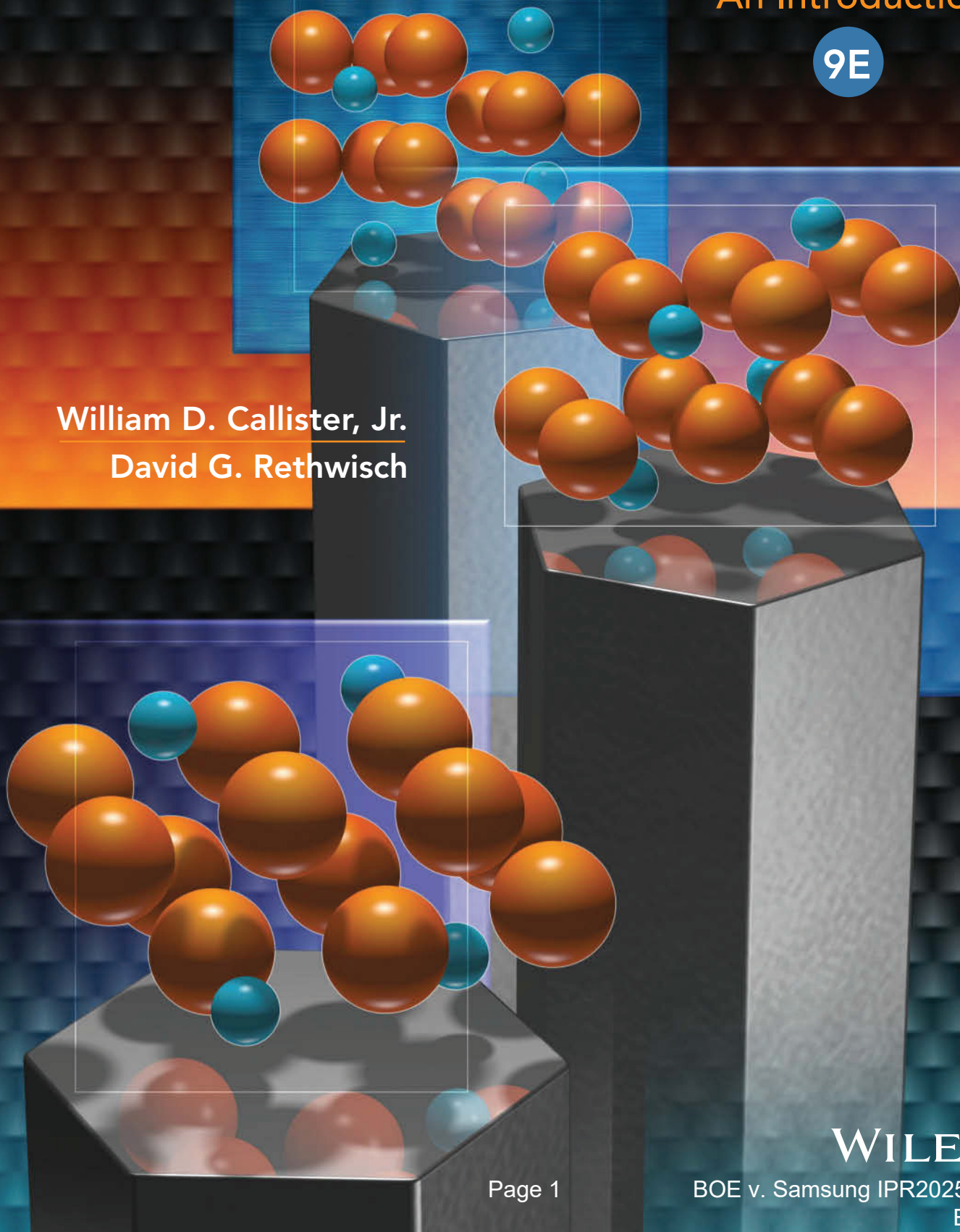


MATERIALS SCIENCE and ENGINEERING

An Introduction

9E

William D. Callister, Jr.
David G. Rethwisch



9th Edition

Materials Science and Engineering

AN INTRODUCTION

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Front Cover: Depiction of a unit cell for iron carbide (Fe_3C) from three different perspectives. Brown and blue spheres represent iron and carbon atoms, respectively.

Back Cover: Three representations of the unit cell for body-centered cubic iron (α -ferrite); each unit cell contains an interstitial carbon atom.

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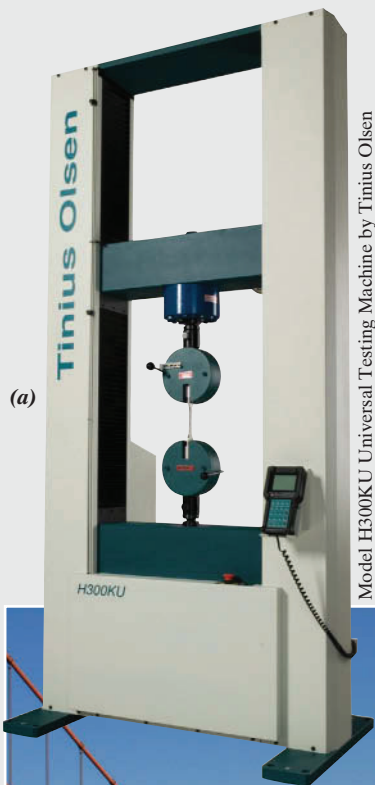
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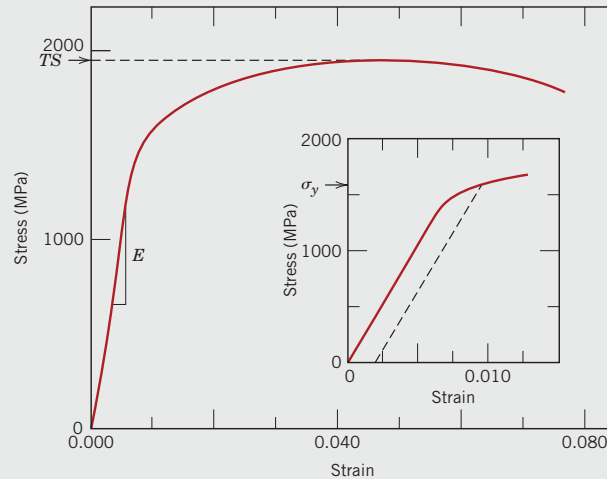
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(c)



(b)

Figure (a) shows an apparatus that measures the mechanical properties of metals using applied tensile forces (Sections 6.3, 6.5, and 6.6). Figure (b) was generated from a tensile test performed by an apparatus such as this on a steel specimen. Data plotted are stress (vertical axis—a measure of applied force) versus strain (horizontal axis—related to the degree of specimen elongation). The mechanical properties of modulus of elasticity (stiffness, E), yield strength (σ_y), and tensile strength (TS) are determined as noted on these graphs.

Figure (c) shows a suspension bridge. The weight of the bridge deck and automobiles imposes tensile forces on the vertical suspender cables. These forces are transferred to the main suspension cable, which sags in a more-or-less parabolic shape. The metal alloy(s) from which these cables are constructed must meet certain stiffness and strength criteria. Stiffness and strength of the alloy(s) may be assessed from tests performed using a tensile-testing apparatus (and the resulting stress-strain plots) similar to those shown.

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WHY STUDY *The Mechanical Properties of Metals*?

It is incumbent on engineers to understand how the various mechanical properties are measured and what these properties represent; they may be called upon to design structures/components using predetermined

materials such that unacceptable levels of deformation and/or failure will not occur. We demonstrate this procedure with respect to the design of a tensile-testing apparatus in Design Example 6.1.

Learning Objectives

After studying this chapter, you should be able to do the following:

1. Define engineering stress and engineering strain.
2. State Hooke's law and note the conditions under which it is valid.
3. Define Poisson's ratio.
4. Given an engineering stress-strain diagram, determine (a) the modulus of elasticity, (b) the yield strength (0.002 strain offset), and (c) the tensile strength and (d) estimate the percentage elongation.
5. For the tensile deformation of a ductile cylindrical specimen, describe changes in specimen profile to the point of fracture.
6. Compute ductility in terms of both percentage elongation and percentage reduction of area for a material that is loaded in tension to fracture.
7. Give brief definitions of and the units for modulus of resilience and toughness (static).
8. For a specimen being loaded in tension, given the applied load, the instantaneous cross-sectional dimensions, and original and instantaneous lengths, be able to compute true stress and true strain values.
9. Name the two most common hardness-testing techniques; note two differences between them.
10. (a) Name and briefly describe the two different microindentation hardness testing techniques, and (b) cite situations for which these techniques are generally used.
11. Compute the working stress for a ductile material.

6.1 INTRODUCTION

Many materials are subjected to forces or loads when in service; examples include the aluminum alloy from which an airplane wing is constructed and the steel in an automobile axle. In such situations it is necessary to know the characteristics of the material and to design the member from which it is made such that any resulting deformation will not be excessive and fracture will not occur. The mechanical behavior of a material reflects its response or deformation in relation to an applied load or force. Key mechanical design properties are stiffness, strength, hardness, ductility, and toughness.

The mechanical properties of materials are ascertained by performing carefully designed laboratory experiments that replicate as nearly as possible the service conditions. Factors to be considered include the nature of the applied load and its duration, as well as the environmental conditions. It is possible for the load to be tensile, compressive, or shear, and its magnitude may be constant with time, or it may fluctuate continuously. Application time may be only a fraction of a second, or it may extend over a period of many years. Service temperature may be an important factor.

Mechanical properties are of concern to a variety of parties (e.g., producers and consumers of materials, research organizations, government agencies) that have differing interests. Consequently, it is imperative that there be some consistency in the manner in which tests are conducted and in the interpretation of their results. This consistency is accomplished by using standardized testing techniques. Establishment

and publication of these standards are often coordinated by professional societies. In the United States the most active organization is the American Society for Testing and Materials (ASTM). Its *Annual Book of ASTM Standards* (<http://www.astm.org>) comprises numerous volumes that are issued and updated yearly; a large number of these standards relate to mechanical testing techniques. Several of these are referenced by footnote in this and subsequent chapters.

The role of structural engineers is to determine stresses and stress distributions within members that are subjected to well-defined loads. This may be accomplished by experimental testing techniques and/or by theoretical and mathematical stress analyses. These topics are treated in traditional texts on stress analysis and strength of materials.

Materials and metallurgical engineers, however, are concerned with producing and fabricating materials to meet service requirements as predicted by these stress analyses. This necessarily involves an understanding of the relationships between the microstructure (i.e., internal features) of materials and their mechanical properties.

Materials are frequently chosen for structural applications because they have desirable combinations of mechanical characteristics. The present discussion is confined primarily to the mechanical behavior of metals; polymers and ceramics are treated separately because they are, to a large degree, mechanically different from metals. This chapter discusses the stress–strain behavior of metals and the related mechanical properties, and also examines other important mechanical characteristics. Discussions of the microscopic aspects of deformation mechanisms and methods to strengthen and regulate the mechanical behavior of metals are deferred to later chapters.

6.2 CONCEPTS OF STRESS AND STRAIN

If a load is static or changes relatively slowly with time and is applied uniformly over a cross section or surface of a member, the mechanical behavior may be ascertained by a simple stress–strain test; these are most commonly conducted for metals at room temperature. There are three principal ways in which a load may be applied: namely, tension, compression, and shear (Figures 6.1*a*, *b*, *c*). In engineering practice many loads are torsional rather than pure shear; this type of loading is illustrated in Figure 6.1*d*.

Tension Tests¹

One of the most common mechanical stress–strain tests is performed in *tension*. As will be seen, the tension test can be used to ascertain several mechanical properties of materials that are important in design. A specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied uniaxially along the long axis of a specimen. A standard tensile specimen is shown in Figure 6.2. Normally, the cross section is circular, but rectangular specimens are also used. This “dogbone” specimen configuration was chosen so that, during testing, deformation is confined to the narrow center region (which has a uniform cross section along its length) and also to reduce the likelihood of fracture at the ends of the specimen. The standard diameter is approximately 12.8 mm (0.5 in.), whereas the reduced section length should be at least four times this diameter; 60 mm (2 $\frac{1}{4}$ in.) is common. Gauge length is used in ductility computations, as discussed in Section 6.6; the standard value is 50 mm (2.0 in.). The specimen is mounted by its ends into the holding grips of the

¹ASTM Standards E8 and E8M, “Standard Test Methods for Tension Testing of Metallic Materials.”

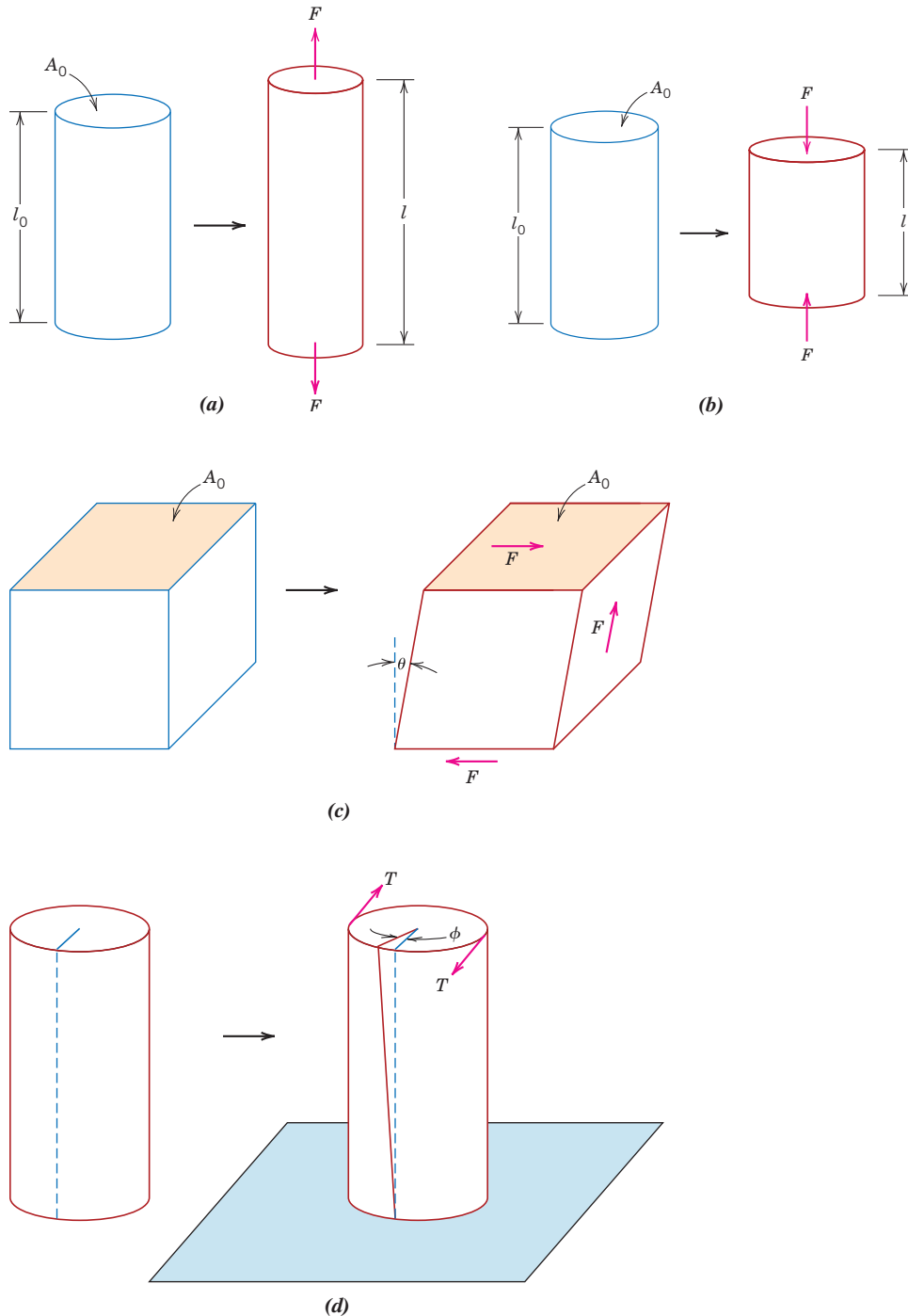
Figure 6.1

(a) Schematic illustration of how a tensile load produces an elongation and positive linear strain.

(b) Schematic illustration of how a compressive load produces contraction and a negative linear strain.

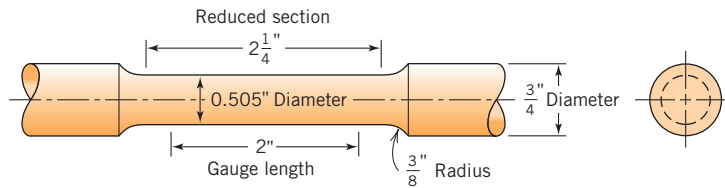
(c) Schematic representation of shear strain γ , where $\gamma = \tan \theta$.

(d) Schematic representation of torsional deformation (i.e., angle of twist ϕ) produced by an applied torque T .



testing apparatus (Figure 6.3). The tensile testing machine is designed to elongate the specimen at a constant rate, and to continuously and simultaneously measure the instantaneous applied load (with a load cell) and the resulting elongations (using an extensometer). A stress-strain test typically takes several minutes to perform and is destructive; that is, the test specimen is permanently deformed and usually fractured. [Photograph (a) opening this chapter is of a modern tensile-testing apparatus.]

Figure 6.2 A standard tensile specimen with circular cross section.



The output of such a tensile test is recorded (usually on a computer) as load or force versus elongation. These load–deformation characteristics depend on the specimen size. For example, it requires twice the load to produce the same elongation if the cross-sectional area of the specimen is doubled. To minimize these geometrical factors, load and elongation are normalized to the respective parameters of **engineering stress** and **engineering strain**. Engineering stress σ is defined by the relationship

$$\sigma = \frac{F}{A_0} \quad (6.1)$$

in which F is the instantaneous load applied perpendicular to the specimen cross section, in units of newtons (N) or pounds force (lb_f), and A_0 is the original cross-sectional area before any load is applied (m² or in.²). The units of engineering stress (referred to subsequently as just *stress*) are megapascals, MPa (SI) (where 1 MPa = 10⁶ N/m²), and pounds force per square inch, psi (customary U.S.).²

Engineering strain ϵ is defined according to

$$\epsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0} \quad (6.2)$$

in which l_0 is the original length before any load is applied and l_i is the instantaneous length. Sometimes the quantity $l_i - l_0$ is denoted as Δl and is the deformation elongation or change in length at some instant, as referenced to the original length. Engineering strain (subsequently called just *strain*) is unitless, but meters per meter or inches per inch is often used; the value of strain is obviously independent of the unit system. Sometimes strain is also expressed as a percentage, in which the strain value is multiplied by 100.

engineering stress engineering strain

Definition of
engineering stress
(for tension and
compression)

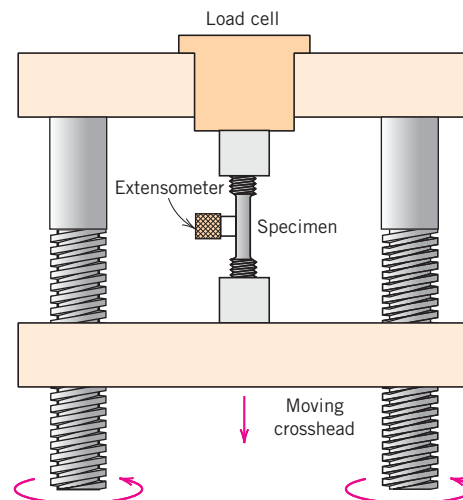
Definition of
engineering strain
(for tension and
compression)

WileyPLUS

Tutorial Video: Tensile Test

What are the
Differences between
Stress and Strain?

Figure 6.3 Schematic representation of the apparatus used to conduct tensile stress–strain tests. The specimen is elongated by the moving crosshead; load cell and extensometer measure, respectively, the magnitude of the applied load and the elongation. (Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2. Copyright © 1965 by John Wiley & Sons, New York.)



²Conversion from one system of stress units to the other is accomplished by the relationship 145 psi = 1 MPa.

Compression Tests³

Compression stress–strain tests may be conducted if in-service forces are of this type. A compression test is conducted in a manner similar to the tensile test, except that the force is compressive and the specimen contracts along the direction of the stress. Equations 6.1 and 6.2 are utilized to compute compressive stress and strain, respectively. By convention, a compressive force is taken to be negative, which yields a negative stress. Furthermore, because l_0 is greater than l_i , compressive strains computed from Equation 6.2 are necessarily also negative. Tensile tests are more common because they are easier to perform; also, for most materials used in structural applications, very little additional information is obtained from compressive tests. Compressive tests are used when a material's behavior under large and permanent (i.e., plastic) strains is desired, as in manufacturing applications, or when the material is brittle in tension.

Shear and Torsional Tests⁴

For tests performed using a pure shear force as shown in Figure 6.1c, the shear stress τ is computed according to

$$\tau = \frac{F}{A_0} \quad (6.3)$$

where F is the load or force imposed parallel to the upper and lower faces, each of which has an area of A_0 . The shear strain γ is defined as the tangent of the strain angle θ , as indicated in the figure. The units for shear stress and strain are the same as for their tensile counterparts.

Torsion is a variation of pure shear in which a structural member is twisted in the manner of Figure 6.1d; torsional forces produce a rotational motion about the longitudinal axis of one end of the member relative to the other end. Examples of torsion are found for machine axles and drive shafts as well as for twist drills. Torsional tests are normally performed on cylindrical solid shafts or tubes. A shear stress τ is a function of the applied torque T , whereas shear strain γ is related to the angle of twist, ϕ in Figure 6.1d.

Geometric Considerations of the Stress State

Stresses that are computed from the tensile, compressive, shear, and torsional force states represented in Figure 6.1 act either parallel or perpendicular to planar faces of the bodies represented in these illustrations. Note that the stress state is a function of the orientations of the planes upon which the stresses are taken to act. For example, consider the cylindrical tensile specimen of Figure 6.4 that is subjected to a tensile stress σ applied parallel to its axis. Furthermore, consider also the plane p - p' that is oriented at some arbitrary angle θ relative to the plane of the specimen end-face. Upon this plane p - p' , the applied stress is no longer a pure tensile one. Rather, a more complex stress state is present that consists of a tensile (or normal) stress σ' that acts normal to the p - p' plane and, in addition, a shear stress τ' that acts parallel to this plane; both of these stresses are represented in the figure. Using

Definition of shear stress

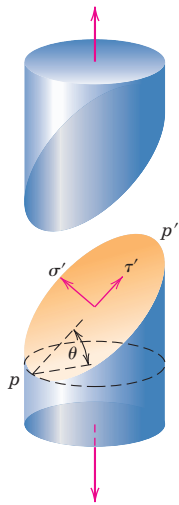


Figure 6.4
Schematic representation showing normal (σ') and shear (τ') stresses that act on a plane oriented at an angle θ relative to the plane taken perpendicular to the direction along which a pure tensile stress (σ) is applied.

³ASTM Standard E9, “Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature.”

⁴ASTM Standard E143, “Standard Test Method for Shear Modulus at Room Temperature.”

mechanics-of-materials principles,⁵ it is possible to develop equations for σ' and τ' in terms of σ and θ , as follows:

$$\sigma' = \sigma \cos^2 \theta = \sigma \left(\frac{1 + \cos 2\theta}{2} \right) \tag{6.4a}$$

$$\tau' = \sigma \sin \theta \cos \theta = \sigma \left(\frac{\sin 2\theta}{2} \right) \tag{6.4b}$$

These same mechanics principles allow the transformation of stress components from one coordinate system to another coordinate system with a different orientation. Such treatments are beyond the scope of the present discussion.

Elastic Deformation

6.3 STRESS–STRAIN BEHAVIOR

Hooke’s law—
relationship between
engineering stress
and engineering
strain for elastic
deformation (tension
and compression)

modulus of elasticity
elastic deformation



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Metal Alloys

The degree to which a structure deforms or strains depends on the magnitude of an imposed stress. For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship

$$\sigma = E\epsilon \tag{6.5}$$

This is known as *Hooke’s law*, and the constant of proportionality E (GPa or psi)⁶ is the **modulus of elasticity**, or *Young’s modulus*. For most typical metals, the magnitude of this modulus ranges between 45 GPa (6.5×10^6 psi), for magnesium, and 407 GPa (59×10^6 psi), for tungsten. Modulus of elasticity values for several metals at room temperature are presented in Table 6.1.

Deformation in which stress and strain are proportional is called **elastic deformation**; a plot of stress (ordinate) versus strain (abscissa) results in a linear relationship, as shown in Figure 6.5. The slope of this linear segment corresponds to the modulus of elasticity E . This modulus may be thought of as stiffness, or a material’s resistance to elastic deformation. The greater the modulus, the stiffer the material, or the smaller the elastic strain that results

Table 6.1

Room-Temperature
Elastic and Shear
Moduli and Poisson’s
Ratio for Various
Metal Alloys

Metal Alloy	Modulus of Elasticity		Shear Modulus		Poisson’s Ratio
	GPa	10 ⁶ psi	GPa	10 ⁶ psi	
Aluminum	69	10	25	3.6	0.33
Brass	97	14	37	5.4	0.34
Copper	110	16	46	6.7	0.34
Magnesium	45	6.5	17	2.5	0.29
Nickel	207	30	76	11.0	0.31
Steel	207	30	83	12.0	0.30
Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

⁵See, for example, W. F. Riley, L. D. Sturges, and D. H. Morris, *Mechanics of Materials*, 6th edition, Wiley, Hoboken, NJ, 2006.

⁶The SI unit for the modulus of elasticity is *gigapascal* (GPa), where 1 GPa = 10^9 N/m² = 10^3 MPa.

pieces. Beyond the mist is the *hackle*, which has an even rougher texture. The hackle is composed of a set of striations or lines that radiate away from the crack source in the direction of crack propagation; they intersect near the crack initiation site and may be used to pinpoint its location.

Qualitative information regarding the magnitude of the fracture-producing stress is available from measurement of the mirror radius (r_m in Figure 12.28). This radius is a function of the acceleration rate of a newly formed crack—that is, the greater this acceleration rate, the sooner the crack reaches its critical velocity, and the smaller the mirror radius. Furthermore, the acceleration rate increases with stress level. Thus, as fracture stress level increases, the mirror radius decreases; experimentally it has been observed that

$$\sigma_f \propto \frac{1}{r_m^{0.5}} \quad (12.6)$$

Here, σ_f is the stress level at which fracture occurred.

Elastic (sonic) waves are also generated during a fracture event, and the locus of intersections of these waves with a propagating crack front gives rise to another type of surface feature known as a *Wallner line*. Wallner lines are arc shaped, and they provide information regarding stress distributions and directions of crack propagation.

12.9 STRESS–STRAIN BEHAVIOR

Flexural Strength

The stress–strain behavior of brittle ceramics is not usually ascertained by a tensile test as outlined in Section 6.2, for three reasons. First, it is difficult to prepare and test specimens having the required geometry. Second, it is difficult to grip brittle materials without fracturing them. Third, ceramics fail after only about 0.1% strain, which necessitates that tensile specimens be perfectly aligned to avoid the presence of bending stresses, which are not easily calculated. Therefore, a more suitable transverse bending test is most frequently used in which a rod specimen having either a circular or rectangular cross section is bent until fracture using a three- or four-point loading technique.³ The three-point loading scheme is illustrated in Figure 12.30. At the point of loading, the top surface of the specimen is placed in a state of compression, whereas the bottom surface is in tension. Stress is computed from the specimen thickness, the bending moment, and the moment of inertia of the cross section; these parameters are noted in Figure 12.30 for rectangular and circular cross sections. The maximum tensile stress (as determined using these stress expressions) exists at the bottom specimen surface directly below the point of load application. Because the tensile strengths of ceramics are about one-tenth of their compressive strengths, and because fracture occurs on the tensile specimen face, the flexure test is a reasonable substitute for the tensile test.

flexural strength

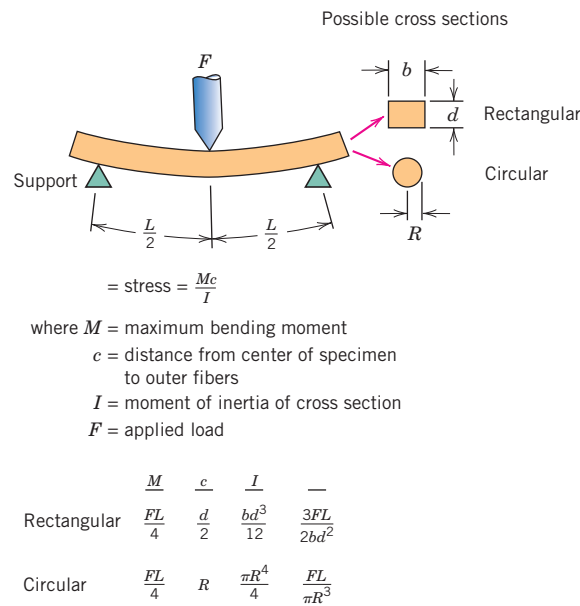
The stress at fracture using this flexure test is known as the **flexural strength**, *modulus of rupture*, *fracture strength*, or *bend strength*, an important mechanical parameter for brittle ceramics. For a rectangular cross section, the flexural strength σ_{fs} is given by

Flexural strength for a specimen having a rectangular cross section

$$\sigma_{fs} = \frac{3F_f L}{2bd^2} \quad (12.7a)$$

³ASTM Standard C1161, “Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature.”

Figure 12.30 A three-point loading scheme for measuring the stress–strain behavior and flexural strength of brittle ceramics, including expressions for computing stress for rectangular and circular cross sections.



where F_f is the load at fracture, L is the distance between support points, and the other parameters are as indicated in Figure 12.30. When the cross section is circular, then

Flexural strength for a specimen having a circular cross section

$$\sigma_{fs} = \frac{F_f L}{\pi R^3} \tag{12.7b}$$

where R is the specimen radius.

Characteristic flexural strength values for several ceramic materials are given in Table 12.5. Furthermore, σ_{fs} depends on specimen size; as explained previously, with increasing specimen volume (i.e., specimen volume exposed to a tensile stress) there is an

Table 12.5
Tabulation of Flexural Strength (Modulus of Rupture) and Modulus of Elasticity for Ten Common Ceramic Materials

Material	Flexural Strength		Modulus of Elasticity	
	MPa	ksi	GPa	10 ⁶ psi
Silicon nitride (Si ₃ N ₄)	250–1000	35–145	304	44
Zirconia ^a (ZrO ₂)	800–1500	115–215	205	30
Silicon carbide (SiC)	100–820	15–120	345	50
Aluminum oxide (Al ₂ O ₃)	275–700	40–100	393	57
Glass-ceramic (Pyroceram)	247	36	120	17
Mullite (3Al ₂ O ₃ –2SiO ₂)	185	27	145	21
Spinel (MgAl ₂ O ₄)	110–245	16–35.5	260	38
Magnesium oxide (MgO)	105 ^b	15 ^b	225	33
Fused silica (SiO ₂)	110	16	73	11
Soda-lime glass	69	10	69	10

^aPartially stabilized with 3 mol% Y₂O₃.
^bSintered and containing approximately 5% porosity.

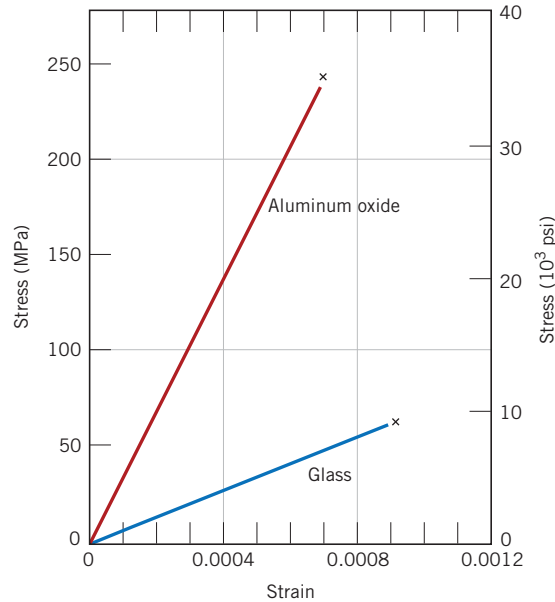


Figure 12.31 Typical stress–strain behavior to fracture for aluminum oxide and glass.

increase in the probability of the existence of a crack-producing flaw and, consequently, a decrease in flexural strength. In addition, the magnitude of flexural strength for a specific ceramic material is greater than its fracture strength measured from a tensile test. This phenomenon may be explained by differences in specimen volume that are exposed to tensile stresses: The entirety of a tensile specimen is under tensile stress, whereas only some volume fraction of a flexural specimen is subjected to tensile stresses—those regions in the vicinity of the specimen surface opposite to the point of load application (see Figure 12.30).

Elastic Behavior

The elastic stress–strain behavior for ceramic materials using these flexure tests is similar to the tensile test results for metals: a linear relationship exists between stress and strain. Figure 12.31 compares the stress–strain behavior to fracture for aluminum oxide and glass. Again, the slope in the elastic region is the modulus of elasticity; the range of moduli of elasticity for ceramic materials is between about 70 and 500 GPa (10×10^6 and 70×10^6 psi), being slightly higher than for metals. Table 12.5 lists values for several ceramic materials. A more comprehensive tabulation is contained in Table B.2 of Appendix B. Also, from Figure 12.31 note that neither material experiences plastic deformation prior to fracture.

12.10 MECHANISMS OF PLASTIC DEFORMATION

Although at room temperature most ceramic materials suffer fracture before the onset of plastic deformation, a brief exploration into the possible mechanisms is worthwhile. Plastic deformation is different for crystalline and noncrystalline ceramics; however, each is discussed.

Crystalline Ceramics

For crystalline ceramics, plastic deformation occurs, as with metals, by the motion of dislocations (Chapter 7). One reason for the hardness and brittleness of these materials is the difficulty of slip (or dislocation motion). For crystalline ceramic materials for which