Unit-IV

Mechanical Failure

- *The design of a component or structure often calls upon the engineer to* ***minimize the possibility of failure****.*

- *Thus, it is important to understand the mechanics of the various failure modes—fracture, fatigue, and creep*

Mechanical Failure

- The failure of engineering materials is almost always an undesirable event for several reasons; these include putting human lives in danger, causing economic losses, and interfering with the availability of products and services.

- Even though the causes of failure and the behavior of materials may be known, prevention of failures is difficult to guarantee.

- The usual causes are improper materials selection and processing and inadequate design of the component or its misuse.

- Also, damage can occur to structural parts during service.

Mechanical Failure

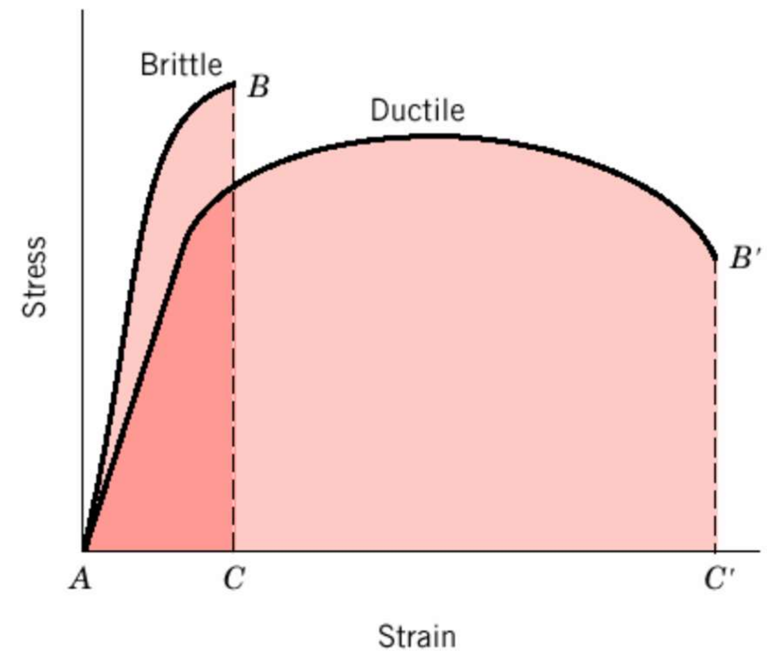
- Regular inspection and repair or replacement are critical to safe design.
- It is the responsibility of the engineer to anticipate and plan for possible failure
- In the event that failure does occur, to assess its cause and then take appropriate preventive measures against future incidents.

FUNDAMENTALS of MECHANICAL FAILURE

- Simple fracture is the separation of a body into two or more pieces in response to an imposed
  - stress that is static (i.e., constant or slowly changing with time) and
  - at temperatures that are low relative to the melting temperature of the material.
- Fracture can also occur from
  - **fatigue** (when cyclic stresses are imposed)
  - **creep** (time-dependent deformation, normally at elevated temperatures);

- For metals, **two fracture modes** are possible: **ductile** and **brittle.**
- Classification is based on the ability of a material to experience plastic deformation.

- Ductile metals typically exhibit substantial plastic deformation with high energy absorption before fracture.
- However, there is normally little or no plastic deformation with low energy absorption accompanying a brittle fracture.



- *Ductile* and *brittle* are relative terms; whether a particular fracture is one mode or the other depends on the situation.
- Ductility may be **quantified** in terms of percent elongation and percent reduction in area.

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

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 or $in.^2$). The units of engineering stress (referred to subsequently as just *stress*) are megapascals, MPa (SI) (where 1 MPa = 10^6 N/m^2), and pounds force per square inch, psi (customary U.S.).[2]

Percent reduction in area (%RA) is defined as

$$\%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100 \tag{6.12}$$

where A_0 is the original cross-sectional area and A_f is the cross-sectional area at the point of fracture.[12] Values of percent reduction in area are independent of both l_0 and A_0. Furthermore, for a given material, the magnitudes of %EL and %RA will, in general, be different. Most metals possess at least a moderate degree of ductility at room temperature; however, some become brittle as the temperature is lowered

- Furthermore, ductility is a function of temperature of the material, the strain rate, and the stress state.

Fracture

Any fracture process involves two steps, inresponse to an imposed stress

1. **Crack formation**
2. **Crack propagation**

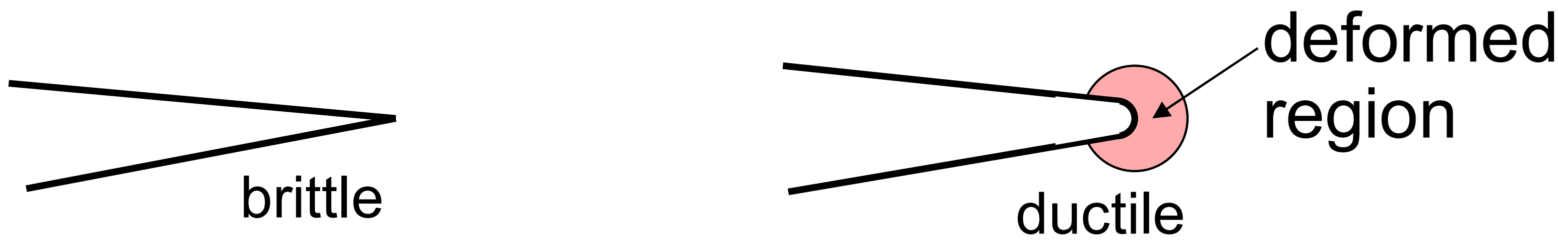
The mode of fracture is highly dependent on the **mechanism of crack propagation**.

- Ductile fracture is characterized by extensive plastic deformation in the vicinity of an advancing crack.
  - The process proceeds relatively slowly as the crack length is extended.
  - Such a crack is often said to be stable—that is, it resists any further extension unless there is an increase in the applied stress.
  - In addition, there typically is evidence of appreciable gross deformation at the fracture surfaces (e.g., twisting and tearing).
- For brittle fracture, cracks may spread extremely rapidly, with very little accompanying plastic deformation.
  - Such cracks may be said to be unstable, and crack propagation, once started, continues spontaneously without an increase in magnitude of the applied stress.

Crack Propagation

Cracks having sharp tips propagate easier than cracks having blunt tips

- A plastic material deforms at a crack tip, which "blunts" the crack.



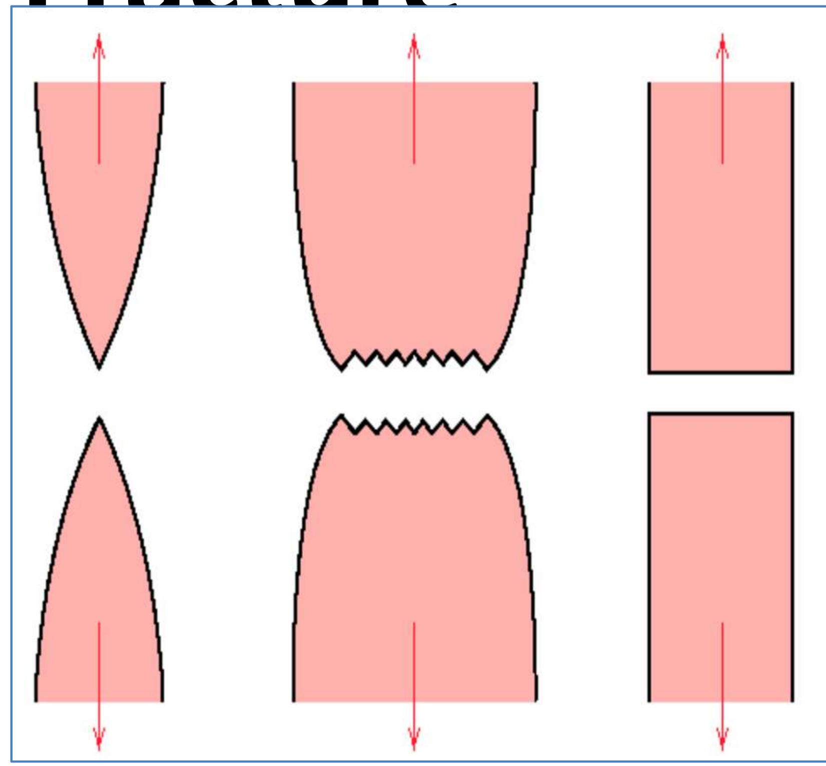
Energy balance on the crack

- Elastic strain energy-
  - Energy stored in material as it is elastically deformed
  - This energy is released when the crack propagates
  - creation of new surfaces requires energy

Ductile fracture is almost always preferred to brittle fracture for two **reasons**:

- First, brittle fracture occurs suddenly and catastrophically without any warning; this is a consequence of the spontaneous and rapid crack propagation. By contrast, in ductile fracture, the presence of plastic deformation gives warning that failure is imminent, allowing preventive measures to be taken.
- Second, more strain energy is required to induce ductile fracture inasmuch as these materials are generally tougher. Under the action of an applied tensile stress, many metal alloys are ductile, whereas ceramics are typically brittle, and polymers may exhibit a range of behaviors.

Brittle vs. Ductile Fracture



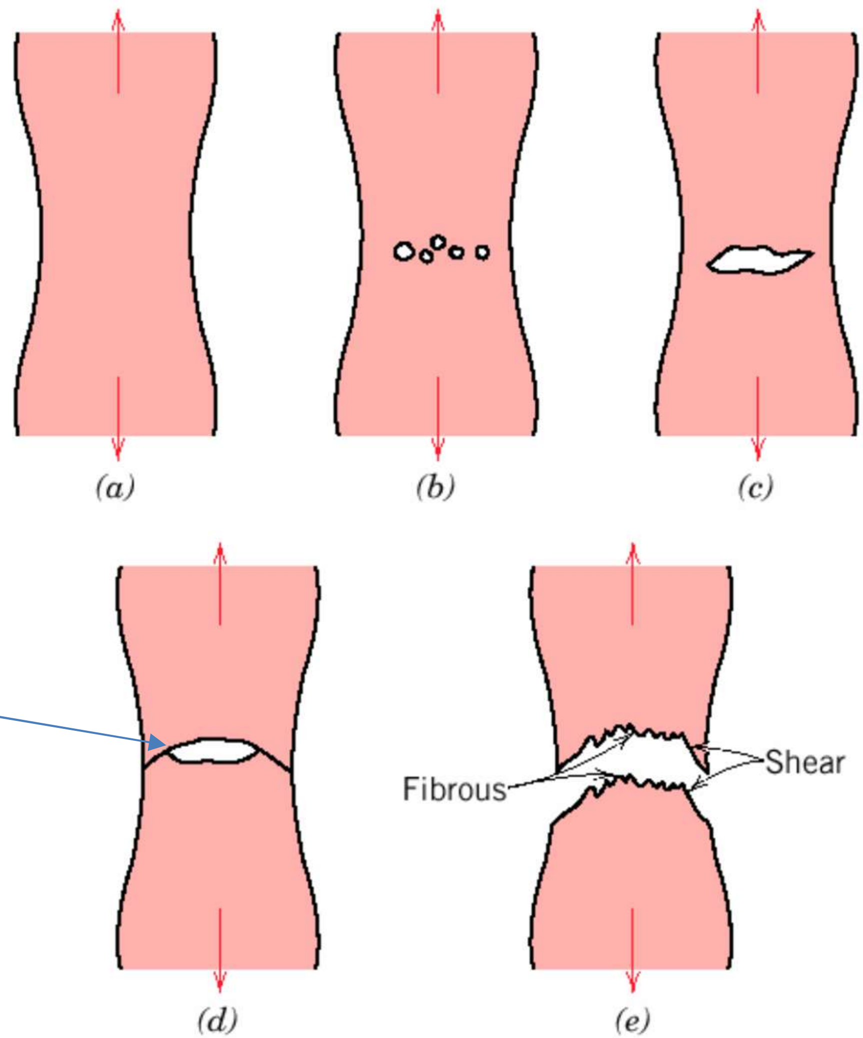
A. Very ductile, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.
B. Moderately ductile fracture, typical for ductile metals
C. Brittle fracture, cold metals, ceramics.

(a) *(b)*

C

Ductile Fracture (Dislocation Mediated)

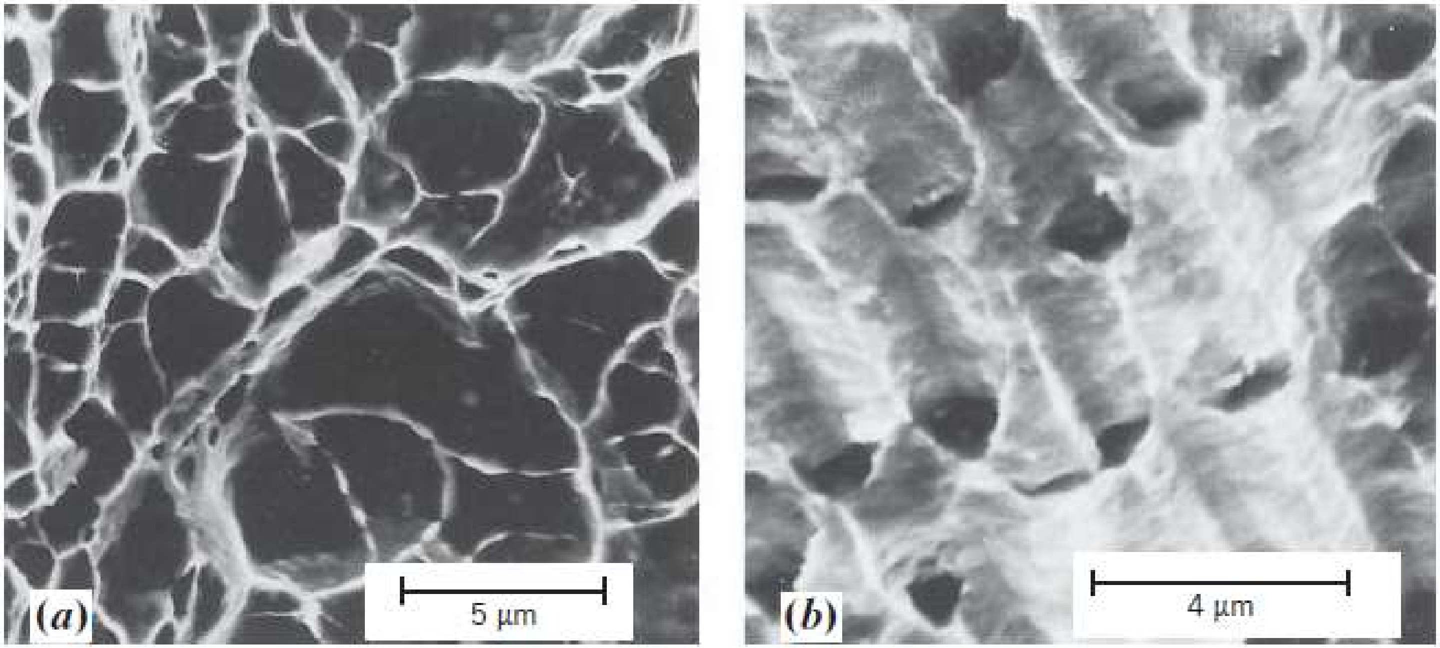
(a) Necking
(b) Formation of microvoids
(c) Coalescence of microvoids to form a crack
(d) Crack propagation by shear deformation
(e) Fracture



Crack grows 90 degree to applied stress

45 degree -Maximum shear stress

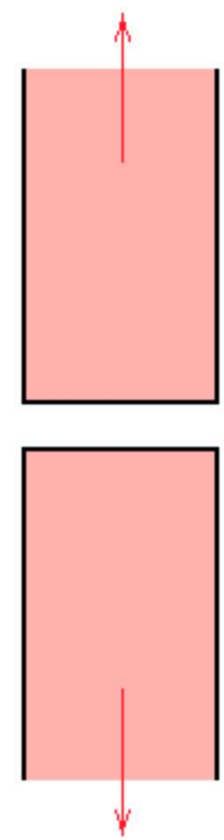
Cup-and-cone fracture



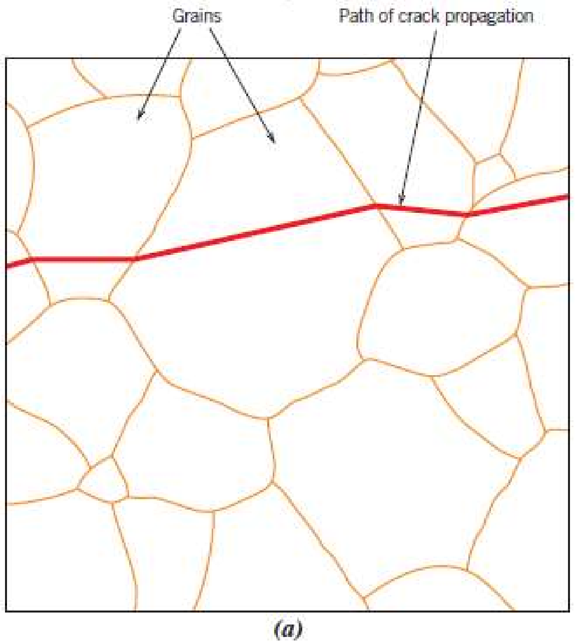
(a) Scanning electron fractograph showing spherical dimples characteristic of ductile fracture resulting
from uniaxial tensile loads. 3300×. (b) Scanning electron fractograph showing parabolic-shaped dimples characteristic
of ductile fracture resulting from shear loading. 5000×.

Brittle Fracture (Limited Dislocation Mobility)

- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by cleavage – breaking of atomic bonds along specific crystallographic planes (cleavage planes).

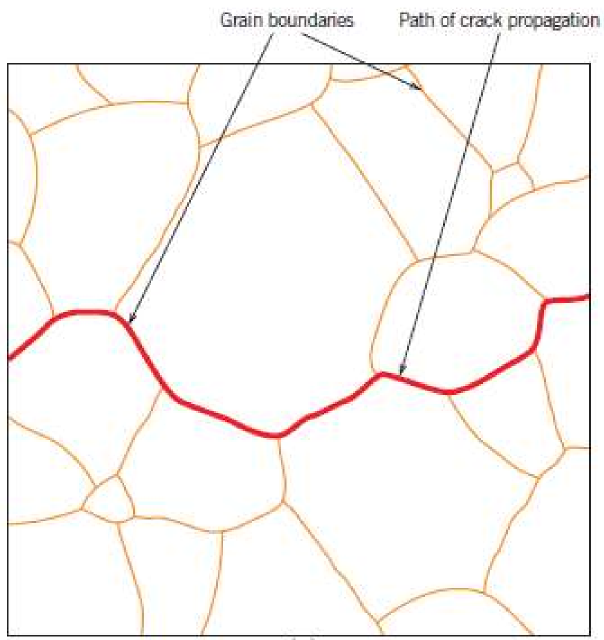


Brittle Fracture



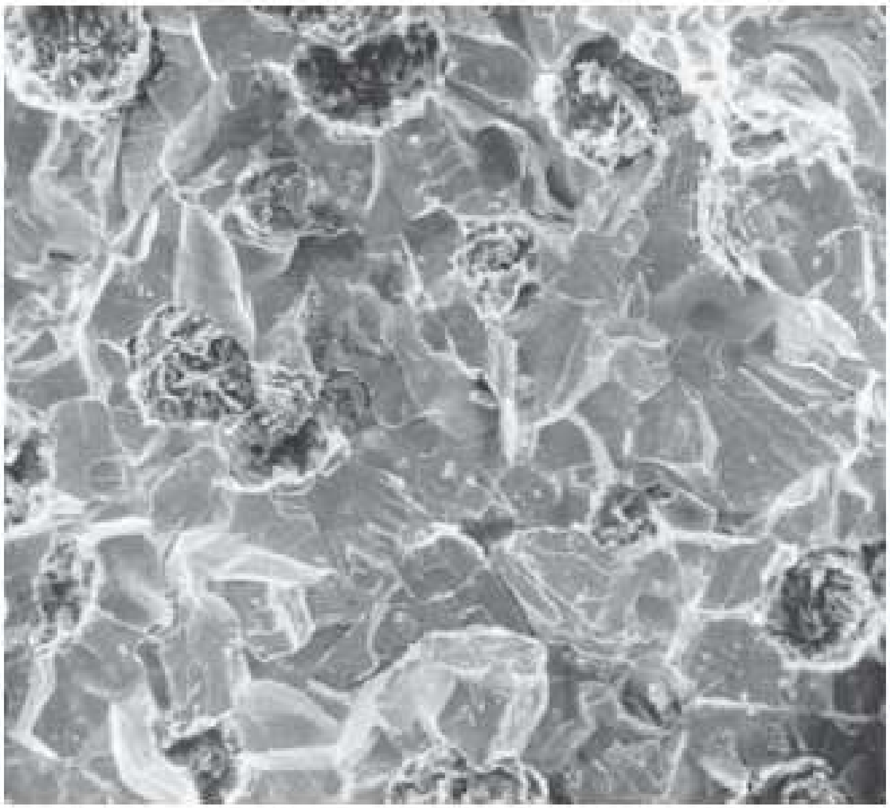
A. Transgranular fracture:

- Fracture cracks pass through grains.
- Fracture surface have faceted texture because of different orientation of cleavage planes in grains.



B. Intergranular fracture:

- Fracture crack propagation is along grain boundaries
- (grain boundaries are weakened or embrittled by impurities segregation etc.)



Transgranular fracture

Intergranular fracture

PRINCIPLES OF FRACTURE MECHANICS

- Normally ductile materials may experience Brittle
  - It demonstrated the need for a better understanding of the mechanisms of fracture

- The subject of **fracture mechanics** allows **quantification** of the relationships among material properties, stress level, the presence of crack-producing flaws, and crack propagation mechanisms.

- Design engineers are now better equipped to anticipate, and thus prevent, structural failures.

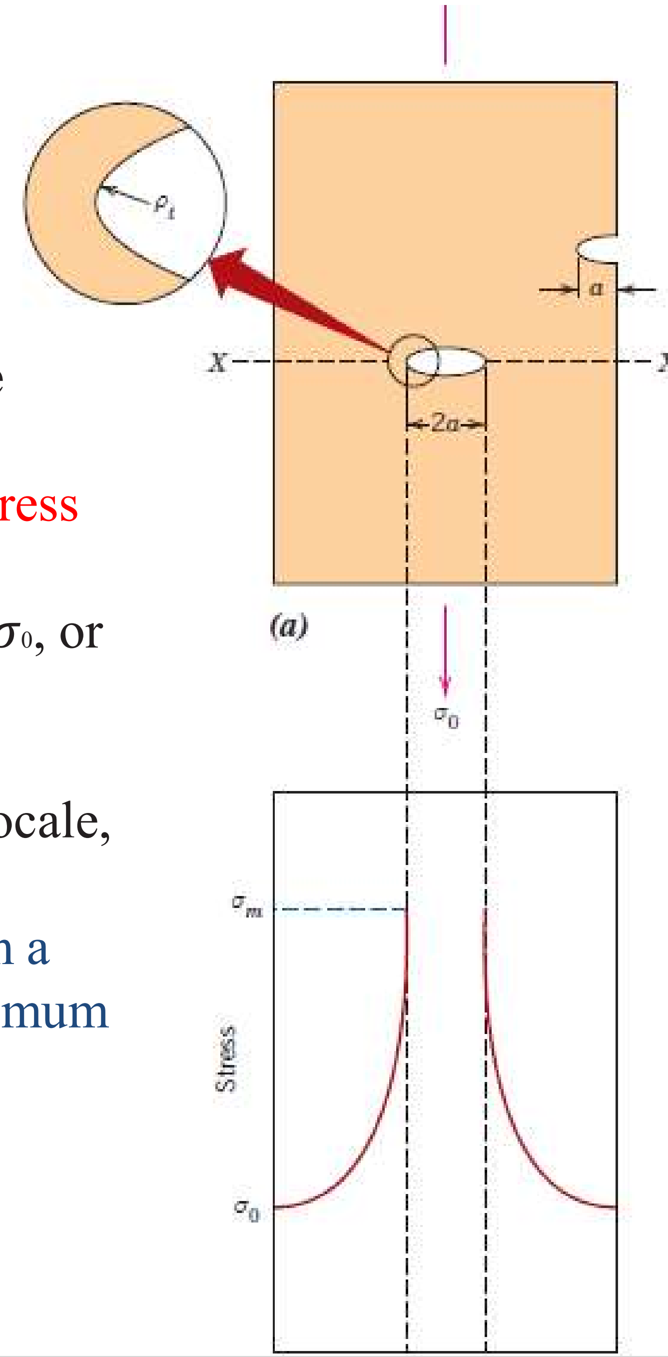
- The present discussion centers on some of the fundamental principles of the mechanics of fracture.

Stress Concentration

- The measured fracture strengths for most materials are significantly lower than those predicted by theoretical calculations based on atomic bonding energies.
- This discrepancy is explained by the **presence of microscopic flaws or cracks** that always exist under normal conditions at the surface and within the interior of a body of material.
- These flaws are a detriment to the fracture strength because an applied stress may be amplified or concentrated at the tip, the magnitude of this amplification depending on crack orientation and geometry.

- This phenomenon is demonstrated in Figure—a **stress profile** across a cross section containing an **internal crack**.
- As indicated by this profile, the magnitude of this localized stress decreases with distance away from the crack tip.
- At positions far removed, the stress is just the nominal stress σ_0, or the applied load divided by the specimen cross-sectional area (perpendicular to this load).
- Because of their ability to amplify an applied stress in their locale, these flaws are sometimes called **stress raisers.**

If it is assumed that a crack is similar to an elliptical hole through a plate and is oriented perpendicular to the applied stress, the maximum stress, σ_m, occurs at the crack tip and may be approximated by



$$\sigma_m = 2\sigma_0\left(\frac{a}{\rho_t}\right)^{1/2}$$

where σ_0 is the magnitude of the nominal applied tensile stress, ρ_t is the radius of curvature of the crack tip (Figure *a*), and *a* represents the length of a surface crack, or half of the length of an internal crack.

The ratio σ_m/σ_0 is denoted the ***stress concentration factor*** K_t: $$K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{a}{\rho_t}\right)^{1/2}$$

--a measure of the degree to which an external stress is amplified at the tip of a crack.

Stress amplification may occur at macroscopic internal discontinuities (e.g., voids or inclusions), sharp corners, scratches, and notches.

The effect of a stress raiser is more significant in **brittle** than in ductile materials.

For a **ductile metal**, plastic deformation takes place when the maximum stress exceeds the yield strength.

This leads to a more **uniform distribution of stress** in the vicinity of the stress raiser and to the development of a maximum stress concentration factor **less** than the theoretical value.

Such yielding and stress redistribution do not occur to any appreciable extent around flaws and discontinuities in **brittle materials**; therefore, essentially the theoretical stress concentration results.

Critical Stress for crack propagation in **Brittle Material**

Using principles of fracture mechanics, it is possible to show that the critical stress σ_c required for crack propagation in a brittle material is described by the expression

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2} \tag{8.3}$$

where E is modulus of elasticity, γ_s is the specific surface energy, and a is one-half the length of an internal crack.

Maximum Flaw Length Computation

A relatively large plate of a glass is subjected to a tensile stress of 40 MPa. If the specific surface energy and modulus of elasticity for this glass are 0.3 J/m^2 and 69 GPa, respectively, determine the maximum length of a surface flaw that is possible without fracture.

Maximum Flaw Length Computation

A relatively large plate of a glass is subjected to a tensile stress of 40 MPa. If the specific surface energy and modulus of elasticity for this glass are 0.3 J/m^2 and 69 GPa, respectively, determine the maximum length of a surface flaw that is possible without fracture.

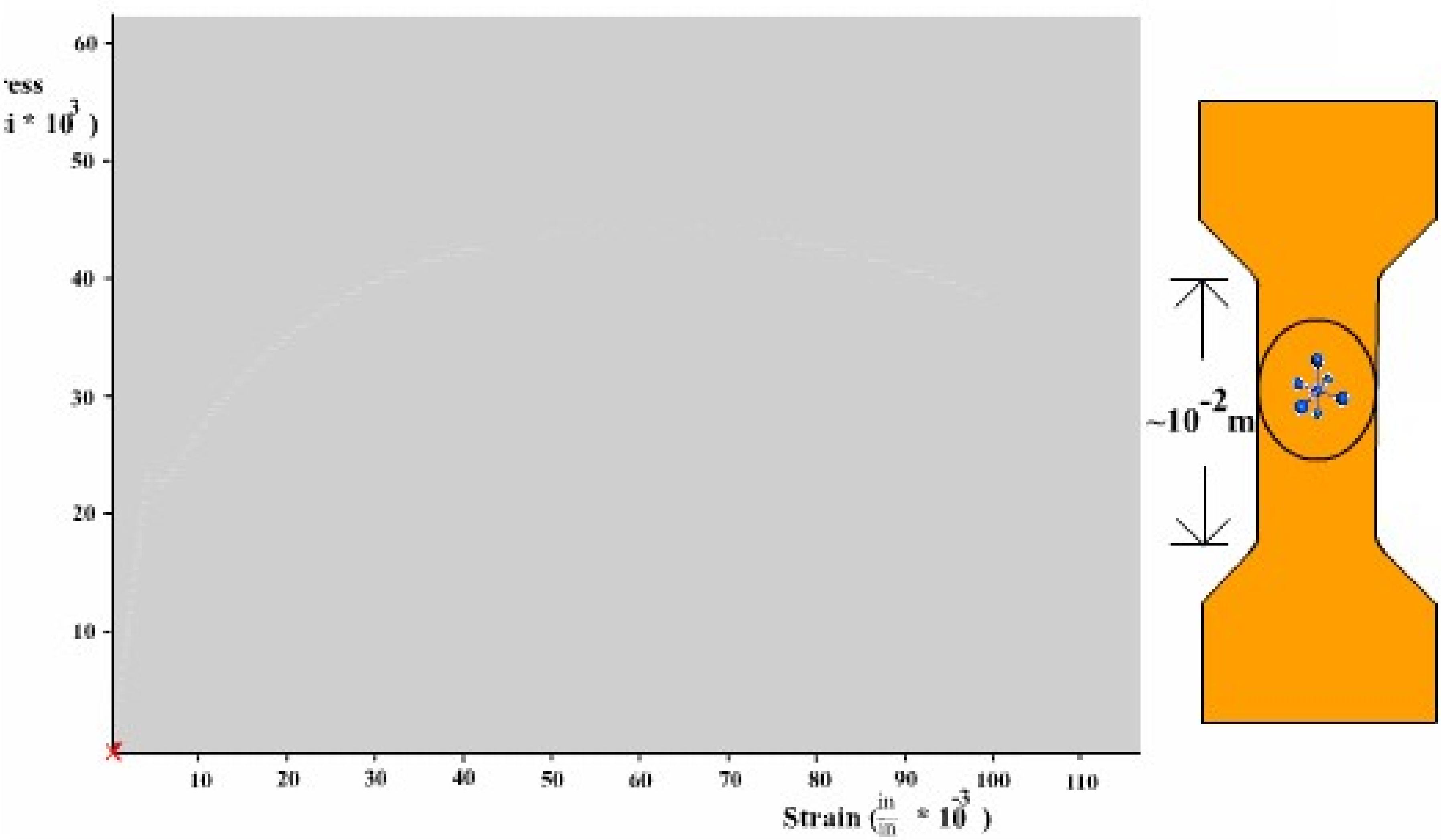
Solution

To solve this problem it is necessary to employ Equation 8.3. Rearranging this expression such that a is the dependent variable, and realizing that $\sigma = 40$ MPa, $\gamma_s = 0.3$ J/m^2, and $E = 69$ GPa, leads to

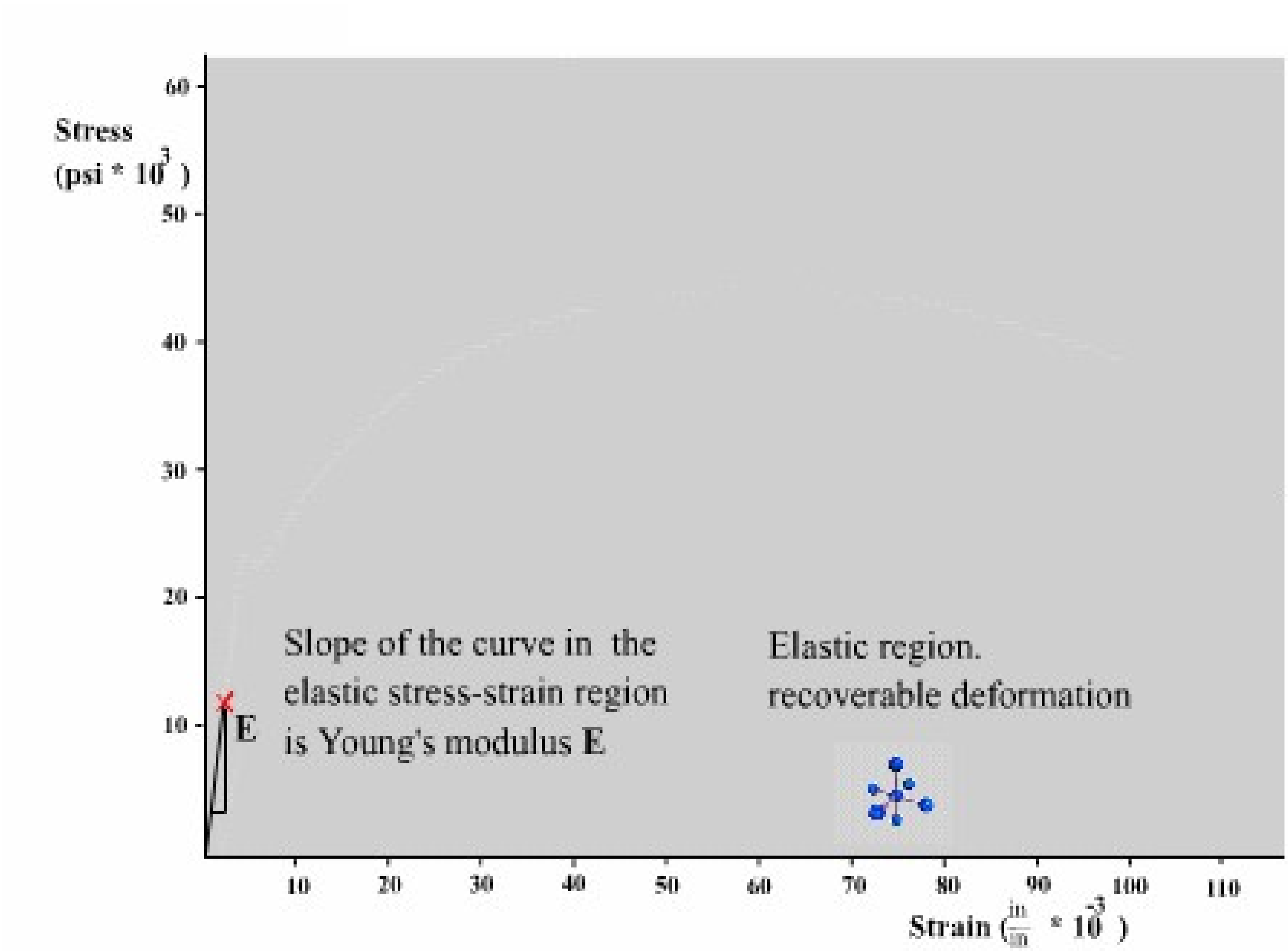
$$
\begin{aligned}
a &= \frac{2E\gamma_s}{\pi\sigma^2} \\
&= \frac{(2)(69 \times 10^9 \text{ N/m}^2)(0.3 \text{ N/m})}{\pi(40 \times 10^6 \text{ N/m}^2)^2} \\
&= 8.2 \times 10^{-6} \text{ m} = 0.0082 \text{ mm} = 8.2\ \mu\text{m}
\end{aligned}
$$

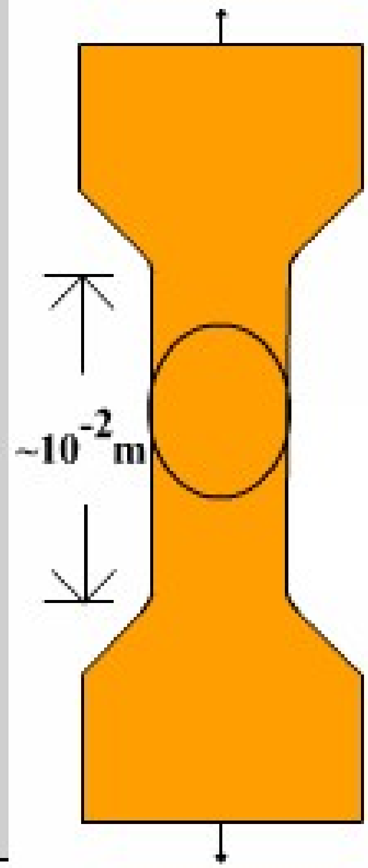
Tensile Test

Tensile Test



Tensile Test

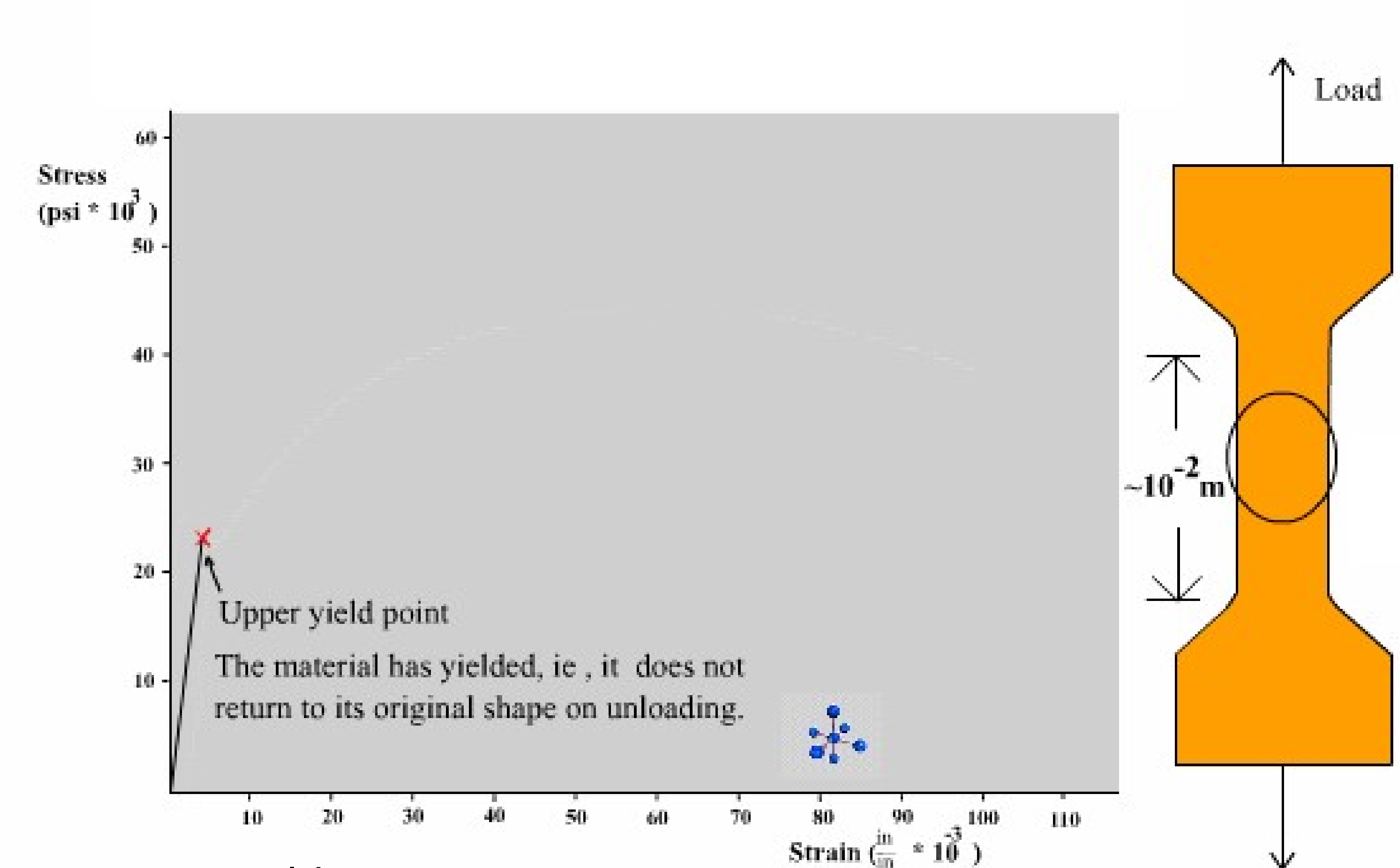




Elastic Region:

•This is the region where stress is proportional to strain

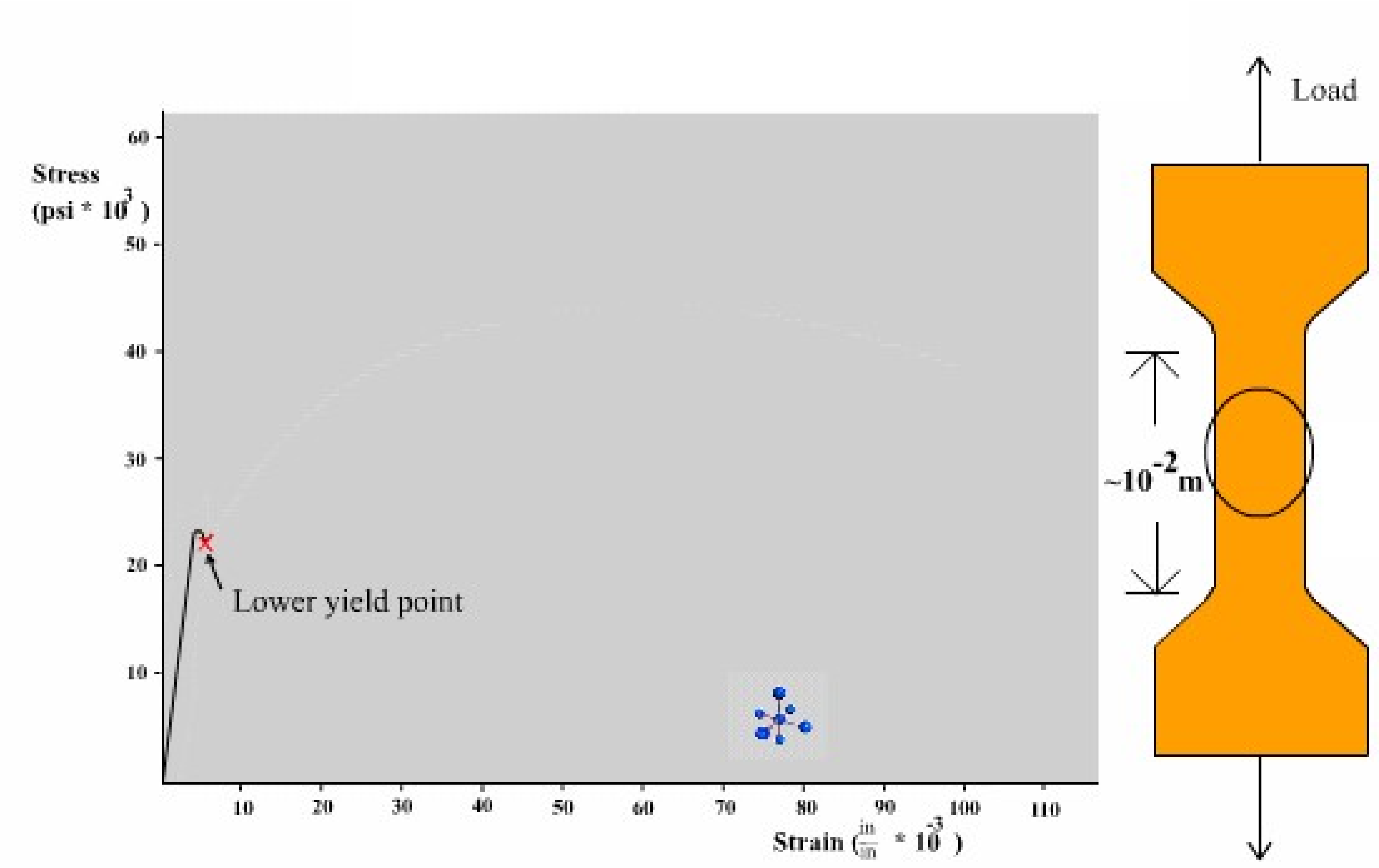
Tensile Test



Yielding Region:

- Upper yield point is where when there is no application of any additional force the material will elongate.

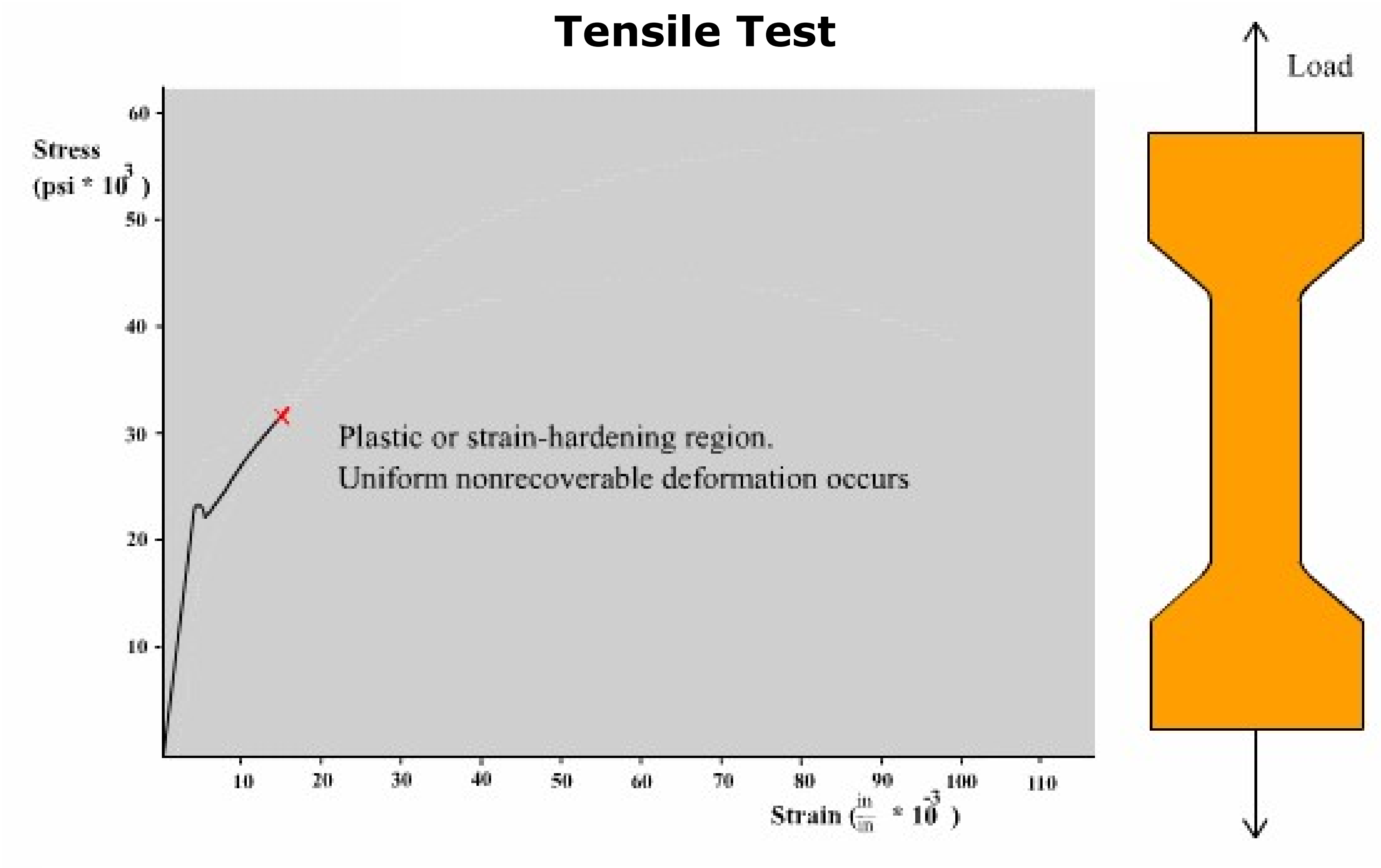
Tensile Test



Lower yield point :

- This is the point where yielding will end .

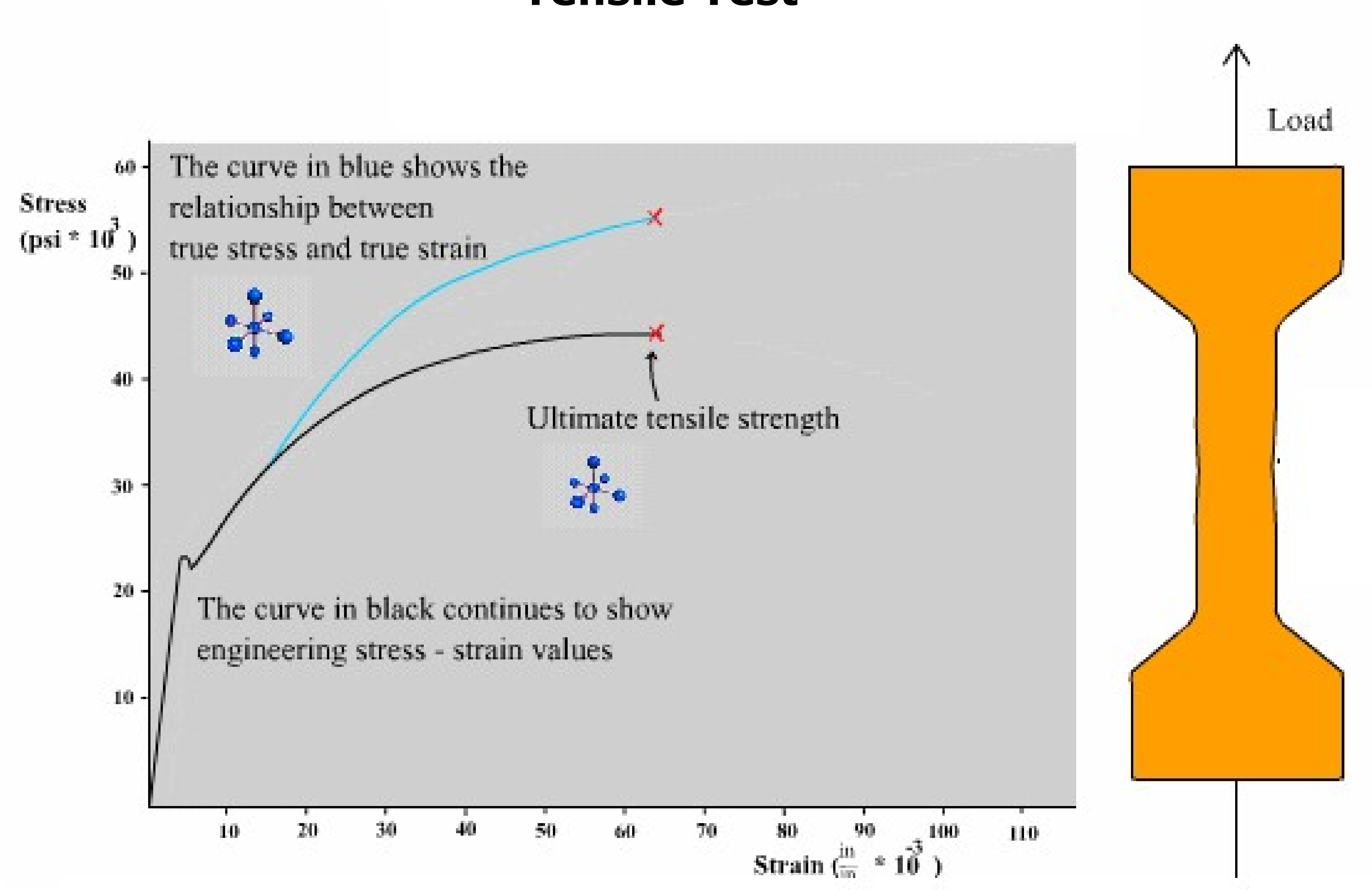
Tensile Test



Proportionality region:

- This is the region where stress is proportional to strain.

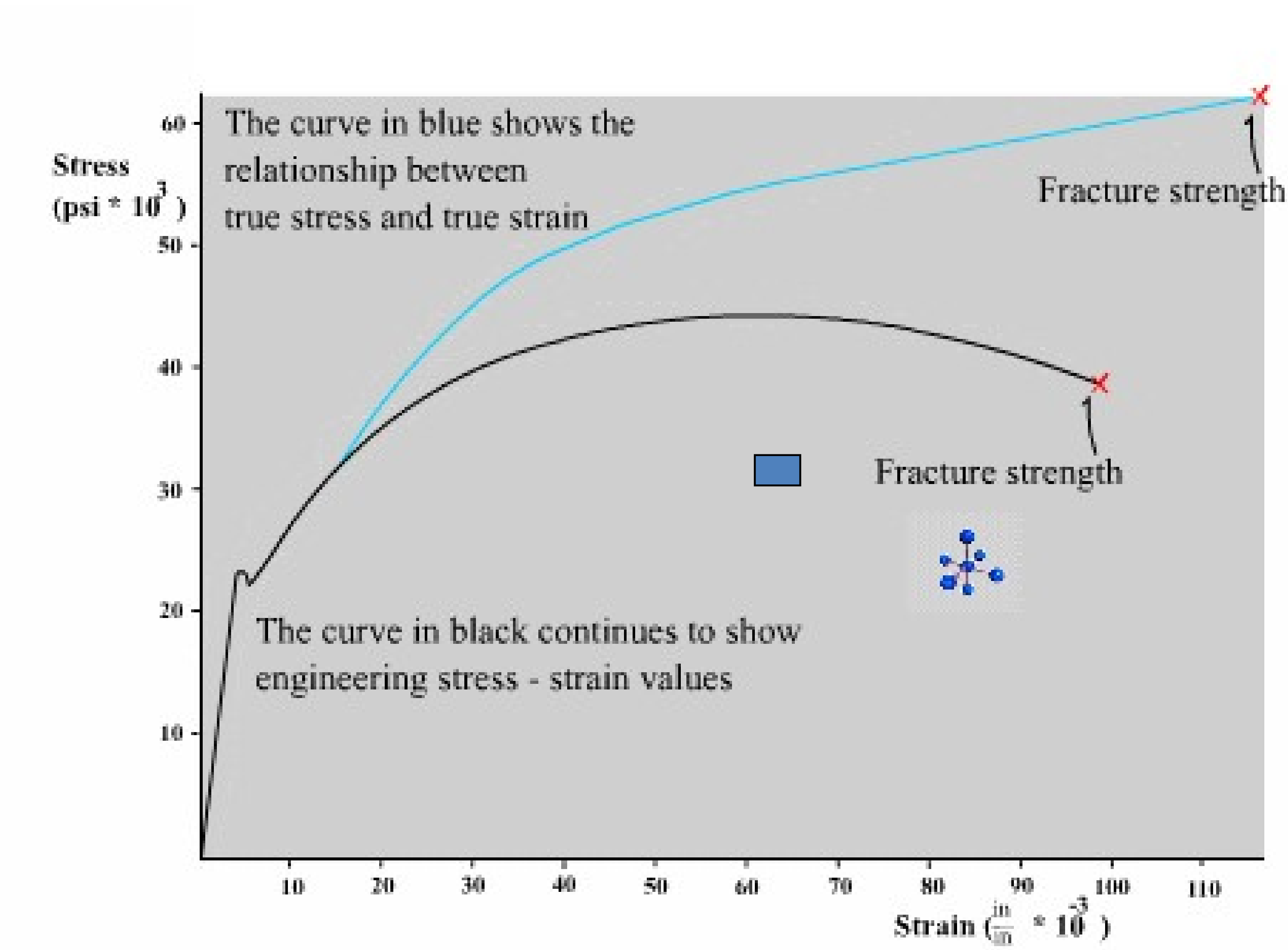
Tensile Test

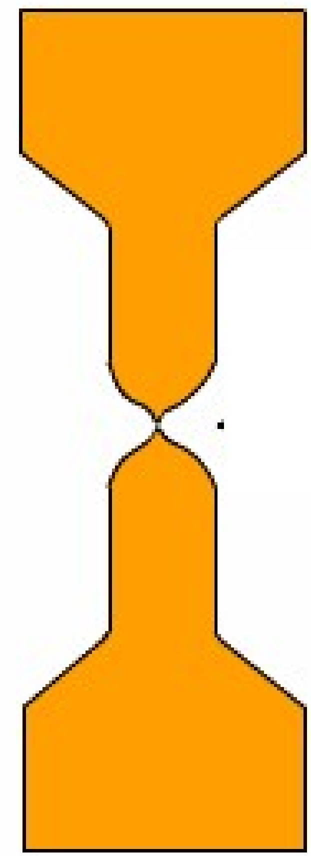


Ultimate Tensile Strength:

- The maximum loading occurs in this region.

Tensile Test





Necking:

- Fracture of material occurs by reduction of area.

FATIGUE

Fatigue

- **Fatigue** is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses (e.g., bridges, aircraft, machine components).

- Under these circumstances, it is possible for failure to occur at a stress level considerably lower than the tensile or yield strength for a static load.

- The term *fatigue* is used because this type of failure normally occurs after a lengthy period of repeated stress or strain cycling. .

- Fatigue is important inasmuch as it is the single largest cause of failure in metals, estimated to be involved in approximately 90% of all metallic failures; polymers and ceramics (except for glasses) are also susceptible to this type of failure.

- Furthermore, fatigue is catastrophic and insidious, occurring very suddenly and without warning.

Fatigue

- Fatigue failure is **brittle-like in nature** even in normally ductile metals in that there is very little, if any, gross plastic deformation associated with failure.

- The process occurs by the initiation and propagation of cracks, and typically the fracture surface is perpendicular to the direction of an applied tensile stress.

CYCLIC STRESSES

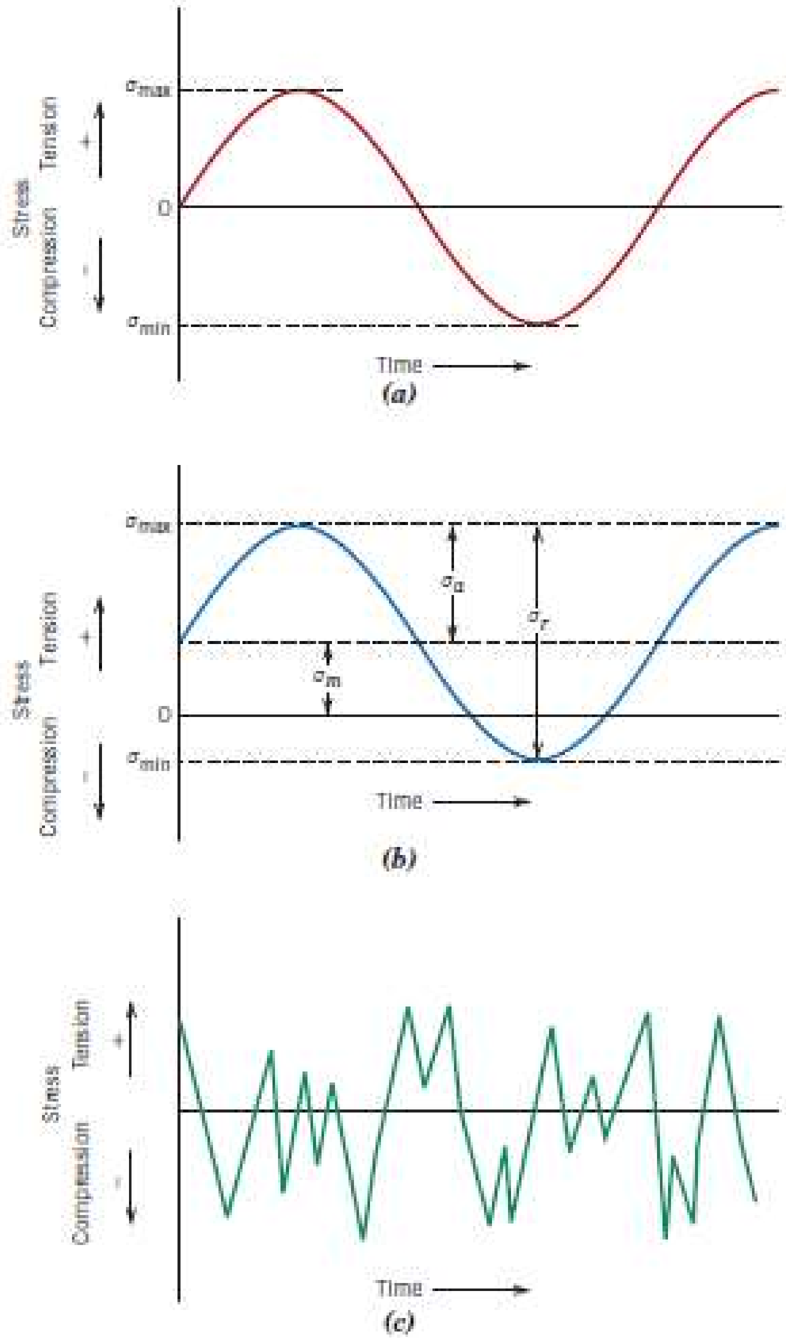


Figure 8.18 Variation of stress with time that accounts for fatigue failures. (*a*) Reversed stress cycle, in which the stress alternates from a maximum tensile stress (+) to a maximum compressive stress (−) of equal magnitude. (*b*) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero-stress level; mean stress σ_m, range of stress σ_r, and stress amplitude σ_a are indicated. (*c*) Random stress cycle.

- The applied stress may be axial (tension–compression), flexural (bending), or torsional (twisting) in nature.

- In general, three different fluctuating stress–time modes are possible.

- One is represented schematically by a regular and sinusoidal time dependence in Figure *a*, where the amplitude is symmetrical about a mean zero stress level, for example, alternating from a maximum tensile stress (σmax) to a minimum compressive stress (σmin) of equal magnitude; this is referred to as a *reversed stress cycle*.

- Another type, termed a *repeated stress cycle,* is illustrated in Figure b; the maxima and minima are asymmetrical relative to the zero stress level.

- Finally, the stress level may vary randomly in amplitude and frequency, as exemplified in Figure *c*.

Also indicated in Figure 8.18*b* are several parameters used to characterize the fluctuating stress cycle. The stress amplitude alternates about a *mean stress*

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$$

The *range of stress* σ_r is the difference between $\sigma_{\max}$ and $\sigma_{\min}$, namel

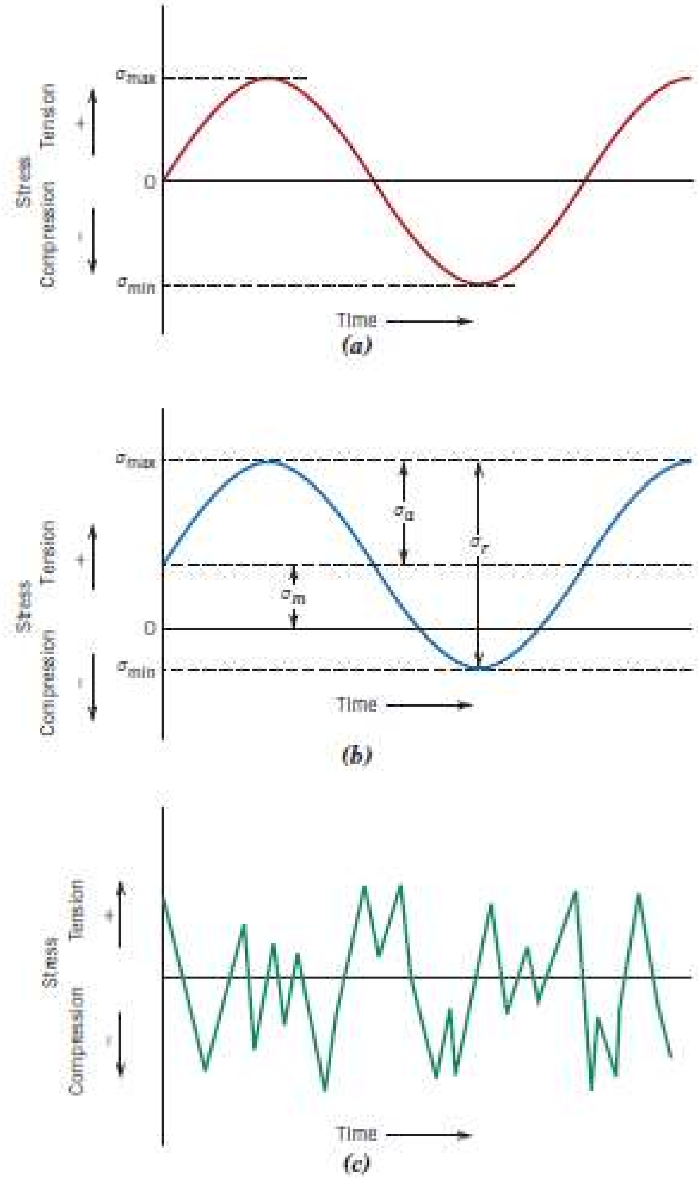
$$\sigma_r = \sigma_{\max} - \sigma_{\min}$$

Stress amplitude σ_a is one-half of this range of stress, or

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$

Finally, the *stress ratio* R is the ratio of minimum and maximum stre

$$R = \frac{\sigma_{\min}}{\sigma_{\max}}$$



Fatigue Test

- As with other mechanical characteristics, the fatigue properties of materials can be determined from **laboratory tests**.

- A test apparatus should be designed to duplicate as nearly as possible the service stress conditions (stress level, time frequency, stress pattern, etc.).

- The most common type of test conducted in a laboratory setting employs a rotating–bending beam: alternating tension and compression stresses of equal magnitude are imposed on the specimen as it is simultaneously bent and rotated.

- In this case, the stress cycle is reversed—that is, $R = -1$.

Fatigue Test

Schematic diagrams of the apparatus and test specimen commonly used for this type of fatigue testing are shown in Figures 8.19*a* and 8.19*b*, respectively.

From Figure 8.19*a,* during rotation, the lower surface of the specimen is subjected to a tensile (i.e., positive) stress, whereas the upper surface experiences compression (i.e., negative) stress.

Furthermore, anticipated in-service conditions may call for conducting simulated laboratory fatigue tests that use either uniaxial tension–compression or torsional stress cycling instead of rotating–bending.

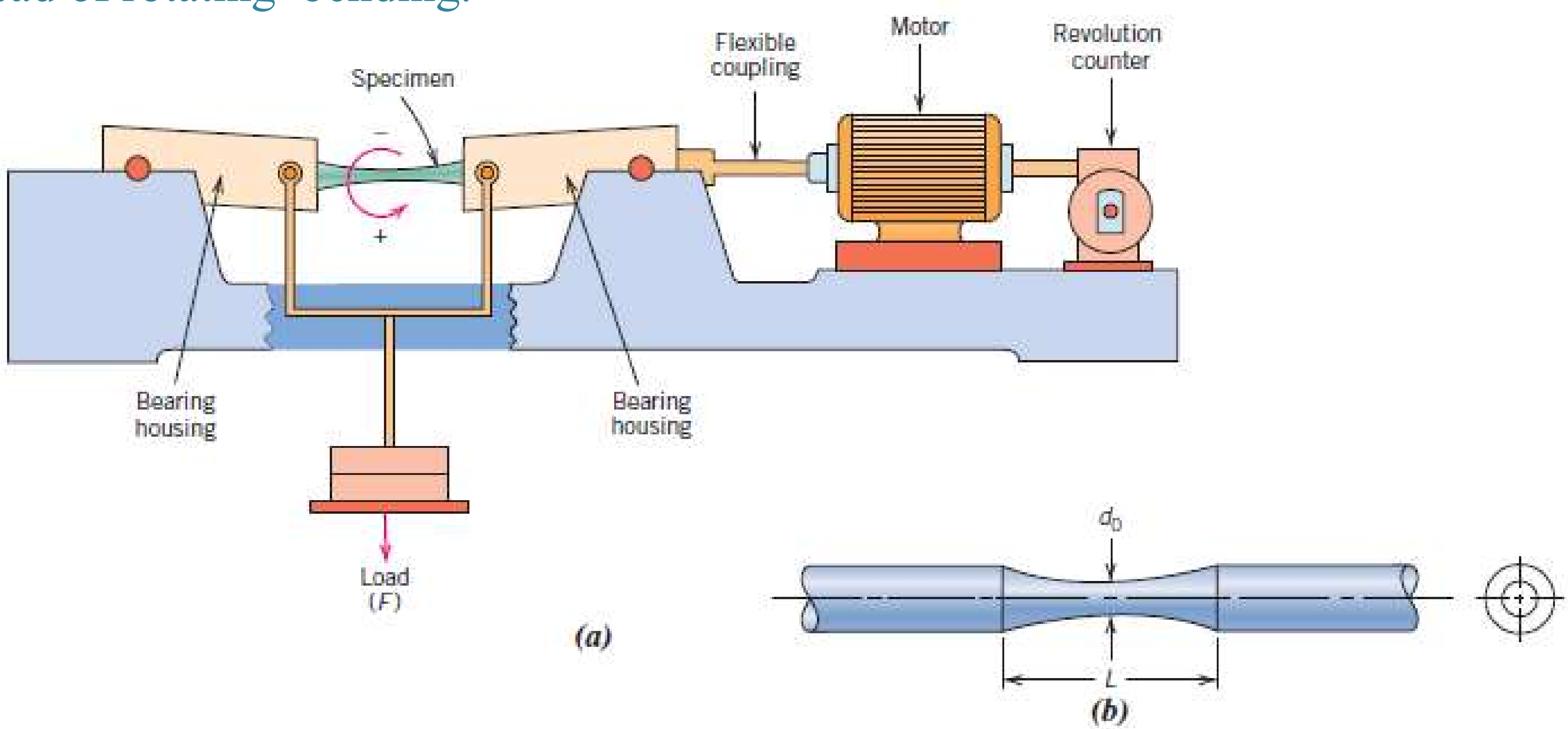


Figure 8.19 For rotating–bending fatigue tests, schematic diagrams of (*a*) a testing apparatus, and (*b*) a test specimen.

Fatigue Test

- A series of tests is commenced by subjecting a specimen to stress cycling at a relatively large maximum stress (σ_{max}), usually on the order of two-thirds of the static tensile strength; number of cycles to failure is counted and recorded.

- This procedure is repeated on other specimens at progressively decreasing maximum stress levels.

- Data are plotted as stress *S* versus the logarithm of the number *N* of cycles to failure for each of the specimens.

- The *S* parameter is normally taken as either maximum stress (σ_{max}) or stress amplitude (σ_a).