ENGINEERING MATERIALS I(ME 281)

MECHANICAL PROPERTIES OF METALS

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Outline

- Concepts of Stress and Strain
- Elastic Deformation
- Plastic Deformation
- Elastic Recovery after Plastic Deformation
- Design Considerations

Learning Objectives

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

- Explain the concepts of stress and strain.
- Describe elastic deformation using stress-strain diagram.
- State Hooke's law and note the conditions under which it is valid.
- Define Poisson's ratio
- Determine the modulus of elasticity given a stress-strain diagram.
- Explain the tensile properties of materials under plastic deformation
- Compute the working stress for a ductile material.

Introduction

- The mechanical behavior of a material reflects the relationship between its response and deformation to an applied load or force.
- The ability of a material to withstand the applied force without any deformation is expressed in two ways, i.e. strength and hardness.

✓ **Strength** is defined in many ways as per the design requirements.

✓ **Hardness** may be defined as resistance to indentation or scratch.

- Material deformation can be permanent or temporary.

✓ **Permanent (plastic) deformation** is irreversible (stays even after the applied force is removed).

✓ **Temporary (elastic) deformation** is recoverable (disappears after removing the applied force).

Types of Loading

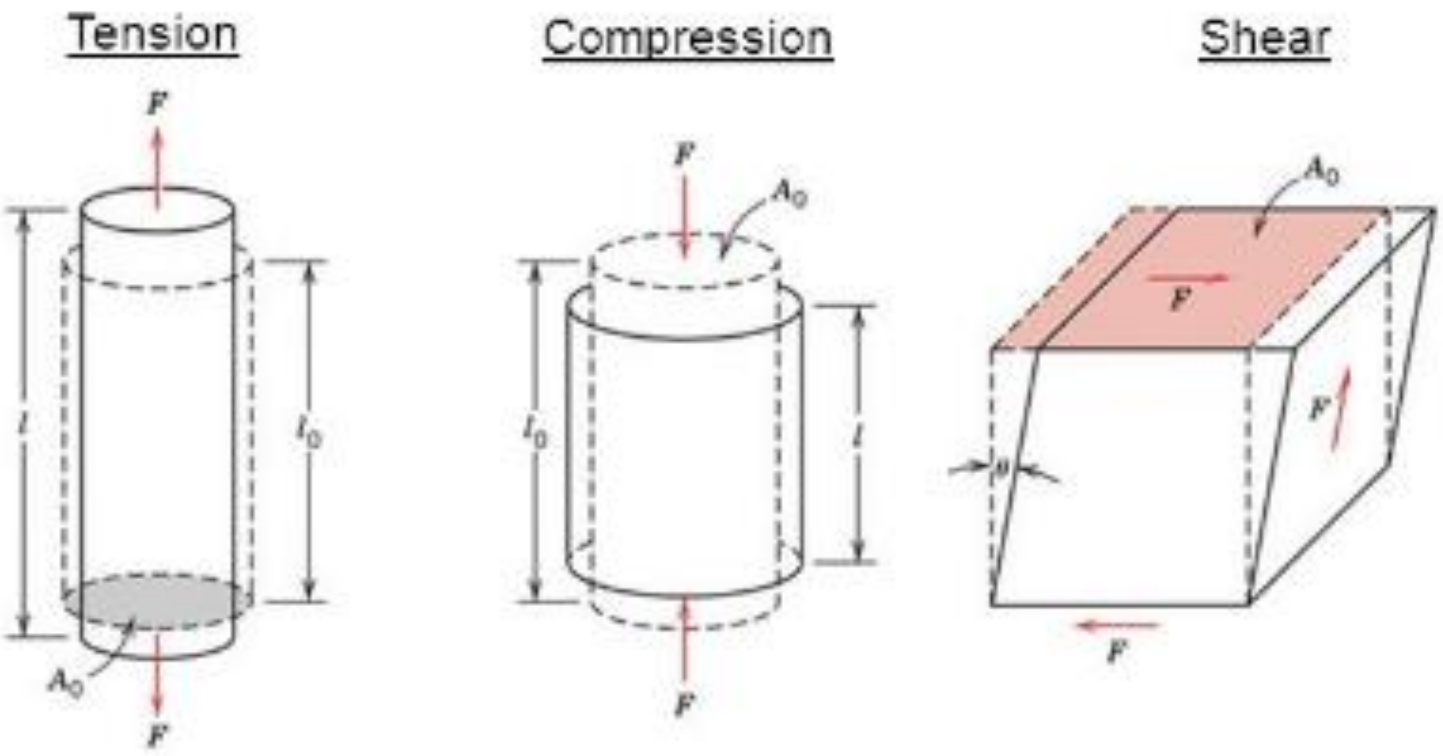
- The extent of elastic and plastic deformations will primarily depend on

✓ kind of material

✓ rate of load application

✓ ambient temperature

✓ other factors



- It is possible for the load to be tensile, compressive, or shear, and its magnitude may be constant with time, or fluctuate continuously.

Concepts of Stress and Strain

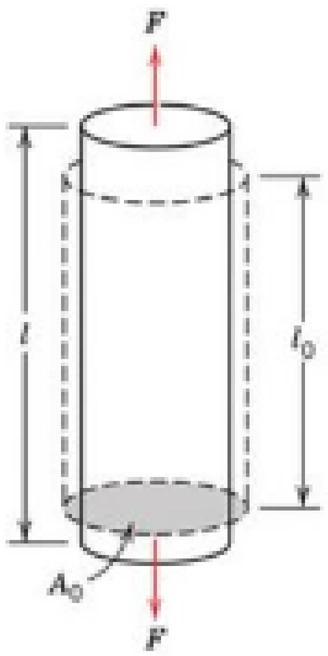
- **Engineering stress** (or simply stress) is defined by:

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

- **Engineering strain** (or simply strain) is defined by:

$$\varepsilon = \frac{\Delta l}{l_o} = \frac{l_i - l_o}{l_o}$$

- F is the instantaneous load applied perpendicular to the specimen cross section.
- A_o is the original cross sectional area before any load is applied.
- l_o is the original length before any load is applied
- l_i is the instantaneous length.
- Δl is the deformation elongation



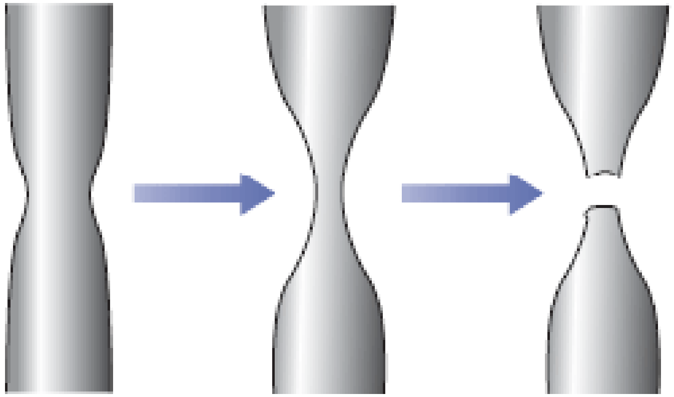
- **For tensile loads: Stress and strain are positive**
- **For compressive loads: stress and strain are negative.**

- These definitions of stress and strain allow one to compare test results for specimens of different cross-sectional area A_0 and of different length l_0.

Concepts of Stress and Strain

Note:

- When the load is applied continuously, the dimensions of the material change. Hence, engineering stress and strain values do not indicate the true deformation characteristics of the material.
- **Concept of true strain and stress was then proposed by Ludwick.**



- **True stress** is defined as the load divided by the actual area over which it acts at any instant.:

$$\boldsymbol{\sigma_t = \frac{F}{A} = \frac{F}{A_o} \cdot \frac{A_o}{A} = \sigma(\varepsilon + 1)}$$

- **True strain** is conveniently defined by:

$$\boldsymbol{\varepsilon_t = ln\frac{l}{l_o} = ln\frac{A_o}{A} = ln(\varepsilon + 1)}$$

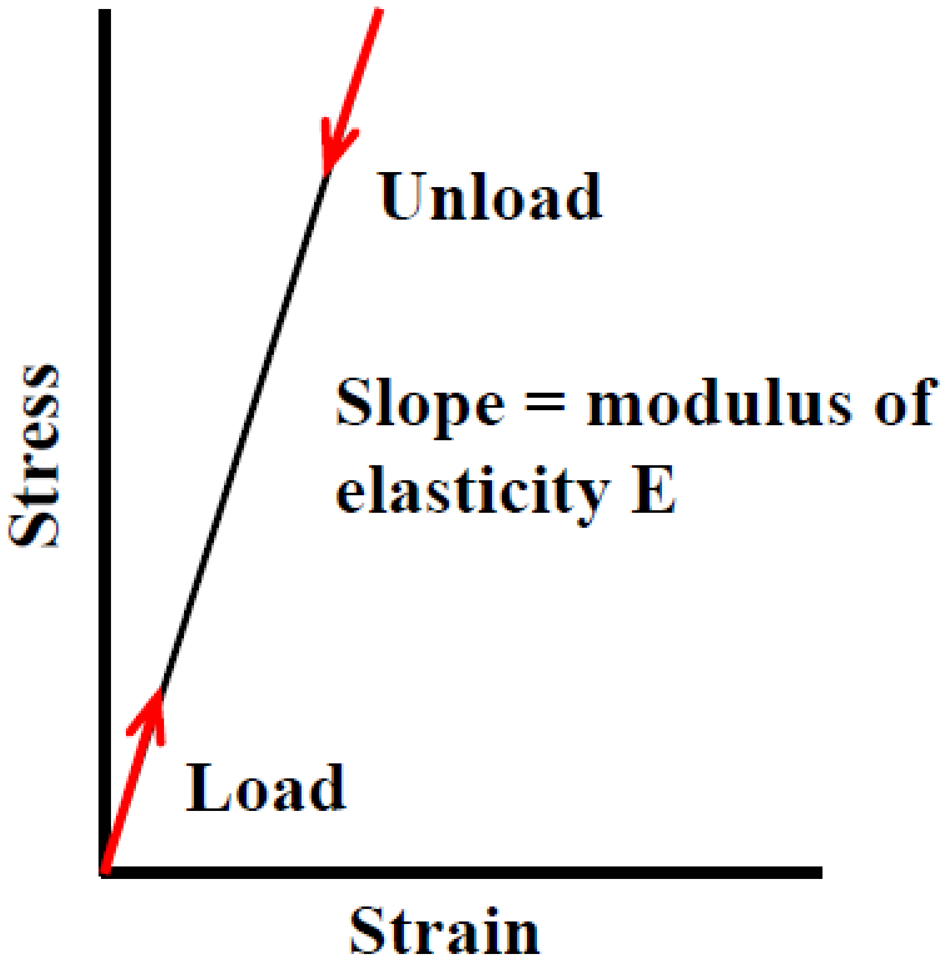
- Engineering stress is equal to true stress up to the elastic limit of the material.
- After the elastic limit i.e. once the material starts deforming plastically, engineering values and true values of stresses and strains differ.
- The equation relating engineering and true stress-strains are valid only up to the limit of uniform deformation i.e. up to the onset of necking in tension test.

Elastic Deformation: Stress-Strain Behaviour

- The degree to which a structure deforms or strains depends on the magnitude of an imposed stress.
- In tensile tests, if the deformation is elastic, the stress and strain are proportional through the relationship;

$$\sigma = E\varepsilon$$

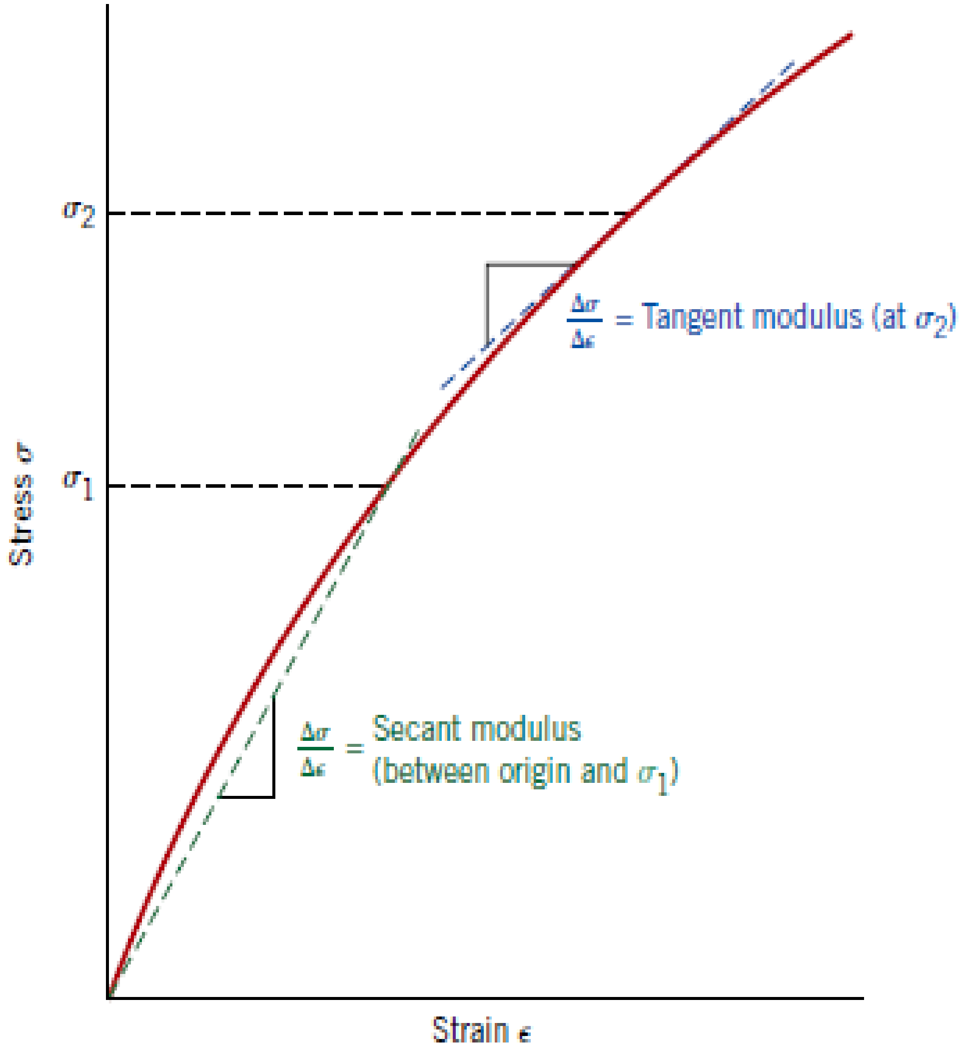
- This is known as **Hooke's law**, and the constant of proportionality, E, is the modulus of elasticity, or Young's modulus.
- For most typical metals, E ranges between 45 GPa (6.5×10^6 psi), for magnesium, and 407 GPa (59×10^6 psi), for tungsten.
- The modulus is an important design parameter used for computing elastic deflections.



Elastic Deformation: Stress-Strain Behaviour

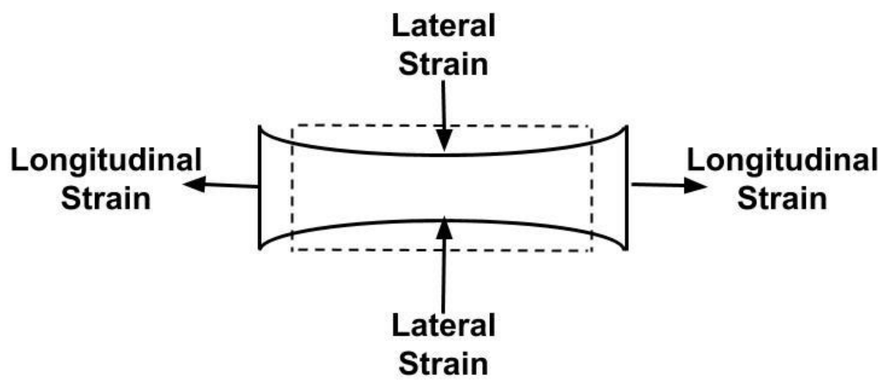
- There are some materials such as gray cast iron, concrete, etc. for which the elastic portion of the stress–strain curve is not linear.
- . For this nonlinear behavior, either tangent or secant modulus is normally used.

- **Tangent modulus** is taken as the slope of the stress–strain curve at some specified level of stress.
- **Secant modulus** represents the slope of a secant drawn from the origin to some given point of the curve.



Elastic Deformation: Stress-Strain Behaviour

- Poisson's ratio measures the deformation in the material in a direction perpendicular to the direction of the applied force.
- Materials subject to tension shrink laterally.
- This lateral (transverse) strain is related to the applied longitudinal (axial) strain by empirical means.
- **The ratio of transverse strain to longitudinal strain is known as Poisson's ratio (ν).**
- Transverse strain can be expected to be opposite in nature to longitudinal strain, and both longitudinal and transverse strains are linear strains.



$$\text{Poisson's Ratio} = \frac{\text{Lateral Strain}}{\text{Longitudinal Strain}}$$

- **For most metals, ν are close to 0.33,**
- **For polymers, ν is between 0.4 – 0.5,**
- **For ionic solids, ν is around 0.2.**

Elastic Deformation: Stress-Strain Behaviour

- The stress–strain characteristics at low stress levels are virtually the same for both tensile and compressive situations, to include the magnitude of the modulus of elasticity.
- Shear stress (τ) and shear strain (γ) in elastic range are related through the expression

$$\tau = G\gamma$$

- Where G is known as Shear modulus of the material. It is also known as modulus of elasticity in shear.
- It is related with Young's modulus, E, through Poisson's ratio, ν, as;

$$G = \frac{E}{2(1+\nu)}$$

- Bulk modulus or volumetric modulus of elasticity K, of a material is defined as the ratio of hydrostatic or mean stress (σ_m) to the volumetric strain (Δ).
- The relation between E and K is given by

$$K = \frac{\sigma_m}{\Delta} = \frac{E}{3(1-2\nu)}$$

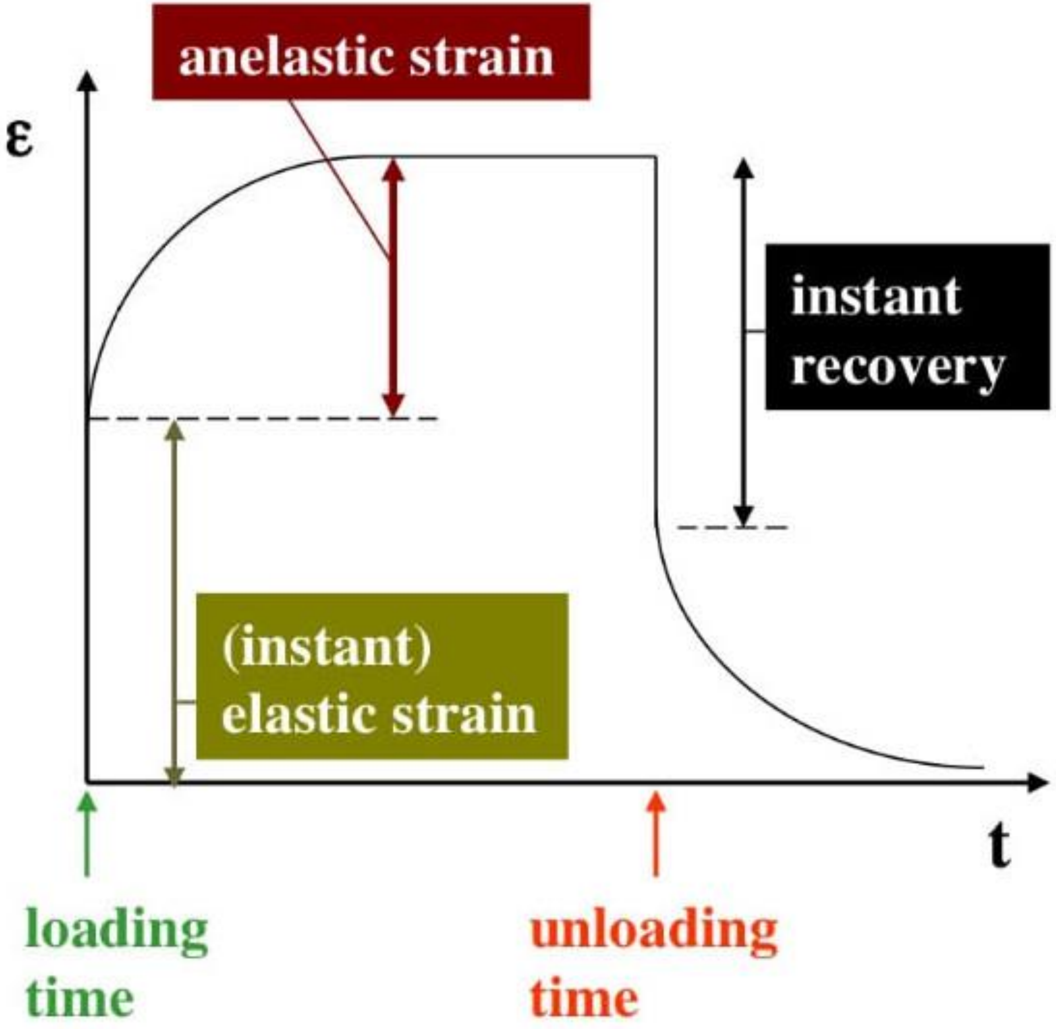
Elastic Deformation: Stress-Strain Behaviour

Metal Alloy	Modulus of Elasticity GPa	Modulus of Elasticity 10^6 psi	Shear Modulus GPa	Shear Modulus 10^6 psi	Poisson's Ratio
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

Elastic Deformation: Stress-Strain Behaviour

Assumptions

- Up to this point , it has been assumed that elastic deformation is time independent (i.e. applied stress produces instantaneous elastic strain that remains constant over the period of time the stress is maintained).
- It has also been assumed that upon release of the load the strain is totally recovered; thus, the strain immediately returns to zero.
- However, in most engineering materials, there exist a time-dependent elastic strain component.
- Elastic deformation will continue after the stress application, and upon load release some finite time is required for complete recovery.
- **This time-dependent elastic behavior is known as anelasticity**,



Elastic Deformation: Worked Example

Question

- A piece of copper originally 305 mm (12 in.) long is pulled in tension with a stress of 276 MPa (40,000 psi). If the deformation is entirely elastic, what will be the resultant elongation?

Solution

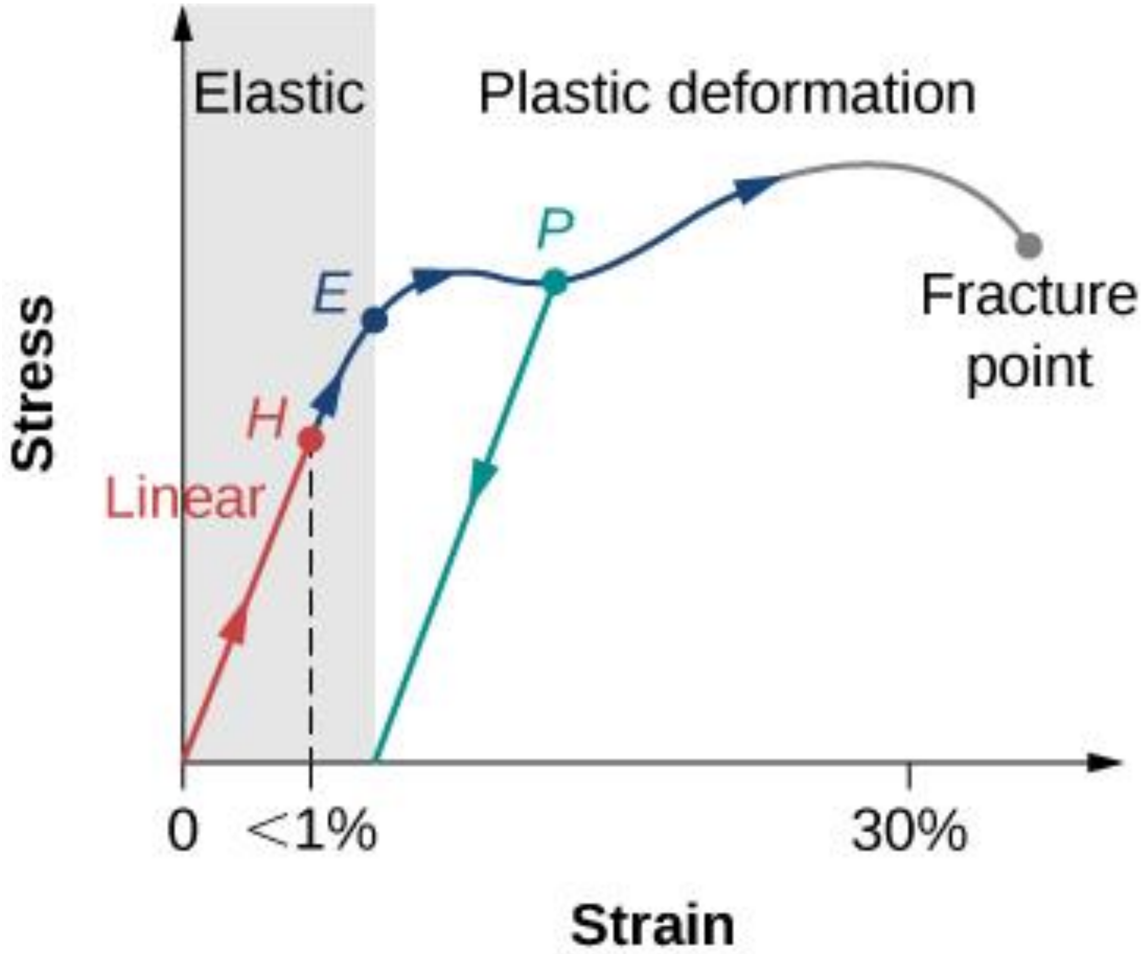
- Since the deformation is elastic, strain is dependent on stress. Also, the elongation Δl is related to the original length l_o. Combining these two expressions and solving for Δl gives;

$$\boldsymbol{\sigma = \varepsilon E = \left(\frac{\Delta l}{l_o}\right) E \Rightarrow \Delta l = \frac{\sigma l_o}{E}}$$

$$\boldsymbol{\Delta l = \frac{\sigma l_o}{E} = \frac{(270\ MPa) \cdot (305\ mm)}{(110\ x\ 10^3\ MPa)} = 0.77\ mm\ (0.03\ in.)}$$

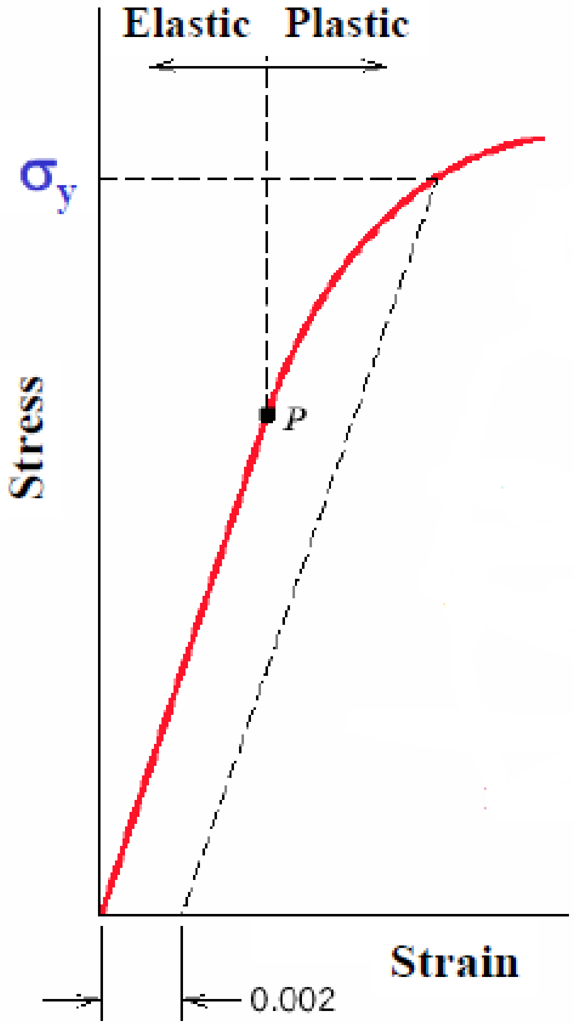
Plastic Deformation: Stress-strain Behaviour

- For most metallic materials, elastic deformation persists only to strains of about 0.005.
- Stress and strain are not proportional to each other beyond this point (Hooke's law ceases to be valid).
- Deformation is irreversible (non-recoverable)
- Deformation occurs by breaking and re-arrangement of atomic bonds (in crystalline materials, it is primarily as a result of slip, which involves the motion of dislocations.)



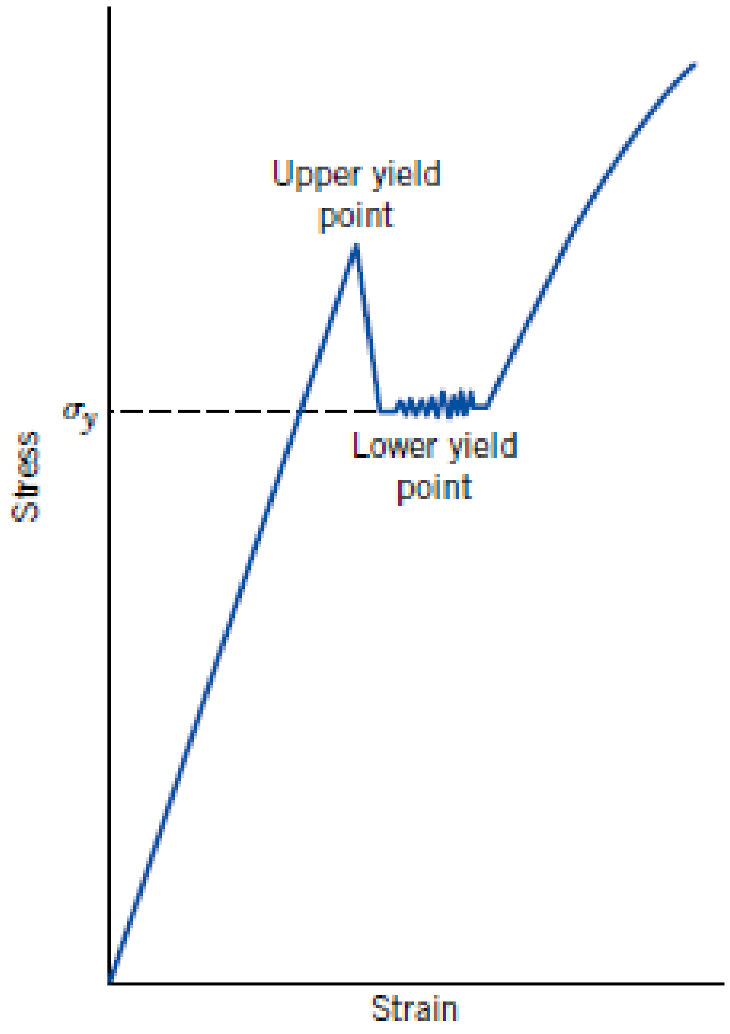
Tensile Properties: Yielding

- It is important to know the stress level at which plastic deformation begins, or where yielding occurs because a structure or component with a permanent change in shape, may not be capable of functioning as intended.
- At the **Yield point, P** - the strain deviates from being proportional to the stress (the proportional limit). It represents the onset of plastic deformation on a microscopic level.
- A straight line parallel to the elastic portion of the stress–strain curve at some specified strain offset, usually 0.002 is used to determine, P.
- The **Yield strength, σ_y** is the intersection point between the parallel line and the stress-strain curve.



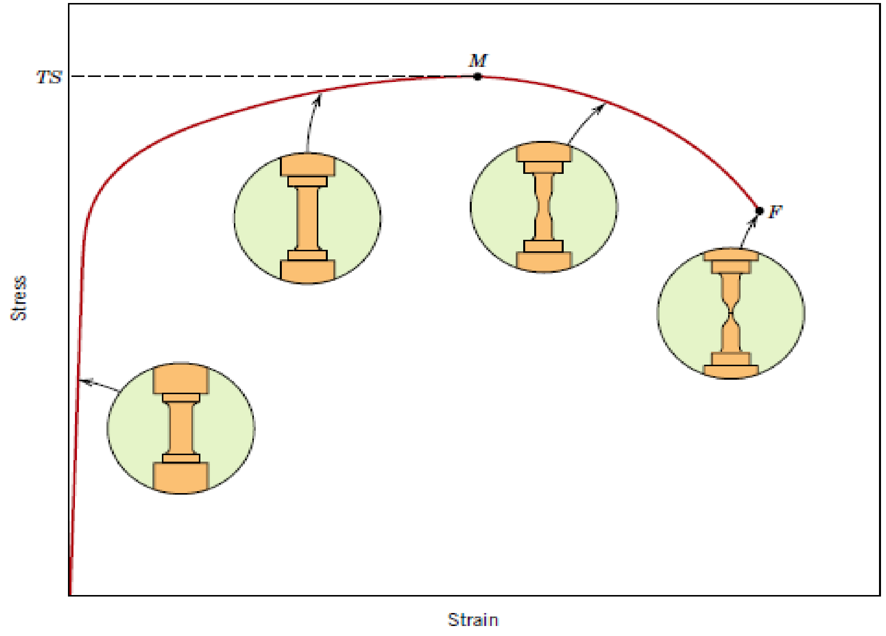
Tensile Properties: Yielding

- In some materials (e.g. low-carbon steel), the stress- strain curve includes two yield points (upper and lower). The yield strength is defined in this case as the average stress at the lower yield point.
- At the upper yield point, plastic deformation is initiated with an apparent decrease in stress.
- At lower yield point, continued deformation fluctuates slightly about some constant stress value.
- The magnitude of yield strength for a metal is a measure of its resistance to plastic deformation.
- Yield strength values range from 35 MPa (5000 psi) for a low strength aluminum to over 1400 MPa (200,000 psi) for high-strength steels.

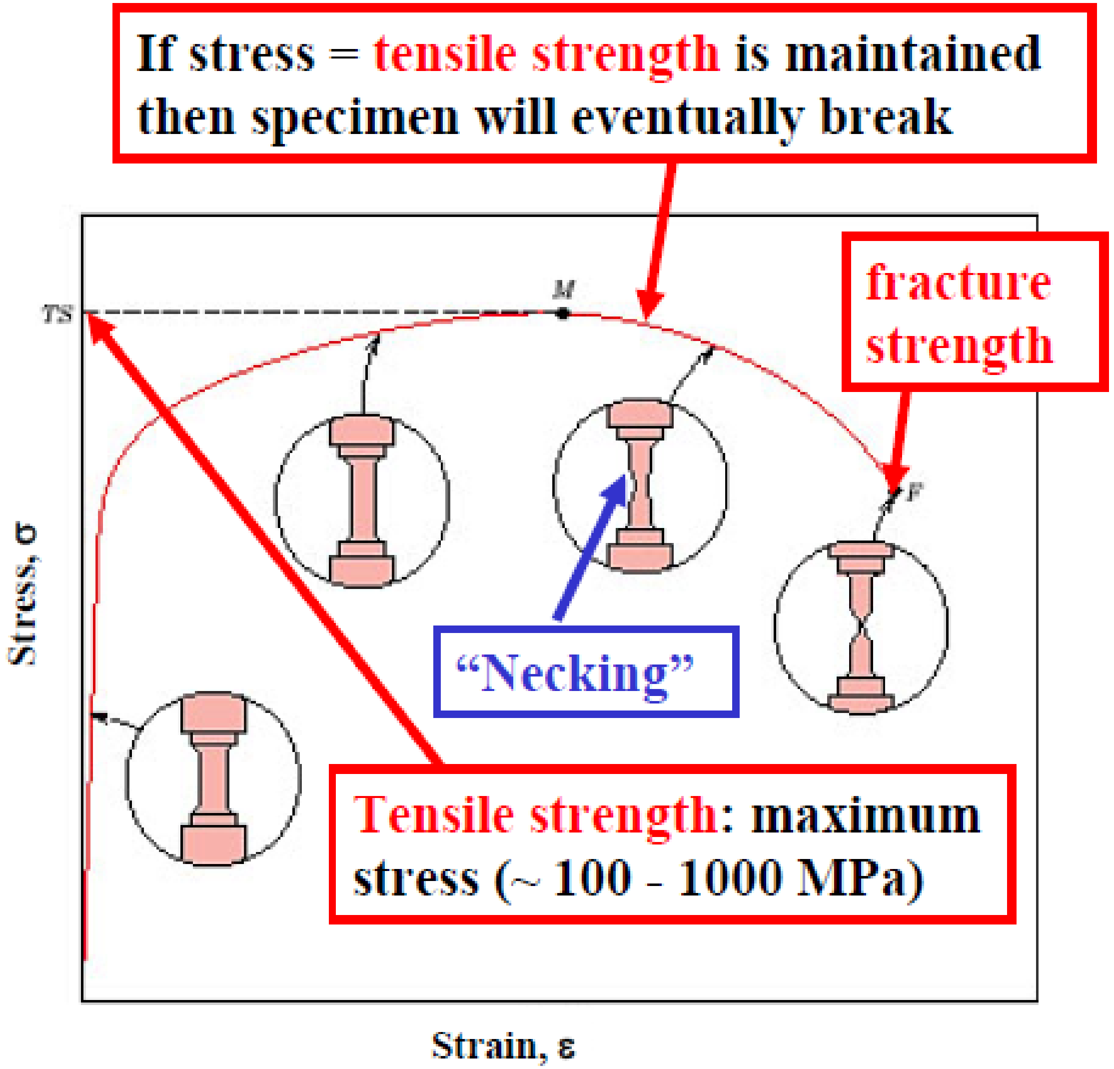


Tensile Properties: Tensile Strength

- The **tensile strength**, TS (MPa or psi) is the maximum stress on the stress–strain curve.



For structural applications, the yield stress is usually a more important property than the tensile strength, since once the yield stress has passed, the structure has deformed beyond acceptable limits.



Tensile Properties: Example

Question

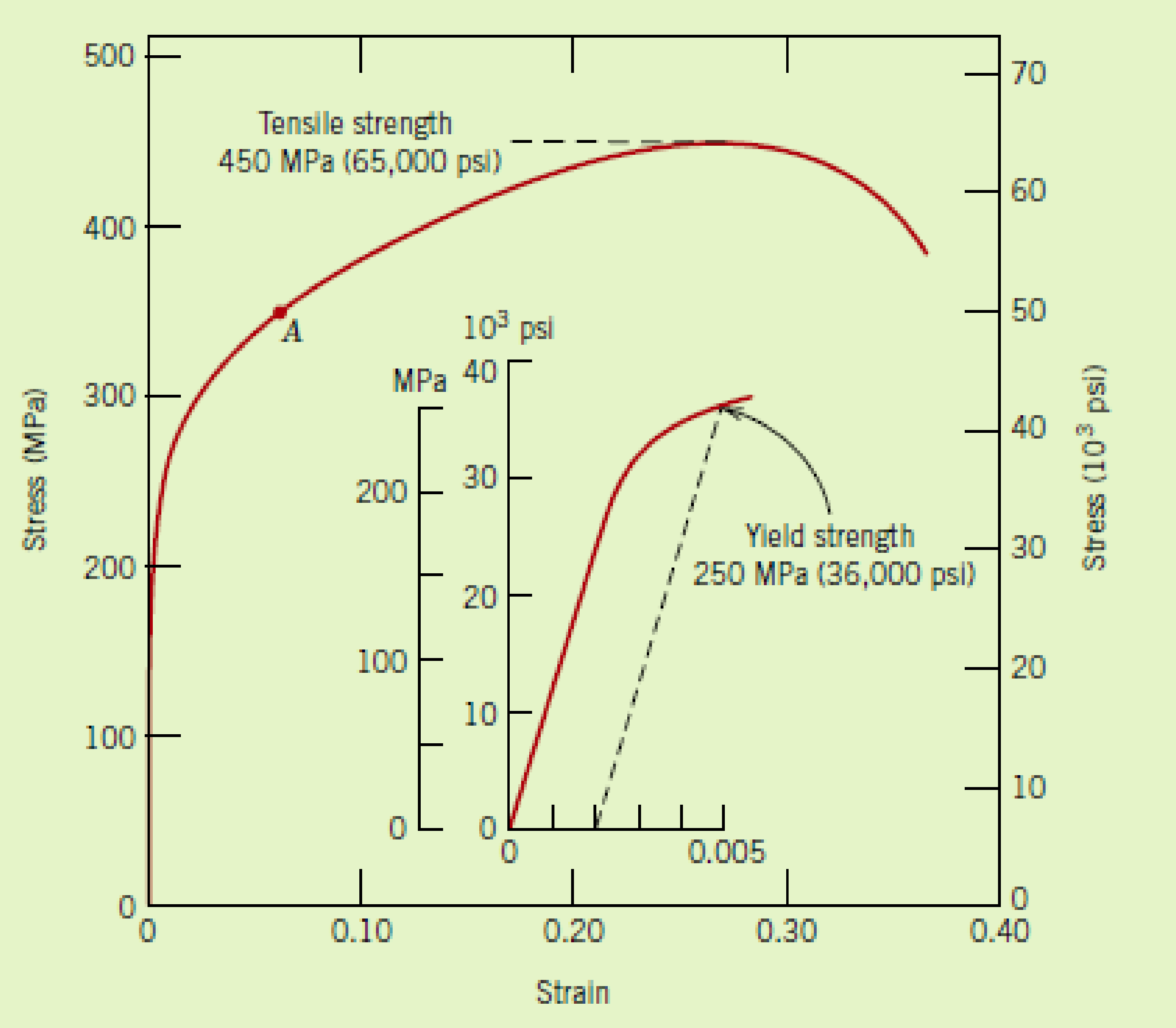
- Using the tensile stress–strain behavior for the brass specimen in the figure provided, determine the following:

✓ The modulus of elasticity

✓ The yield strength at a strain offset of 0.002

✓ The maximum load that can be sustained by a cylindrical specimen having an original diameter of 12.8 mm (0.505 in.)

✓ The change in length of a specimen originally 250 mm (10 in.) long that is subjected to a tensile stress of 345 MPa (50,000 psi)



Tensile Properties: Example 1

Solution

(a) The modulus of elasticity

$$E = slope = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$$

It is convenient to take both σ_1 and ε_1 as zero. If σ_2 is arbitrarily taken as 150 MPa, then ε_2 will have a value of 0.0016. Therefore,

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} = \frac{150 - 0}{0.0016 - 0}$$

$$= 93.8\ GPa\ (13.6\ x\ 10^6\ psi)$$

This is very close to the value of 97 GPa (14 x 10^6 psi) given for brass in Tables.

Solution

(b) The 0.002 strain offset line is constructed as shown in the inset; its intersection with the stress–strain curve is at approximately 250 MPa (36,000 psi), which is the yield strength of the brass

Solution

(c) The maximum load is determined as;

$$F = \sigma \cdot A_o = \sigma \cdot \pi \left(\frac{d_o}{2}\right)^2$$

$$F = (450\ x\ 10^6\ \ N/m^2) \times \pi \times \left(\frac{0.00128\ m}{2}\right)^2 = 57{,}900\ N$$

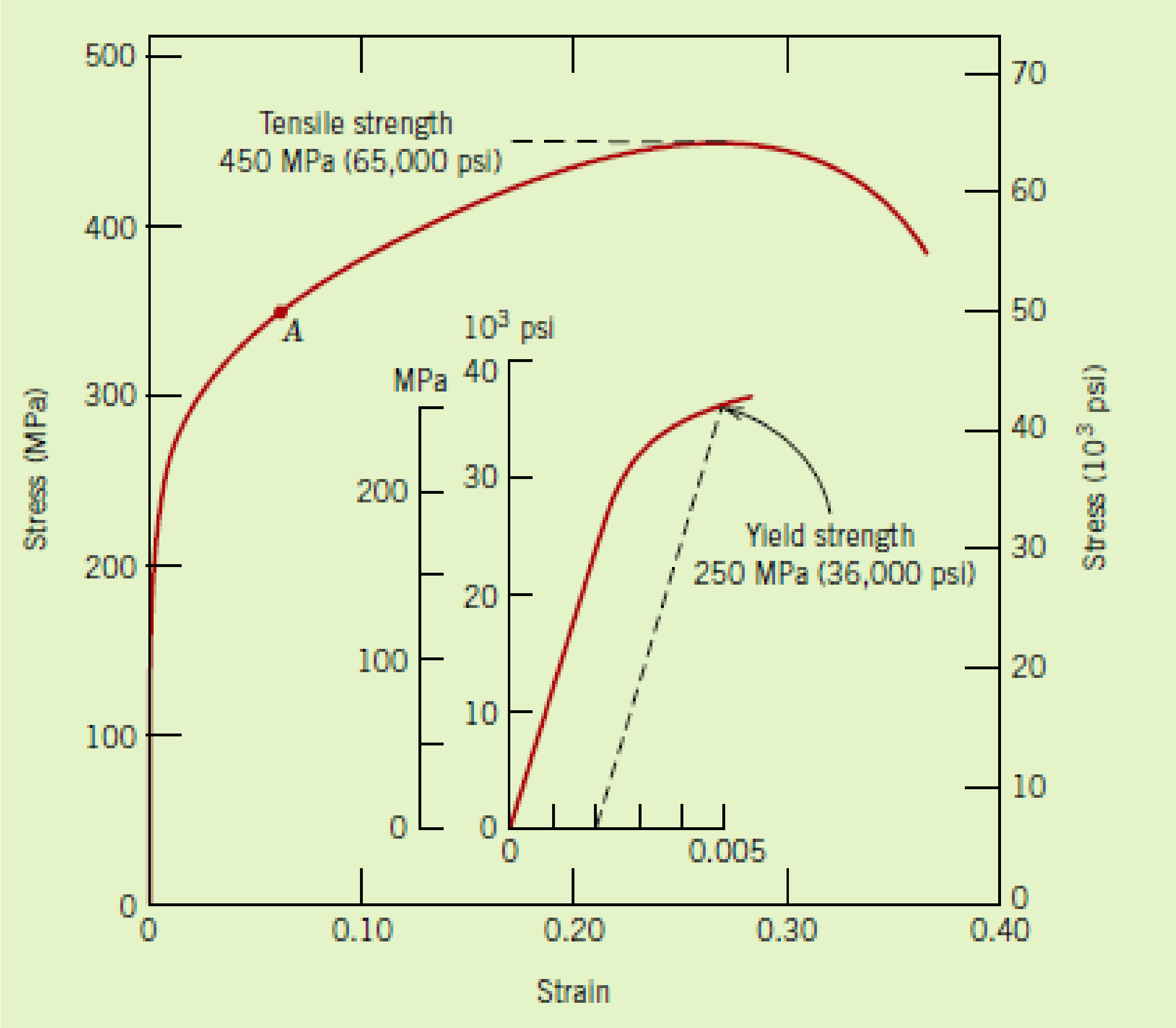
Tensile Properties: Example 1

Solution

(d) To compute the change in length, Δl, first

- Determine the strain that is produced by a stress of 345 MPa.
- Locate the stress point on the stress–strain curve, (**point A**)
- Read the corresponding strain from the strain axis, which is approximately 0.06.
- As lo is given as 250 mm, the elongation becomes;

$$\Delta l = \varepsilon l_o = 0.06 \times 250\ mm$$
$$= 15\ mm\ (0.6\ in.)$$



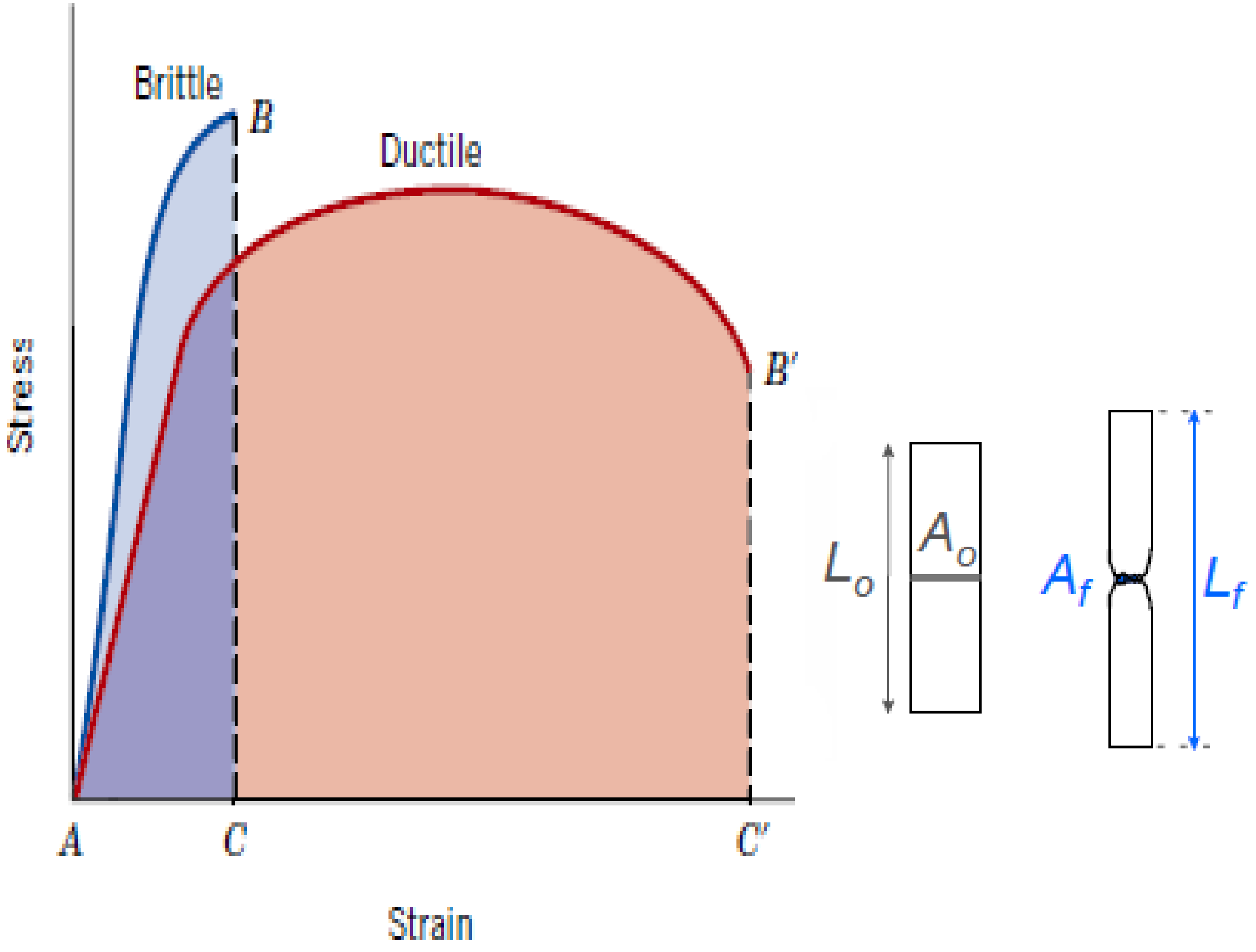
Tensile Properties: Ductility

- **Ductility** 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**.
- It is defined by percent elongation (plastic tensile strain at fracture) as;

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

- Or percent reduction in area

$$\%RA = \left(\frac{A_o - A_f}{A_o}\right)$$



Tensile Properties of Metals

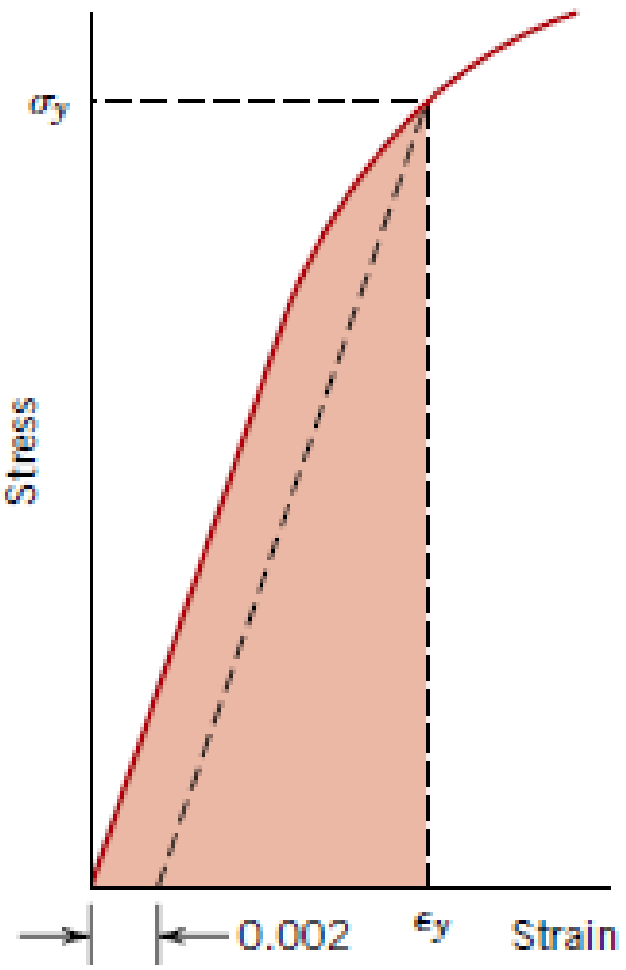
Metal Alloy	*Yield Strength, MPa (ksi)*	*Tensile Strength, MPa (ksi)*	*Ductility, %EL [in 50 mm (2 in.)]*
Aluminum	35 (5)	90 (13)	40
Copper	69 (10)	200 (29)	45
Brass (70Cu–30Zn)	75 (11)	300 (44)	68
Iron	130 (19)	262 (38)	45
Nickel	138 (20)	480 (70)	40
Steel (1020)	180 (26)	380 (55)	25
Titanium	450 (65)	520 (75)	25
Molybdenum	565 (82)	655 (95)	35

Tensile Properties: 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 **modulus of resilience, Ur**, is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding.
- It is computed as the area under the stress–strain curve taken to yielding (assuming a linear elastic region).

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

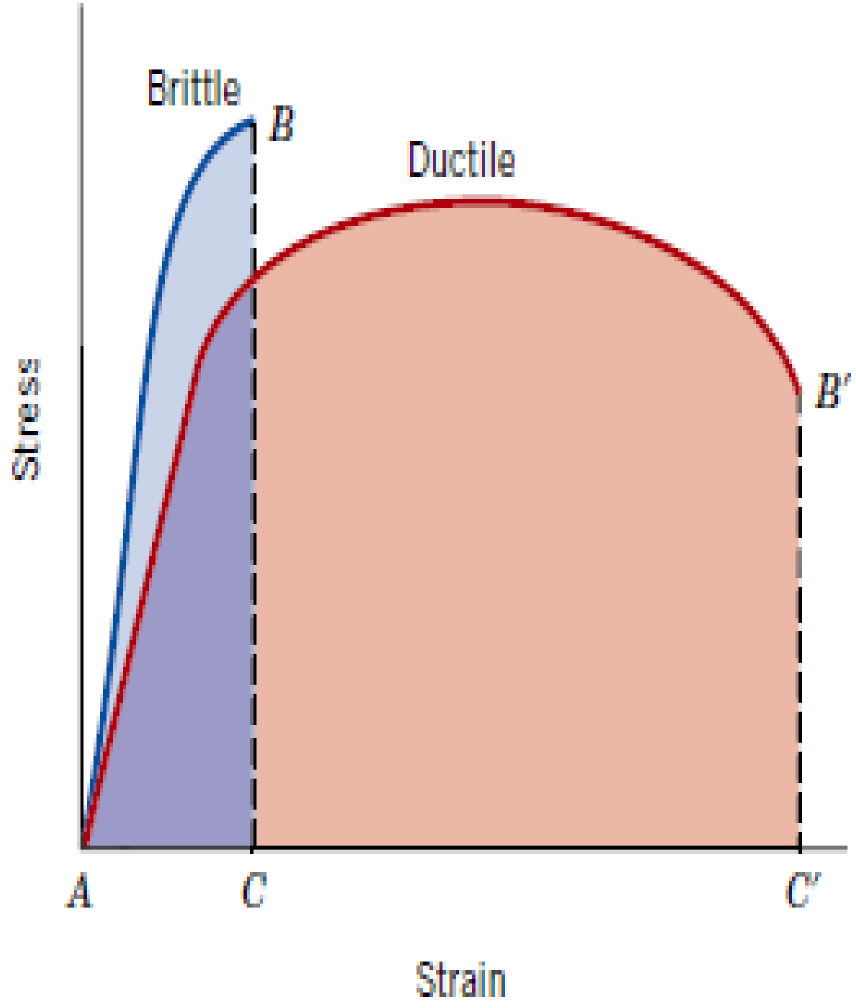
- Resilient materials are those having high yield strengths and low moduli of elasticity.
- The SI unit of resilience is joules per cubic meter (J/m^3)



Tensile Properties: Toughness

- **Toughness** is the ability of a material to absorb energy up to fracture. It is equal to the total area under the strain-stress curve up to 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.

- **As shown in the Figure, though the brittle metal has higher yield and tensile strengths, it has a lower toughness than the ductile one, as can be seen by comparing the areas ABC and AB'C'**



Tensile Properties: Example 2

Question

Cylindrical specimen of steel having an original diameter of 12.8 mm (0.505 in.) is tensile tested to fracture and found to have an engineering fracture strength of 460 MPa (67,000 psi). If its cross-sectional diameter at fracture is 10.7 mm (0.422 in.), determine:

(a) The ductility in terms of percent reduction in area

(b) The true stress at fracture

Tensile Properties: Example 2

Solution

(a) **Ductility is computed**

$$\%RA = \left(\frac{A_o - A_f}{A_o}\right)$$

$$= \frac{\pi \cdot \left(\frac{12.8\ mm}{2}\right)^2 - \pi \cdot \left(\frac{10.7\ mm}{2}\right)^2}{\pi \cdot \left(\frac{12.8\ mm}{2}\right)^2} \times 100$$

$$= 30\%$$

Solution

(b) The load at fracture must first be computed from the fracture strength as

$$F = \sigma_f \cdot A_o$$

$$= (460 \times 10^6\ N/m^2)(128.7\ mm^2)\left(\frac{1\ m^2}{10^6\ mm^2}\right)$$

$$= 59{,}200\ N$$

$$\sigma_t = \frac{F}{A_f} = \frac{59{,}200\ N}{(89.9\ mm^2)\left(\frac{1\ m^2}{10^6\ mm^2}\right)} = 6.6 \times 10^8\ N/m^2$$

$$= 660\ MPa$$

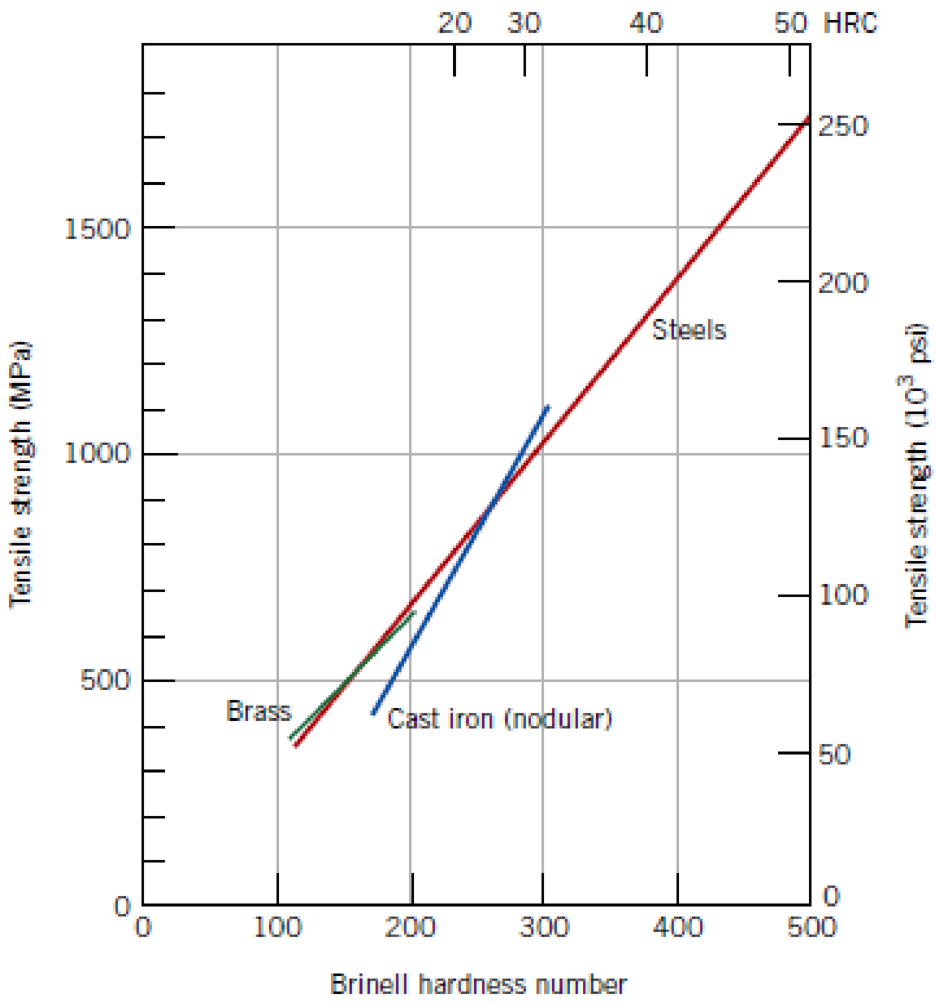
Hardness

- Hardness, is a measure of a material's resistance to localized plastic deformation (e.g., a small dent or a scratch).
- Both tensile strength and hardness may be regarded as degree of resistance to plastic deformation.
- Hardness is proportional to the tensile strength but the constant of proportionality is different for different materials.

$$TS\ (MPa) = 3.45 \times HB$$

$$TS\ (psi) = 500 \times HB$$

- **HB is the Brinell harness number**

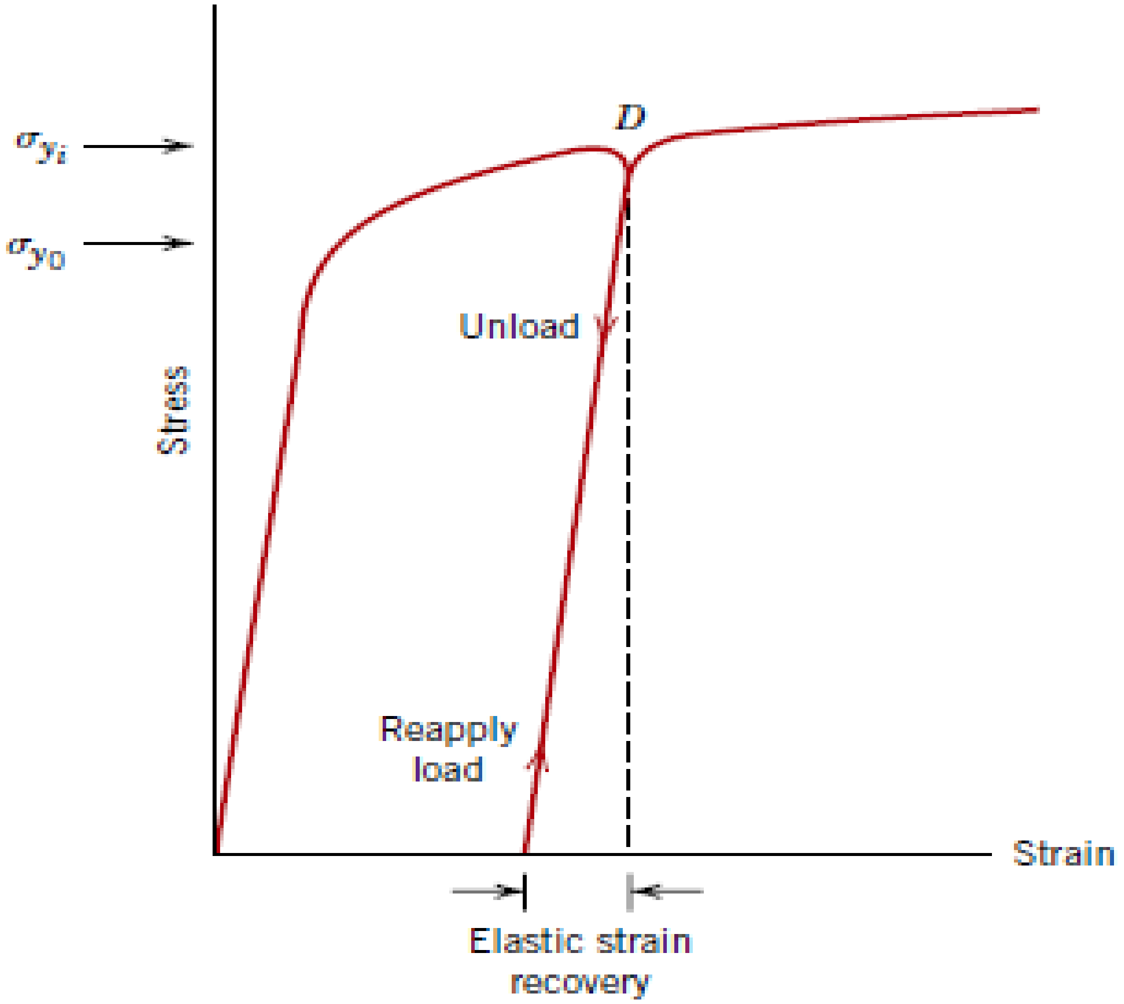


Elastic Recovery after Plastic Deformation

- If a material is deformed plastically and the stress is then released, the material ends up with a permanent strain.

- If the stress is reapplied, the material again responds elastically at the beginning up to a new yield point that is **higher than the original yield point**.

- The amount of elastic strain that it will take before reaching the yield point is called **elastic strain recovery.**



Design Considerations

- For less critical static situations and when tough materials are used, a design stress, σ_d, is taken as the calculated stress level σ_c (on the basis of the estimated maximum load) multiplied by a design factor, N_d.

$$\sigma_d = N_d \cdot \sigma_c$$

- Alternatively, a safe stress or working stress, σ_w, is used instead of design stress. This safe stress is based on the yield strength of the material and is defined as the yield strength divided by a factor of safety.

$$\sigma_w = \frac{\sigma_y}{N_s}$$

The choice of an appropriate value of N_s is necessary.
If N_s is too large, component will result in overdesign;
Values normally range between 1.2 and 4.0.

Design Considerations: Example

Question

- A tensile-testing apparatus is to be constructed that must withstand a maximum load of 220,000 N. The design calls for two cylindrical support posts, each of which is to support half of the maximum load. Furthermore, plain-carbon (1045) steel ground and polished shafting rounds are to be used; the minimum yield and tensile strengths of this alloy are 310 MPa and 565 MPa, respectively. Specify a suitable diameter for these support posts.

Design Considerations: Example

Solution

- First, decide on a factor of safety, Ns, which allows you to determine working stress.
- In addition, to ensure that the apparatus will be safe to operate, any elastic deflection of the rods during testing should be minimized; therefore, a relatively conservative factor of safety is to be used, say 5.
- Thus, the working stress becomes;

$$\sigma_w = \frac{\sigma_y}{N_s} = \frac{310\ MPa}{5} = 62\ MPa \qquad A_o = \left(\frac{d}{2}\right)^2 \cdot \pi = \frac{F}{\sigma_w} \Rightarrow d = 2\sqrt{\frac{F}{\pi\sigma_w}}$$

$$d = 2\sqrt{\frac{110{,}00\ N}{\pi \times 62 \times 10^6\ N/m^2}} = 0.00475\ m = 47.5\ mm$$


THANK
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