Materials testing

Chapter 1

INTRODUCTION to mechanical fundamentals

1-1. Scope of materials testing

The current course is concerned primarily with the response of metals to forces or loads. It is a combination of many disciplines and many approaches to the problem of understanding the response of materials to forces. On the one hand is the approach used in reference to strength of materials and in the theories of elasticity and plasticity, where a metal is considered to be a homogeneous material whose mechanical behavior can be rather precisely described on the basis of only a very few material constants. This approach is the basis for the rational design of structural members and machine parts.

1-2. Strength of Materials—Basic Assumptions

Strength of materials is the body of knowledge which deals with the relation between internal forces, deformation, and external loads. In the general method of analysis used in strength of materials the first step is to assume that the member is in equilibrium. The equations of static equilibrium are applied to the forces acting on some part of the body in order to obtain a relationship between the external forces acting on the member and the internal forces resisting the action of the external loads. Since the equations of equilibrium must be expressed in terms of forces acting external to the body, it is necessary to make the internal resisting forces into external forces. This is done by passing a plane through the body at the point of interest. The part of the body lying on one side of the cutting plane is removed and replaced by the forces it exerted on the cut section of the part of the body that remains. Since the forces acting on the "free body" hold it in equilibrium, the equations of equilibrium may be applied to the problem.

The internal resisting forces are usually expressed by the stress (*is defined as force per unit area “**σ**”. The companion term strain “**ε**” is defined as the change in length per unit length. More complete definitions will be given later.*) acting over a certain area, so that the internal force is the integral of the stress times the differential area over which it acts. In order to evaluate this integral, it is necessary to know the distribution of the stress over the area of the cutting plane. The stress distribution is arrived at by observing and measuring the strain distribution in the member, since stress cannot be physically measured. However, since stress is proportional to strain for the small deformations involved in most work, the determination of the strain distribution provides the stress distribution. The expression for the stress is then substituted into the equations of equilibrium, and they are solved for stress in terms of the loads and dimensions of the member.

Important assumptions in strength of materials are that the body which is being analyzed is continuous, homogeneous, and isotropic. A continuous body is one which does not contain voids or empty spaces of any kind. A body is homogeneous if it has identical properties at all points. A body is considered to be isotropic with respect to some property when that property does not vary with direction or orientation. A property which varies with orientation with respect to some system of axes is said to be anisotropic.

1-3. Elastic and Plastic Behavior

Experience shows that all solid materials can be deformed when subjected to external load. It is further found that up to certain limiting loads a solid will recover its original dimensions when the load is removed.

The recovery of the original dimensions of a deformed body when the load is removed is known as elastic behavior. The limiting load beyond which the material no longer behaves elastically is the elastic limit. If the elastic limit is exceeded, the body will experience a permanent set or deformation when the load is removed. A body which is permanently deformed is said to have undergone plastic deformation.

For most materials, as long as the load does not exceed the elastic limit, the deformation is proportional to the load. This relationship is known as Hooke's law; it is more frequently stated as stress is proportional to strain. Hooke's law requires that the load-deformation relationship should be linear. However, it does not necessarily follow that all materials which behave elastically will have a linear stress-strain relationship.

Rubber is an example of a material with a nonlinear stress-strain relationship that still satisfies the definition of an elastic material.

Elastic deformations in metals are quite small and require very sensitive instruments for their measurement. Ultrasensitive instruments have shown that the elastic limits of metals are much lower than the values usually measured in engineering tests of materials. As the measuring devices become more sensitive, the elastic limit is decreased, so that for most metals there is only a rather narrow range of loads over which Hooke's law strictly applies. This is, however, primarily of academic importance. Hooke's law remains a quite valid relationship for engineering design.

1-4. Average Stress and Strain

As a starting point in the discussion of stress and strain, consider a uniform cylindrical bar which is subjected to an axial tensile load (Fig. 1-1). Assume that two gage marks are put on the surface of the bar in its unstrained state and that Lo is the gage length between these marks. A load P is applied to one end of the bar, and the gage length undergoes a slight increase in length and decrease in diameter. The distance between the gage marks has increased by an amount δ, called the deformation. The average linear strain ε is the ratio of the change in length to the original length. Strain is a dimensionless quantity since both δ and Lo are expressed in units of length. **$\varepsilon = \delta/L_o$.**

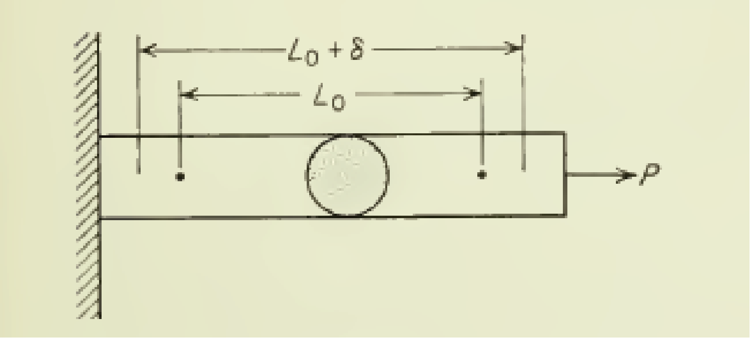

Fig. 1-1. Cylindrical bar subjected to axial load.

The external load P is balanced by the internal resisting force ($P=\int \sigma dA$), where σ is the stress normal to the cutting plane and A is the cross-sectional area of the bar. If the stress is distributed uniformly over the area A, that is, if σ is constant, **$\sigma = P/A$.**

The elastic limit Hooke's law can be considered valid, so that the average stress is proportional to the average strain, **$E = \sigma/\varepsilon$ = Constant**. The constant **E** is the modulus of elasticity, or Young's modulus.

1-5. Tensile Deformation of Ductile Metal

The basic data on the mechanical properties of a ductile metal are obtained from a tension test, in which a suitably designed specimen is subjected to increasing axial load until it fractures. The load and elongation are measured at frequent intervals during the test and are expressed as average stress and strain according to the equations in the previous section. The data obtained from the tension test are generally plotted as a stress-strain diagram.

Figure 1-2 shows a typical stress-strain curve for a metal such as aluminum or copper. The initial linear portion of the curve OA is the elastic region within which Hooke's law is obeyed. Point A is **the elastic limit**, defined as the greatest stress that the metal can withstand without experiencing a permanent strain when the load is removed.

The determination of the elastic limit is quite tedious, not at all routine, and dependent on the sensitivity of the strain-measuring instrument. For these reasons it is often replaced by the proportional limit, point A'. **The proportional limit** is the stress at which the stress-strain curve deviates from linearity. The slope of the stress-strain curve in this region is the **modulus of elasticity**.

For engineering purposes the limit of usable elastic behavior is described by the yield strength, point B. **The yield strength** is defined as the stress which will produce a small amount of permanent deformation, generally a strain equal to 0.2 per cent or 0.002 inches per inch. In Fig. 1-2 this permanent strain, or offset, is OC. Plastic deformation begins when the elastic limit is exceeded. As the plastic deformation of the specimen increases, the metal becomes stronger (**strain hardening**) so that the load required to extend the specimen increases with further straining. Eventually the load reaches a maximum value. The maximum load divided by the original area of the specimen is **the ultimate tensile strength.** For a ductile metal the diameter of the specimen begins to decrease rapidly beyond maximum load, so that the load required to continue deformation drops off until the specimen fractures. Since the average stress is based on the original area of the specimen, it also decreases from maximum load to fracture.

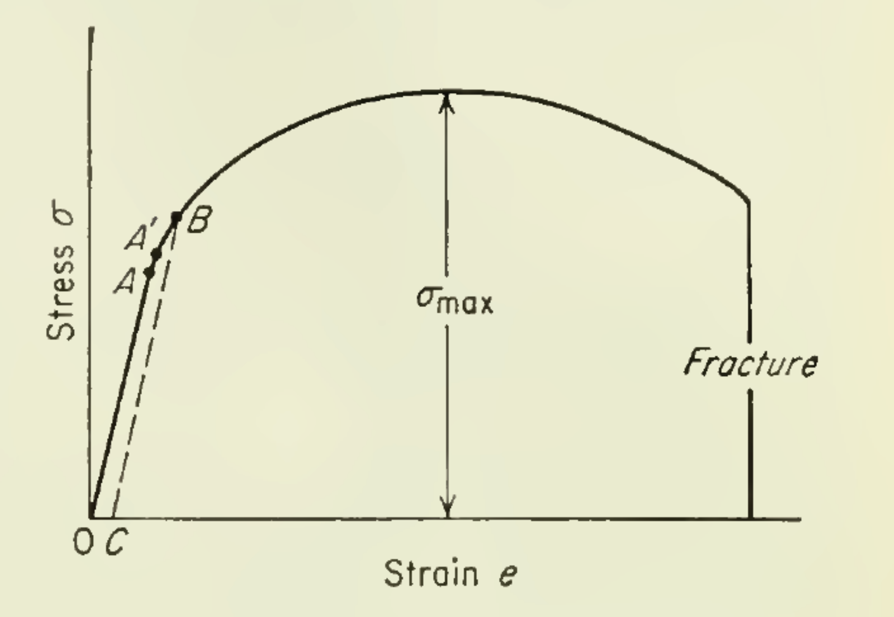

Fig. 1-2. Typical tension stress-strain curve.

1-6. Ductile vs. Brittle Behavior

The general behavior of materials under load can be classified as **ductile or brittle** depending upon whether or not the material exhibits **the ability to undergo plastic deformation**. Figure 1-2 illustrates the tension stress-strain curve of a ductile material. A completely brittle material would fracture almost at the elastic limit (Fig. 1-3a), while a brittle metal, such as white cast iron, shows some slight measure of plasticity before fracture (Fig. 1-3b). Adequate ductility is an important engineering consideration, because it allows the material to **redistribute localized stresses**.

When localized stresses at notches and other accidental stress concentrations do not have to be considered, it is possible to design for static situations on the basis of average stresses. However, with brittle materials, localized stresses continue to build up when there is no local yielding. Finally, a crack forms at one or more points of stress concentration, and it spreads rapidly over the section. Even if no stress concentrations are present in a brittle material, fracture will still occur suddenly because the yield stress and tensile strength are practically identical.

It is important to note that brittleness is not an absolute property of a metal. A metal such as **tungsten**, which is brittle at room temperature, is ductile at an elevated temperature. A metal which is brittle in tension may be ductile under hydrostatic compression. Furthermore, a metal which is ductile in tension at room temperature can become brittle in the presence of notches, low temperature, high rates of loading, or embrittling agents such as **hydrogen**.

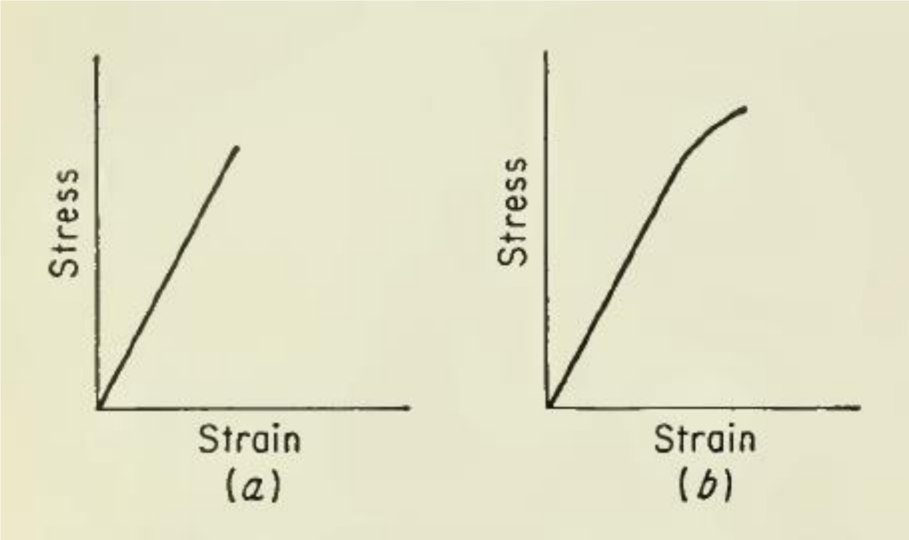

Fig. 1-3. (a) Stress-strain curve for completely brittle material (ideal behavior); (b) stress-strain curve for brittle metal with slight amount of ductility.

1-7. What Constitutes Failure?

Structural members and machine elements can fail to perform their intended functions in three general ways:

1. Excessive elastic deformation
2. Yielding, or excessive plastic deformation
3. Fracture

An understanding of the common types of failure is important in good design because it is always necessary to relate the loads and dimensions of the member to some significant material parameter which limits the load-carrying capacity of the member. For different types of failure, different significant parameters will be important.

Two general types of excessive elastic deformation may occur: (1) excessive deflection under conditions of stable equilibrium, such as the deflection of beam under gradually applied loads; (2) sudden deflection, or buckling, under conditions of unstable equilibrium.

Excessive elastic deformation of a machine part can mean failure of the machine just as much as if the part completely fractured. For example, a shaft which is too flexible can cause rapid wear of the bearing, or the excessive deflection of closely mating parts can result in interference and damage to the parts. The sudden **buckling** type of failure may occur in a slender column when the axial load exceeds the Euler critical load or when the external pressure acting against a thin-walled shell exceeds a critical value. Failures due to excessive elastic deformation are controlled by the modulus of elasticity, not by the strength of the material.

Generally, little metallurgical control can be exercised over the elastic modulus. The most effective way to increase the stiffness of a member is usually by changing its shape and increasing the dimensions of its cross section.

Yielding, or excessive plastic deformation, occurs when the elastic limit of the metal has been exceeded. Yielding produces permanent change of shape, which may prevent the part from functioning properly any longer.

In a ductile metal under conditions of static loading at room temperature yielding rarely results in fracture, because the metal strain hardens as it deforms, and an increased stress is required to produce further deformation.

Failure by excessive plastic deformation is controlled by the yield strength of the metal for a uniaxial condition of loading. For more complex loading conditions the yield strength is still the significant parameter, but it must be used with a suitable failure criterion (Sec. 3-4). At temperatures significantly greater than room temperature metals no longer exhibit strain hardening. Instead, metals can continuously deform at constant stress in a time-dependent yielding known as **creep**. The failure criterion under creep conditions is complicated by the fact that stress is not proportional to strain and the further fact that the mechanical properties of the material may change appreciably during service.

The formation of a crack which can result in complete disruption of continuity of the member constitutes fracture. A part made from a ductile metal which is loaded statically rarely fractures like a tensile specimen, because it will first fail by excessive plastic deformation.

However, metals fail by fracture in three general ways: (1) sudden brittle fracture; (2) fatigue, or progressive fracture; (3) delayed fracture.

In the previous section it was shown that a brittle material fractures under static loads with little outward evidence of yielding. A sudden brittle type of fracture can also occur in ordinarily ductile metals under certain conditions. **Plain carbon structural steel** is the most common example of a material with a ductile-to-brittle transition. A **change from the ductile to the brittle type of fracture is promoted by** a decrease in temperature, an increase in the rate of loading, and the presence of a complex state of stress due to a notch.

Most fractures in machine parts are due to fatigue. **Fatigue failures** occur in parts which are subjected to alternating, or fluctuating stresses.

A minute crack starts at a localized spot, generally at a notch or stress concentration, and gradually spreads over the cross section until the member breaks. Fatigue failure occurs without any visible sign of yielding at nominal or average stresses that are well below the tensile strength of the metal. Fatigue failure is caused by a critical localized tensile stress which is very difficult to evaluate, and therefore design for fatigue failure is based primarily on empirical relationships using nominal stresses.

One common type of delayed fracture is stress-rupture failure, which occurs when a metal has been statically loaded at an **elevated temperature** for a long period of time. Depending upon the stress and the temperature there may be no yielding prior to fracture. A similar type of delayed fracture, in which there is no warning by yielding prior to failure, occurs at room temperature when steel is statically loaded in **the presence of hydrogen**.

All engineering materials show a certain variability in mechanical properties, which in turn can be influenced by changes in heat treatment or fabrication. Further, uncertainties usually exist regarding the magnitude of the applied loads, and approximations are usually necessary in calculating the stresses for all but the most simple member.

Allowance must be made for the possibility of accidental loads of high magnitude. Thus, in order to provide a margin of safety and to protect against failure from unpredictable causes, it is necessary that the allowable stresses be smaller than the stresses which produce failure. The value of stress for a particular material used in a particular way which is considered to be a safe stress is usually called the working stress **σw**. For static applications the working stress of ductile metals is usually based on the yield strength **σy** and for brittle metals on the ultimate tensile strength **σu**.

Values of working stress are established by local and Federal agencies and by technical organizations such as the American Society of Mechanical Engineers (**ASME**). The working stress may be considered as either the yield strength or the tensile strength divided by a number called the **factor of safety**.

The value assigned to the factor of safety depends on an estimate of all the factors discussed above. In addition, careful consideration should be given to the consequences which would result from failure. If failure would result in loss of life, the factor of safety should be increased. The type of equipment will also influence the factor of safety. In military equipment, where light weight may be a prime consideration, the factor of safety may be lower than in commercial equipment. The factor of safety will also depend on the expected type of loading. For static loading, as in a building, the factor of safety would be lower than in a machine, which is subjected to vibration and fluctuating stresses.