites. In the laboratory manual, an experiment on dry-rodded unit weight of aggregate that is used in portland cement concrete (PCC) proportioning was added, and the experiment on creep of asphalt concrete was deleted for lack of use.

What's New in This Edition

The primary focus of the updates presented in this edition was on the sustainability of materials used in civil and construction engineering. The information on sustainability in Chapter 1 was updated and expanded to include recent information on sustainability. In addition, a section was added to Chapters 3 through 11 describing the sustainability considerations of each material. The problem set for each chapter was updated and increased to provide some fresh Exercises and to cover other topics discussed in the chapter. References were updated and increased in all chapters to provide students with additional reading on current issues related to different materials. Many figures were added and others were updated throughout the book to provide visual illustrations to students. Other specific updates to the chapters include:

- Chapter 1 now includes a more detailed section on viscoelastic material behavior and a new sample problem.
- Chapter 3 was updated with recent information about the production of steel.
- A sample problem was added to Chapter 5 about the water absorbed by aggregate in order to highlight the fact that absorbed water is not used to hydrate the cement or improve the workability of plastic concrete.
- Two new sample problems were added to Chapter 6 on the acceptable criteria of mixing water and to clarify the effect of water reducer on the properties of concrete.
- Chapter 7 was augmented with a discussion of concrete mixing water and a new sample problem. A section on pervious concrete was added to reflect the current practice on some parking lots and pedestrian walkways.
- Chapter 9 was updated with reference to the multiple stress creep recovery test, and the information about the immersion compression test was replaced with the tensile strength ratio method to reflect current practices. The selection of the binder was refined to incorporate the effect of load and speed. The section on the diameteral tensile resilient modulus was removed for lack of use. The sample problem on the diameteral tensile resilient modulus was also removed and replaced with a sample problem on the freeze-thaw test and the tensile strength ratio.

- Chapter 10 was updated to include more information about wood deterioration and preservation. The first two sample problems were edited to provide more accurate solutions since the shrinkage values used in wood are related to the green dimensions at or above the fiber saturation point (FSP), not the dry dimensions. The third sample problem was expanded to demonstrate how to determine the modulus of elasticity using the third-point bending test.
- Chapter 11 was updated to reflect information about the effective length of fibers and the ductility of fiber-reinforced polymers (FRP). The discussion was expanded with several new figures to incorporate fibers, fabrics, laminates, and composites used in civil engineering applications. The first sample problem was expanded to apply other concepts covered in the chapter.
- The laboratory manual in the appendix was updated to include two new experiments on creep in polymers and the effect of fiber orientation on the elastic modulus of fiber reinforced composites. The experiment on the tensile properties of composites was updated. This would allow more options to the instructor to choose from in assigning lab experiments to students.

Acknowledgments

The authors would like to acknowledge the contributions of many people who assisted with the development of this new edition. First, the authors wish to thank the reviewers and recognize the fact that most of their suggestions have been incorporated into the fourth edition, in particular Dr. Dimitrios Goulias of University of Maryland, Tyler Witthuhn of the National Concrete Masonry Association, Mr. Philip Line of American Wood Council, Dr. Baoshan Huang of University of Tennessee, and Dr. Steve Krause of Arizona State University. Appreciation is also extended to Drs. Narayanan Neithalath, Shane Underwood, Barzin Mobasher, and Kamil Kaloush of Arizona State University for their valuable technical contributions. The photos of FRP materials contributed by Dr. Hota GangaRao of the Constructed Facilities Center at West Virginia University are appreciated. Appreciation also goes to Dr. Javed Bari, formerly with the Arizona Department of Transportation for his contribution in preparing the slides and to Dr. Mena Souliman of the University of Texas at Tyler for his contribution in the preparation of the solution manual.

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About the Authors

Michael S. Mamlouk is a Professor of Civil, Environmental, and Sustainable Engineering at Arizona State University. He has many years of experience in teaching courses of civil engineering materials and other related subjects at both the undergraduate and graduate levels. He has been actively involved in teaching materials and pavement design courses to practicing engineers. Dr. Mamlouk has directed many research projects and is the author of numerous publications in the fields of pavement and materials. He is a professional engineer in the state of Arizona. Dr. Mamlouk is a fellow of the American Society of Civil Engineers and a member of several other professional societies.

John P. Zaniewski is the Asphalt Technology Professor in the Civil and Environmental Engineering Department of West Virginia University. Dr. Zaniewski earned teaching awards at both WVU and Arizona State University. In addition to materials, Dr. Zaniewski teaches graduate and undergraduate courses in pavement materials, design and management, and construction engineering and management. Dr. Zaniewski has been the principal investigator on numerous research projects for state, federal, and international sponsors. He is a member of several professional societies and has been a registered engineer in three states. He is the director of the WV Local Technology Assistance Program and has been actively involved in adult education related to pavement design and materials.

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CHAPTER 1

MATERIALS ENGINEERING CONCEPTS

Materials engineers are responsible for the selection, specification, and quality control of materials to be used in a job. These materials must meet certain classes of criteria or materials properties (Ashby and Jones, 2011). These classes of criteria include

- economic factors
- mechanical properties
- nonmechanical properties
- production/construction considerations
- aesthetic properties

In addition to this traditional list of criteria, civil engineers must be concerned with environmental quality. In 1997, the ASCE *Code of Ethics* was modified to include "sustainable development" as an ethics issue. Sustainable development basically recognizes the fact that our designs should be sensitive to the ability of future generations to meet their needs. There is a strong tie between the materials selected for design and sustainable development.

When engineers select the material for a specific application, they must consider the various criteria and make compromises. Both the client and the purpose of the facility or structure dictate, to a certain extent, the emphasis that will be placed on the different criteria.

Civil and construction engineers must be familiar with materials used in the construction of a wide range of structures. Materials most frequently used include steel, aggregate, concrete, masonry, asphalt, and wood. Materials used to a lesser extent include aluminum, glass, plastics, and fiber-reinforced composites. Geotechnical engineers make a reasonable case for including soil as the most widely used engineering material, since it provides the basic support for all civil engineering structures. However, the properties of soils will not be discussed in this text because soil properties are generally the topic of a separate course in civil and construction engineering curriculums.

Recent advances in the technology of civil engineering materials have resulted in the development of better quality, more economical, and safer materials. These materials are commonly referred to as high-performance materials. Because more is known about the molecular structure of materials and because of the continuous research efforts by scientists and engineers, new materials such as polymers, adhesives, composites, geotextiles, coatings, cold-formed metals, and various synthetic products are competing with traditional civil engineering materials. In addition, improvements have been made to existing materials by changing their molecular structures or including additives to improve quality, economy, and performance. For example, superplasticizers have made a breakthrough in the concrete industry, allowing the production of much stronger concrete. Joints made of elastomeric materials have improved the safety of high-rise structures in earthquake-active areas. Lightweight synthetic aggregates have decreased the weight of concrete structures, allowing small cross-sectional areas of components. Polymers have been mixed with asphalt, allowing pavements to last longer under the effect of vehicle loads and environmental conditions.

The field of fiber composite materials has developed rapidly in the past 30 years. Many recent civil engineering projects have used fiber-reinforced polymer composites. These advanced composites compete with traditional materials due to their higher strength-to-weight ratio and their ability to overcome such shortcomings as corrosion. For example, fiber-reinforced concrete has much greater toughness than conventional portland cement concrete. Composites can replace reinforcing steel in concrete structures. In fact, composites have allowed the construction of structures that could not have been built in the past.

The nature and behavior of civil engineering materials are as complicated as those of materials used in any other field of engineering. Due to the high quantity of materials used in civil engineering projects, the civil engineer frequently works with locally available materials that are not as highly refined as the materials used in other engineering fields. As a result, civil engineering materials frequently have highly variable properties and characteristics.

This chapter reviews the manner in which the properties of materials affect their selection and performance in civil engineering applications. In addition, this chapter reviews some basic definitions and concepts of engineering mechanics required for understanding material behavior. The variable nature of material properties is also discussed so that the engineer will understand the concepts of precision and accuracy, sampling, quality assurance, and quality control. Finally, instruments used for measuring material response are described.

1.1 Economic Factors

The economics of the material selection process are affected by much more than just the cost of the material. Factors that should be considered in the selection of the material include

- availability and cost of raw materials
- manufacturing costs

- transportation
- placing
- maintenance

The materials used for civil engineering structures have changed over time. Early structures were constructed of stone and wood. These materials were in ready supply and could be cut and shaped with available tools. Later, cast iron was used, because mills were capable of crudely refining iron ore. As the industrial revolution took hold, quality steel could be produced in the quantities required for large structures. In addition, portland cement, developed in the mid-1800s, provided civil engineers with a durable inexpensive material with broad applications.

Due to the efficient transportation system in the United States, availability is not as much of an issue as it once was in the selection of a material. However, transportation can significantly add to the cost of the materials at the job site. For example, in many locations in the United States, quality aggregates for concrete and asphalt are in short supply. The closest aggregate source to Houston, Texas, is 150 km from the city. This haul distance approximately doubles the cost of the aggregates in the city, and hence puts concrete at a disadvantage compared with steel.

The type of material selected for a job can greatly affect the ease of construction and the construction costs and time. For example, the structural members of a steel-frame building can be fabricated in a shop, transported to the job site, lifted into place with a crane, and bolted or welded together. In contrast, for a reinforced concrete building, the forms must be built; reinforcing steel placed; concrete mixed, placed, and allowed to cure; and the forms removed. Constructing the concrete frame building can be more complicated and time consuming than constructing steel structures. To overcome this shortcoming, precast concrete units commonly have been used, especially for bridge construction.

All materials deteriorate over time and with use. This deterioration affects both the maintenance cost and the useful life of the structure. The rate of deterioration varies among materials. Thus, in analyzing the economic selection of a material, the life cycle cost should be evaluated in addition to the initial costs of the structure.

1.2 Mechanical Properties

The mechanical behavior of materials is the response of the material to external loads. All materials deform in response to loads; however, the specific response of a material depends on its properties, the magnitude and type of load, and the geometry of the element. Whether the material "fails" under the load conditions depends on the failure criterion. Catastrophic failure of a structural member, resulting in the collapse of the structure, is an obvious material failure. However, in some cases, the failure is more subtle, but with equally severe consequences. For example, pavement may fail due to excessive roughness at the surface, even though the stress levels are well within the capabilities of the material. A building may have to be closed due to excessive vibrations by wind or other live loads, although it could be structurally sound. These are examples of *functional* failures.

1.2.1 Loading Conditions

One of the considerations in the design of a project is the type of loading that the structure will be subjected to during its design life. The two basic types of loads are static and dynamic. Each type affects the material differently, and frequently the interactions between the load types are important. Civil engineers encounter both when designing a structure.

Static loading implies a sustained loading of the structure over a period of time. Generally, static loads are slowly applied such that no shock or vibration is generated in the structure. Once applied, the static load may remain in place or be removed slowly. Loads that remain in place for an extended period of time are called *sustained* (dead) loads. In civil engineering, much of the load the materials must carry is due to the weight of the structure and equipment in the structure.

Loads that generate a shock or vibration in the structure are *dynamic* loads. Dynamic loads can be classified as *periodic, random,* or *transient,* as shown in Figure 1.1 (Richart et al., 1970). A periodic load, such as a harmonic or sinusoidal load, repeats itself with time. For example, rotating equipment in a building can produce a vibratory load. In a random load, the load pattern never repeats, such as that produced by earthquakes. Transient load, on the other hand, is an impulse load that is applied over a short time interval, after which the vibrations decay until the

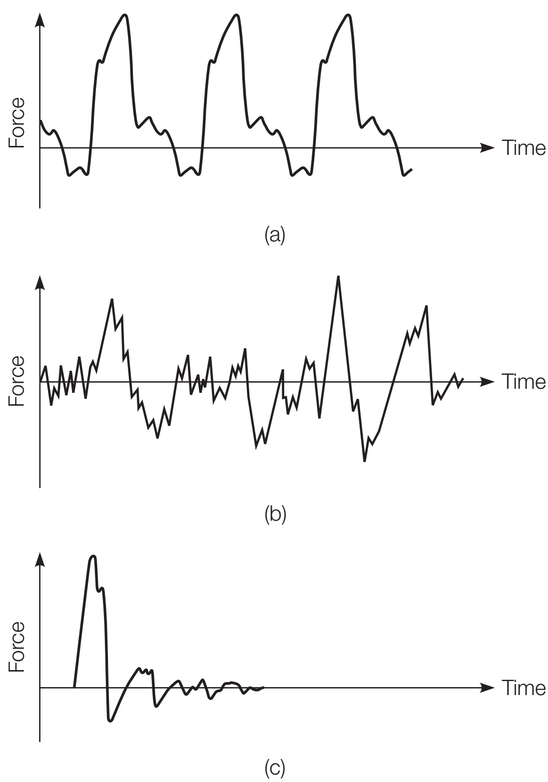

FIGURE 1.1 Types of dynamic loads: (a) periodic, (b) random, and (c) transient.

system returns to a rest condition. For example, bridges must be designed to withstand the transient loads of trucks.

1.2.2 Stress–Strain Relations

Materials deform in response to loads or forces. In 1678, Robert Hooke published the first findings that documented a linear relationship between the amount of force applied to a member and its deformation. The amount of deformation is proportional to the properties of the material and its dimensions. The effect of the dimensions can be normalized. Dividing the force by the cross-sectional area of the specimen normalizes the effect of the loaded area. The force per unit area is defined as the stress σ in the specimen (i.e., σ = force/area). Dividing the deformation by the original length is defined as strain ε of the specimen (i.e., ε = change in length/original length). Much useful information about the material can be determined by plotting the stress–strain diagram.

Figure 1.2 shows typical uniaxial tensile or compressive stress–strain curves for several engineering materials. Figure 1.2(a) shows a linear stress–strain relationship up to the point where the material fails. Glass and chalk are typical of materials exhibiting this tensile behavior. Figure 1.2(b) shows the behavior of steel in tension. Here, a linear relationship is obtained up to a certain point (proportional limit), after which the material deforms without much increase in stress. On the other hand, aluminum alloys in tension exhibit a linear stress–strain relationship up to the proportional limit, after which a nonlinear relation follows, as illustrated in Figure 1.2(c). Figure 1.2(d) shows a nonlinear relation throughout the whole range. Concrete and other materials exhibit this relationship, although the first portion of the curve for concrete is very close to being linear. Soft rubber in tension differs from most materials in such a way that it shows an almost linear stress–strain relationship followed by a reverse curve, as shown in Figure 1.2(e).

1.2.3 Elastic Behavior

If a material exhibits true elastic behavior, it must have an instantaneous response (deformation) to load, and the material must return to its original shape when the load is removed. Many materials, including most metals, exhibit elastic behavior, at

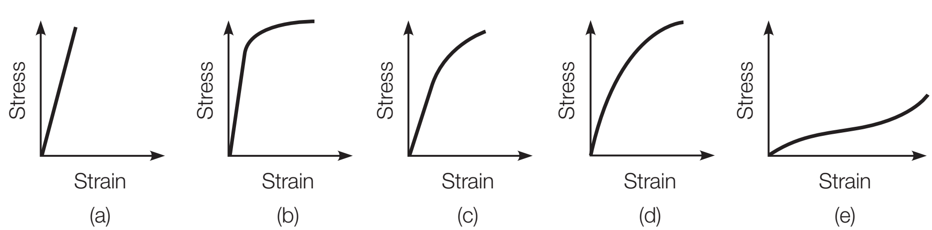

FIGURE 1.2 Typical uniaxial stress–strain diagrams for some engineering materials: (a) glass and chalk, (b) steel, (c) aluminum alloys, (d) concrete, and (e) soft rubber.

least at low stress levels. As will be discussed in Chapter 2, elastic deformation does not change the arrangement of atoms within the material, but rather it stretches the bonds between atoms. When the load is removed, the atomic bonds return to their original position.

Young observed that different elastic materials have different proportional constants between stress and strain. For a homogeneous, isotropic, and linear elastic material, the proportional constant between normal stress and normal strain of an axially loaded member is the *modulus of elasticity* or *Young's modulus, E,* and is equal to

$$E = \frac{\sigma}{\varepsilon} \tag{1.1}$$

where σ is the normal stress and ε is the normal strain.

In the axial tension test, as the material is elongated, there is a reduction of the cross section in the lateral direction. In the axial compression test, the opposite is true. The ratio of the lateral strain, ε_l, to the axial strain, ε_a, is *Poisson's ratio,*

$$v = \frac{-\varepsilon_l}{\varepsilon_a} \tag{1.2}$$

Since the axial and lateral strains will always have different signs, the negative sign is used in Equation 1.2 to make the ratio positive. Poisson's ratio has a theoretical range of 0.0 to 0.5, where 0.0 is for a compressible material in which the axial and lateral directions are not affected by each other. The 0.5 value is for a material that does not change its volume when the load is applied. Most solids have Poisson's ratios between 0.10 and 0.45.

Although Young's modulus and Poisson's ratio were defined for the uniaxial stress condition, they are important when describing the three-dimensional stress–strain relationships, as well. If a homogeneous, isotropic cubical element with linear elastic response is subjected to normal stresses σ_x, σ_y, and σ_z in the three orthogonal directions (as shown in Figure 1.3), the normal strains ε_x, ε_y, and ε_z can be computed by the *generalized Hooke's law,*

$$\varepsilon_x = \frac{\sigma_x - v(\sigma_y + \sigma_z)}{E}$$

$$\varepsilon_y = \frac{\sigma_y - v(\sigma_z + \sigma_x)}{E}$$

$$\varepsilon_z = \frac{\sigma_z - v(\sigma_x + \sigma_y)}{E} \tag{1.3}$$

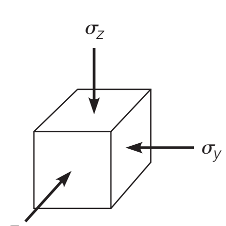

FIGURE 1.3 Normal stresses applied on a cubical element.

Sample Problem 1.1

A cube made of an alloy with dimensions of 50 mm × 50 mm × 50 mm is placed into a pressure chamber and subjected to a pressure of 90 MPa. If the modulus of elasticity of the alloy is 100 GPa and Poisson's ratio is 0.28, what will be the length of each side of the cube, assuming that the material remains within the elastic region?

Solution

$$\varepsilon_x = [\sigma_x - \nu(\sigma_y + \sigma_z)]/E = [-90 - 0.28 \times (-90 - 90)]/100000$$
$$= -0.000396 \text{ m/m}$$
$$\varepsilon_y = \varepsilon_z = -0.000396 \text{ m/m}$$
$$\Delta x = \Delta y = \Delta z = -0.000396 \times 50 = -0.0198 \text{ mm}$$
$$L_{new} = 50 - 0.0198 = 49.9802 \text{ mm}$$

Linearity and elasticity should not be confused. A *linear material*'s stress–strain relationship follows a straight line. An *elastic material* returns to its original shape when the load is removed and reacts instantaneously to changes in load. For example, Figure 1.4(a) represents a linear elastic behavior, while Figure 1.4(b) represents a nonlinear elastic behavior.

For materials that do not display any linear behavior, such as concrete and soils, determining a Young's modulus or elastic modulus can be problematical. There are several options for arbitrarily defining the modulus for these materials. Figure 1.5 shows four options: the initial tangent, tangent, secant, and chord moduli. The *initial tangent modulus* is the slope of the tangent of the stress–strain curve at the origin. The *tangent modulus* is the slope of the tangent at a point on the stress–strain curve. The *secant modulus* is the slope of a chord drawn between the origin and an arbitrary point on the stress–strain curve. The *chord modulus* is the slope of a chord drawn between two points on the stress–strain curve. The selection of which modulus to use for a nonlinear material depends on the stress or strain level at which the material typically is used. Also, when determining the tangent, secant, or chord modulus, the stress or strain levels must be defined.

Table 1.1 shows typical modulus and Poisson's ratio values for some materials at room temperature. Note that some materials have a range of modulus values rather

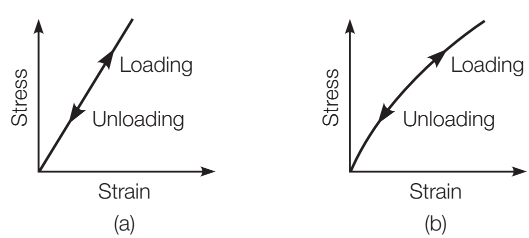

FIGURE 1.4 Elastic behavior: (a) linear and (b) nonlinear.

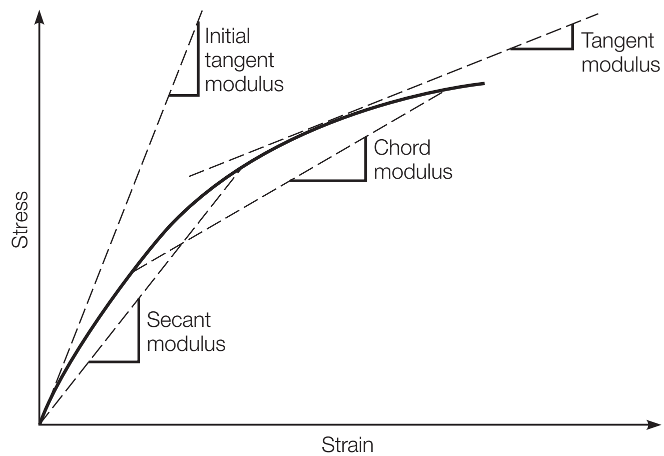

FIGURE 1.5 Methods for approximating modulus.

than a distinct value. Several factors affect the modulus, such as curing level and proportions of components of concrete or the direction of loading relative to the grain of wood.

1.2.4 Elastoplastic Behavior

For some materials, as the stress applied on the specimen is increased, the strain will proportionally increase up to a point; after this point, the strain will increase with little additional stress. In this case, the material exhibits linear elastic behavior

TABLE 1.1 Typical Modulus and Poisson's Ratio Values (Room Temperature)

Material	Modulus GPa	Poisson's Ratio
Aluminum	69–75	0.33
Brick	10–17	0.23–0.40
Cast iron	75–169	0.17
Concrete	14–40	0.11–0.21
Copper	110	0.35
Epoxy	3–140	0.35–0.43
Glass	62–70	0.25
Limestone	58	0.2–0.3
Rubber (soft)	0.001–0.014	0.49
Steel	200	0.27
Tungsten	407	0.28
Wood	6–15	0.29–0.45

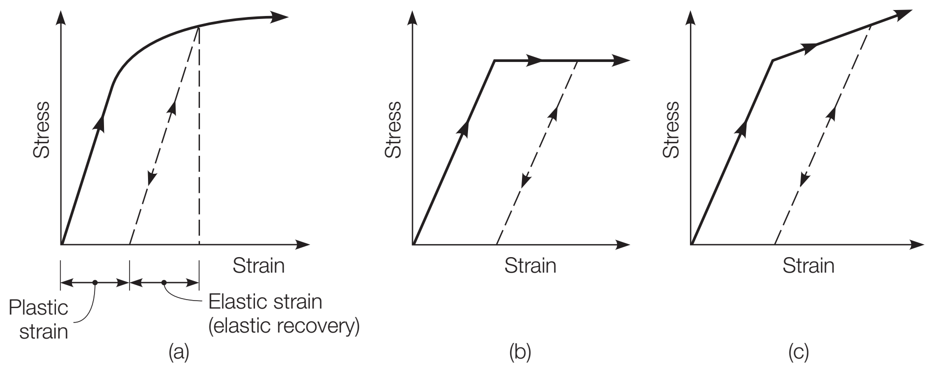

FIGURE 1.6 Stress–strain behavior of plastic materials: (a) example of loading and unloading, (b) elastic–perfectly plastic, and (c) elasto–plastic with strain hardening.

followed by plastic response. The stress level at which the behavior changes from elastic to plastic is the *elastic limit.* When the load is removed from the specimen, some of the deformation will be recovered and some of the deformation will remain as seen in Figure 1.6(a). As discussed in Chapter 2, plastic behavior indicates permanent deformation of the specimen so that it does not return to its original shape when the load is removed. This indicates that when the load is applied, the atomic bonds stretch, creating an elastic response; then the atoms actually slip relative to each other. When the load is removed, the atomic slip does not recover; only the atomic stretch is recovered (Callister, 2006).

Several models are used to represent the behavior of materials that exhibit both elastic and plastic responses. Figure 1.6(b) shows a linear elastic–perfectly plastic response in which the material exhibits a linear elastic response upon loading, followed by a completely plastic response. If such material is unloaded after it has plasticly deformed, it will rebound in a linear elastic manner and will follow a straight line parallel to the elastic portion, while some permanent deformation will remain. If the material is loaded again, it will have a linear elastic response followed by plastic response at the same level of stress at which the material was unloaded (Popov, 1968).

Figure 1.6(c) shows an elastoplastic response in which the first portion is an elastic response followed by a combined elastic and plastic response. If the load is removed after the plastic deformation, the stress–strain relationship will follow a straight line parallel to the elastic portion; consequently, some of the strain in the material will be removed, and the remainder of the strain will be permanent. Upon reloading, the material again behaves in a linear elastic manner up to the stress level that was attained in the previous stress cycle. After that point the material will follow the original stress–strain curve. Thus, the stress required to cause plastic deformation actually increases. This process is called *strain hardening* or *work hardening.* Strain hardening is beneficial in some cases, since it allows more stress to be applied without permanent deformation. In the production of cold-formed steel framing members, the permanent deformation used in the production process can double the yield strength of the member relative to the original strength of the steel.

Some materials exhibit *strain softening,* in which plastic deformation causes weakening of the material. Portland cement concrete is a good example of such a material. In this case, plastic deformation causes microcracks at the interface between aggregate and cement paste.

Sample Problem 1.2

An elastoplastic material with strain hardening has the stress–strain relationship shown in Figure 1.6(c). The modulus of elasticity is 175 GPa, yield strength is 480 MPa, and the slope of the strain-hardening portion of the stress–strain diagram is 20.7 GPa.

a. Calculate the strain that corresponds to a stress of 550 MPa.
b. If the 550-MPa stress is removed, calculate the permanent strain.

Solution

(a) $\varepsilon = (480/175 \times 10^3) + [(550 - 480)/20.7 \times 10^3] = 0.0061 \text{ m/m}$

(b) $\varepsilon_{\text{permanent}} = 0.0061 - [550/(175\times10^3)] = 0.0061 - 0.0031$

$= 0.0030 \text{ m/m}$

Materials that do not undergo plastic deformation prior to failure, such as concrete, are said to be *brittle,* whereas materials that display appreciable plastic deformation, such as mild steel, are *ductile.* Generally, ductile materials are preferred for construction. When a brittle material fails, the structure can collapse in a catastrophic manner. On the other hand, overloading a ductile material will result in distortions of the structure, but the structure will not necessarily collapse. Thus, the ductile material provides the designer with a margin of safety.

Figure 1.7(a) demonstrates three concepts of the stress–strain behavior of elastoplastic materials. The lowest point shown on the diagram is the *proportional limit,* defined as the transition point between linear and nonlinear behavior. The second point is the *elastic limit,* which is the transition between elastic and plastic behavior. However, most materials do not display an abrupt change in behavior from elastic to plastic. Rather, there is a gradual, almost imperceptible transition between the behaviors, making it difficult to locate an exact transition point (Polowski and Ripling, 2005). For this reason, arbitrary methods such as the *offset* and the *extension* methods, are used to identify the elastic limit, thereby defining the *yield stress (yield strength).* In the offset method, a specified offset is measured on the abscissa, and a line with a slope equal to the initial tangent modulus is drawn through this