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 so 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 may fluctuate continuously.

Tension Tests

One of the most common mechanical stress–strain tests is performed in tension. 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 1.

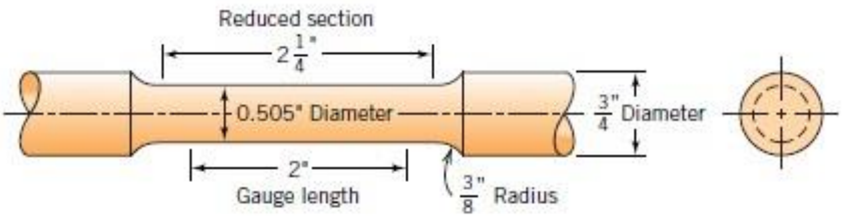

Figure 1. A standard tensile specimen with circular cross section.

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, whereas the reduced section length should be at least four times this diameter; 60 mm. The specimen is mounted by its ends into the holding grips of the testing apparatus (Figure 2). 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 elongation (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.

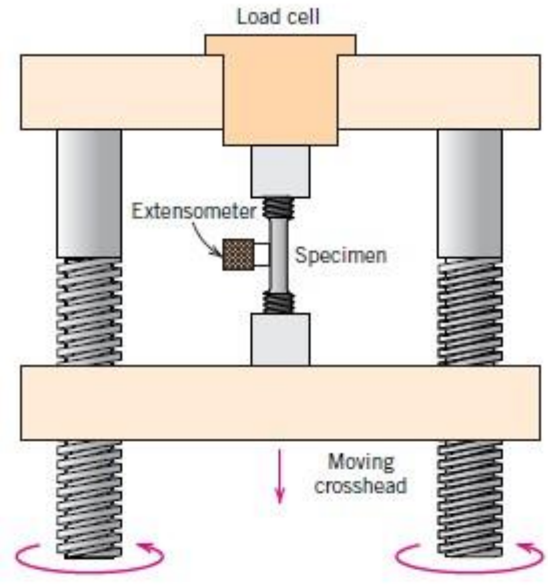

Figure 2. Schematic representation of the apparatus used to conduct tensile stress–strain tests.

The specimen is elongated by the moving crosshead; load cell and extensometer measure, respectively, the magnitude of the applied load and the elongation.

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

$$\sigma = \frac{F}{A_0} \tag{1}$$

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 (m^2). The units of engineering stress (referred to subsequently as just stress) are megapascals, MPa (SI) (where 1 MPa = 10^6 N/mm^2), and pounds force per square inch, psi (customary U.S.). Engineering strain ε is defined according to

$$\varepsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0} \qquad (2)$$

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.

Compression Tests

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 1 and 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 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 Tests

For tests performed using a pure shear force as shown in Figure 3c, the shear stress τ is computed according to

$$\tau = \frac{F}{A_0}$$

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 3d; 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 3d.

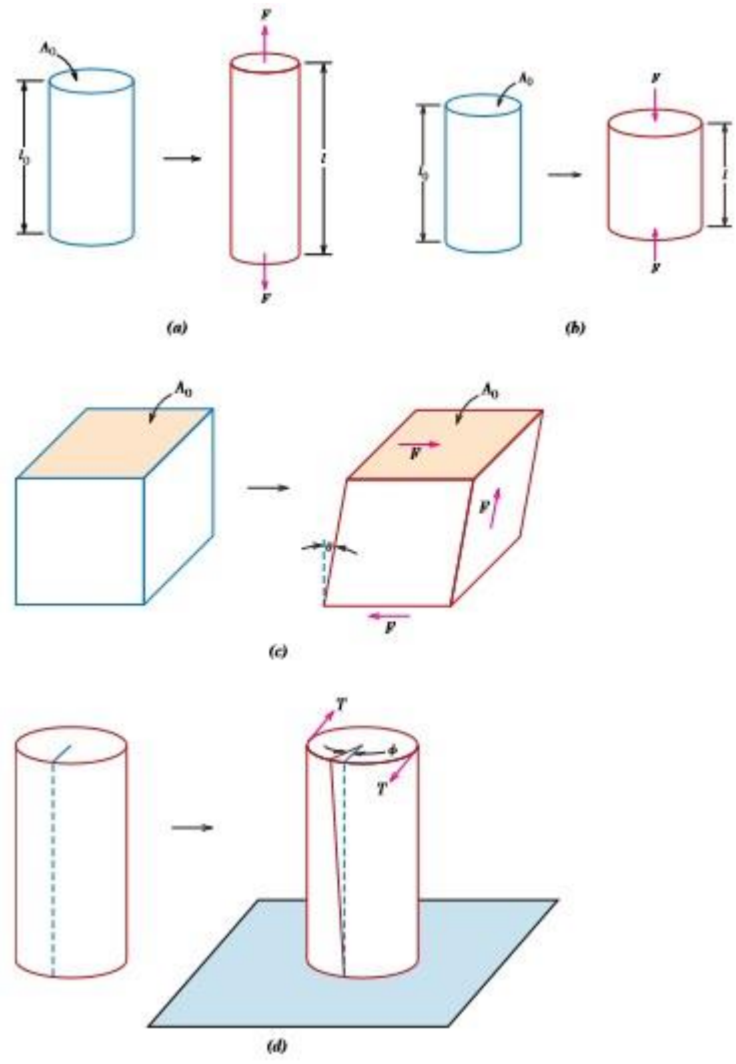

Figure 3

(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 γ = tan θ.

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

Ductility

Ductility is another important mechanical property. It is a measure of the degree of plastic deformation that has been sustained at fracture. A metal that experiences very little or no plastic deformation upon fracture is termed brittle. The tensile stress–strain behaviors for both ductile and brittle metals are schematically illustrated in Figure 4.

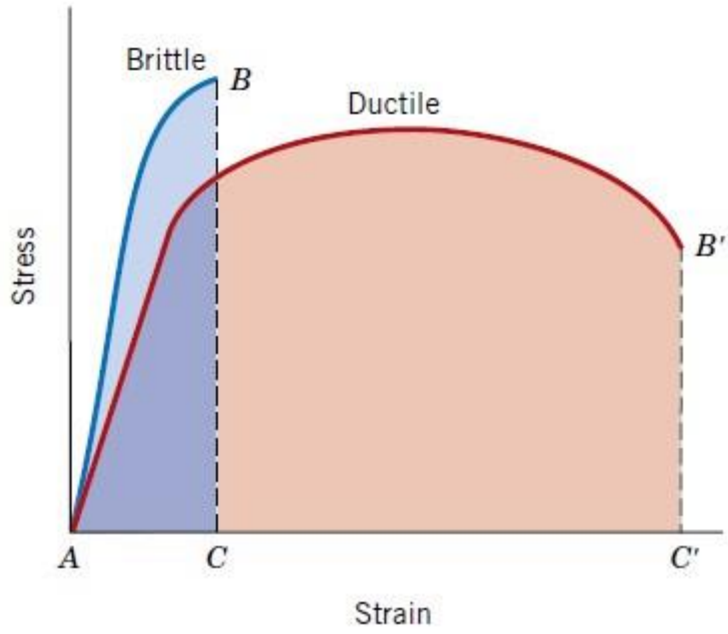

Figure 4. Schematic representations of tensile stress–strain behavior for brittle and ductile metals loaded to fracture.

Ductility may be expressed quantitatively as either percent elongation or percent reduction in area. Percent elongation (%EL) is the percentage of plastic strain at fracture, or

$$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

where lf is the fracture length and l_0 is the original gauge length as given earlier. Inasmuch as a significant proportion of the plastic deformation at fracture is confined to the neck region, the magnitude of $\%EL$ will depend on specimen gauge length. The shorter l_0, the greater is the fraction of total elongation from the neck and, consequently, the higher is the value of $\%EL$. Therefore, l_0 should be specified when percent elongation values are cited; it is commonly 50 mm.

Knowledge of the ductility of materials is important for at least two reasons. First, it indicates to a designer the degree to which a structure will deform plastically before fracture. Second, it specifies the degree of allowable deformation during fabrication operations. We sometimes refer to relatively ductile materials as being “forgiving,” in the sense that they may experience local deformation without fracture, should there be an error in the magnitude of the design stress calculation.

Resilience

Resilience is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered. The associated property is the modulus of resilience, Ur, which is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding.

Computationally, the modulus of resilience for a specimen subjected to a uniaxial tension test is just the area under the engineering stress–strain curve taken to yielding (Figure 4), or

$$Ur = \int_0^{E_y} \sigma d\varepsilon$$

Assuming a linear elastic region, we have

$$Ur = \frac{1}{2}\sigma_y \varepsilon_y$$

in which ε_y is the strain at yielding.

The units of resilience are the product of the units from each of the two axes of the stress–strain plot. For SI units, this is joules per cubic meter (J/m^3, equivalent to Pa), whereas with customary U.S. units it is inch-pounds force per cubic inch ($in.-lb_f/in.^3$, equivalent to psi). Both joules and inch-pounds force are units of energy, and thus this area under the stress–strain curve represents energy absorption per unit volume (in cubic meters or cubic inches) of material.

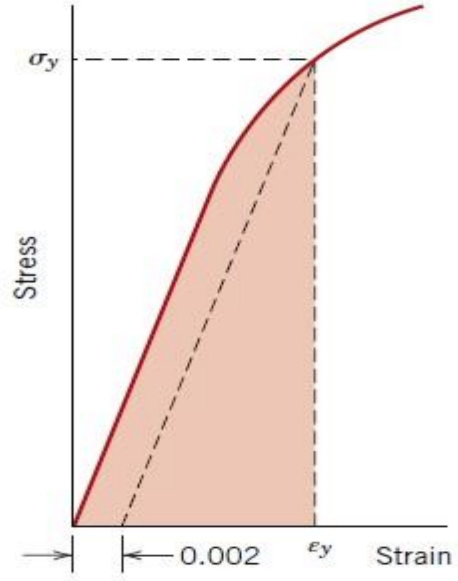

Figure 4. Schematic representation showing how modulus of resilience.

Toughness

Toughness is a mechanical term that may be used in several contexts. For one, toughness (or more specifically, fracture toughness) is a property that is indicative of a material's resistance to fracture when a crack (or other stress-concentrating defect) is present. Because it is nearly impossible (as well as costly) to manufacture materials with zero defects (or to prevent damage during service), fracture toughness is a major consideration for all structural materials.

Another way of defining toughness is as the ability of a material to absorb energy and plastically deform before fracturing. For dynamic (high strain rate) loading conditions and when a notch (or point of stress concentration) is present, notch toughness is assessed by using an impact test. For the static (low strain rate) situation, a measure of toughness in metals (derived from plastic deformation) may be ascertained from the results of a tensile stress–strain test. It is the area under the $\sigma - \varepsilon$ curve up to the point of fracture. The units are the same as for resilience (i.e., energy per unit volume of material). For a metal to be tough, it must display both strength and ductility.