MECHANICAL PROPERTIES OF MATERIALS

Manufacturing materials IE251

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MECHANICAL PROPERTIES OF MATERIALS

1. Stress-Strain Relationships (Slide 4)
2. Tensile Test (Slide 7)
3. Compression Test (Slide 36)

Mechanical Properties in Design and Manufacturing

Mechanical properties determine a material's behavior when subjected to mechanical stresses

- Properties include elastic modulus, ductility, hardness, and various measures of strength

- Dilemma: mechanical properties desirable to the designer, *such as high strength*, usually make manufacturing more difficult

The manufacturing engineer should appreciate the design viewpoint
And the designer should be aware of the manufacturing viewpoint

Strain- Stress Relationship

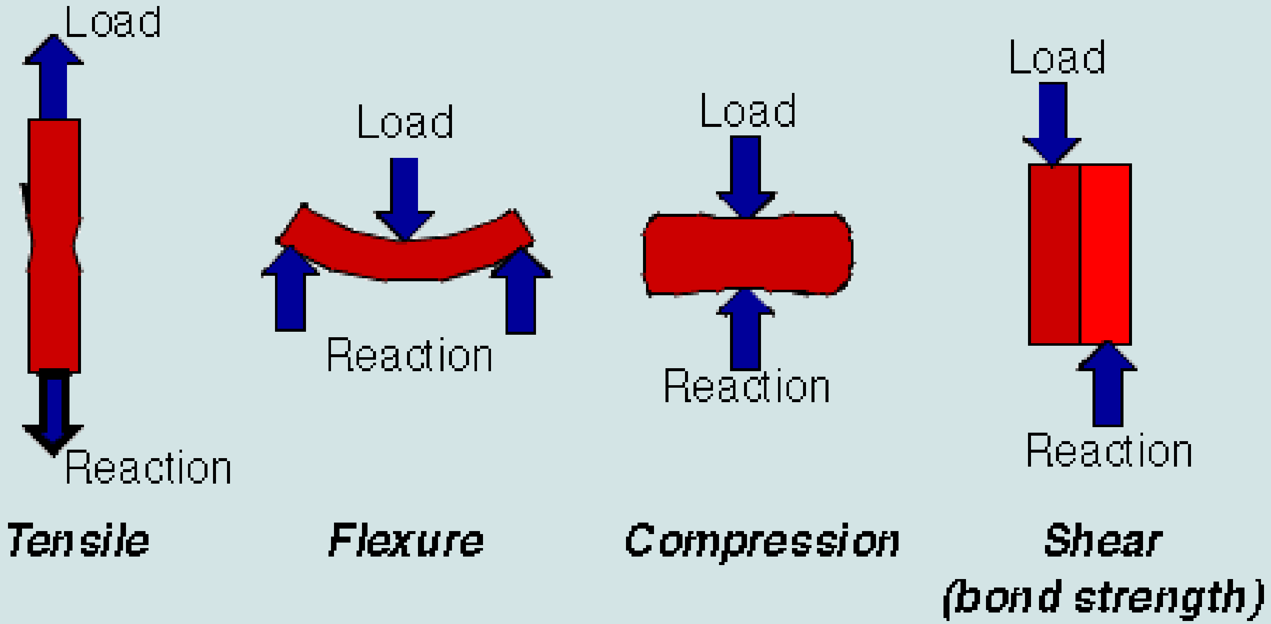
Stress-Strain Relationships

Three types of static stresses to which materials can be subjected:

1. Tensile - tend to stretch the material
2. Compressive - tend to squeeze it
3. Shear - tend to cause adjacent portions of material to slide against each other

- Stress-strain curve - basic relationship that describes mechanical properties for all three types

Various Tests



Tensile Test

Most common test for studying stress-strain relationship, especially metals

In the test, a force pulls the material, elongating it and reducing its diameter

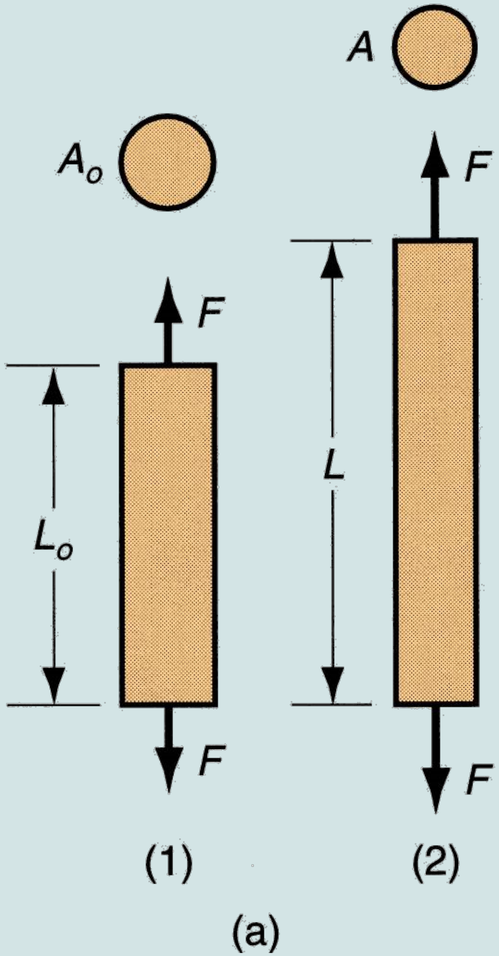


Figure 3.1 Tensile test: (a) tensile force applied in (1) and (2) resulting elongation of material

Tensile Test Specimen

ASTM (*American Society for Testing and Materials*) specifies preparation of test specimen

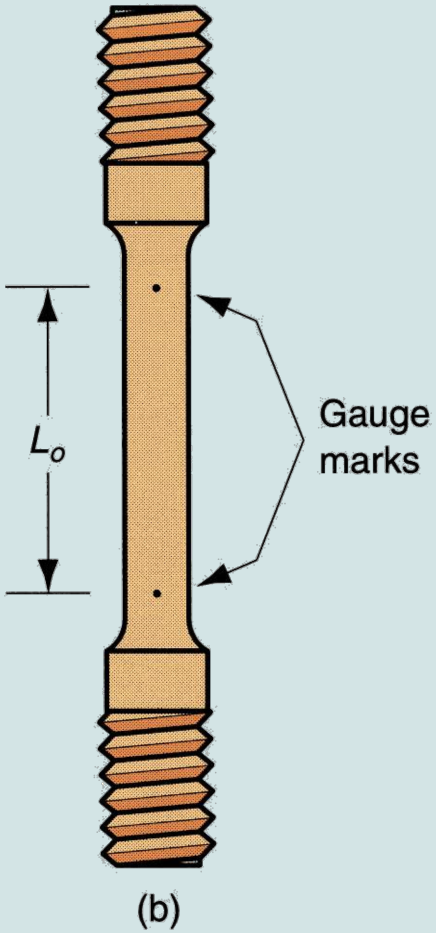
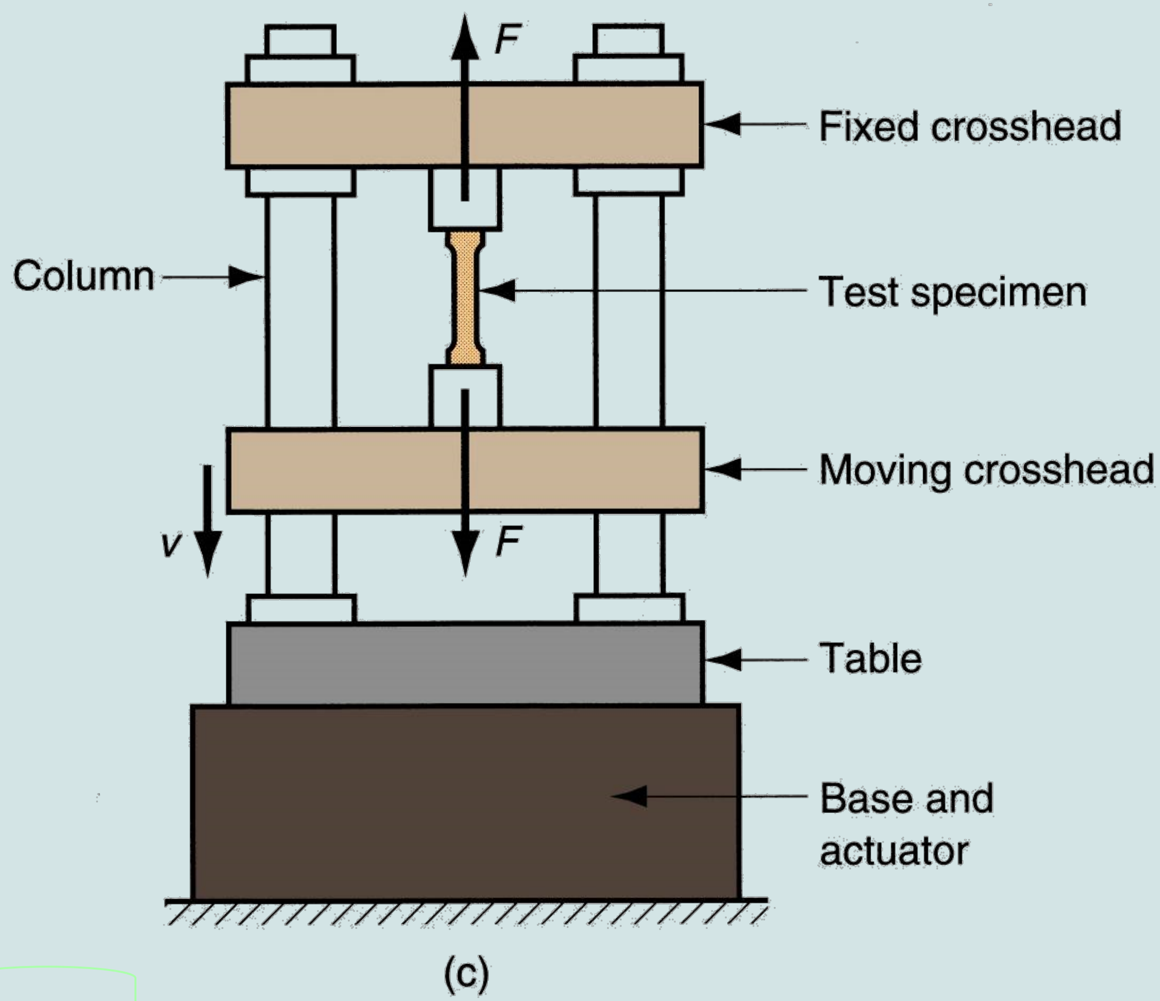


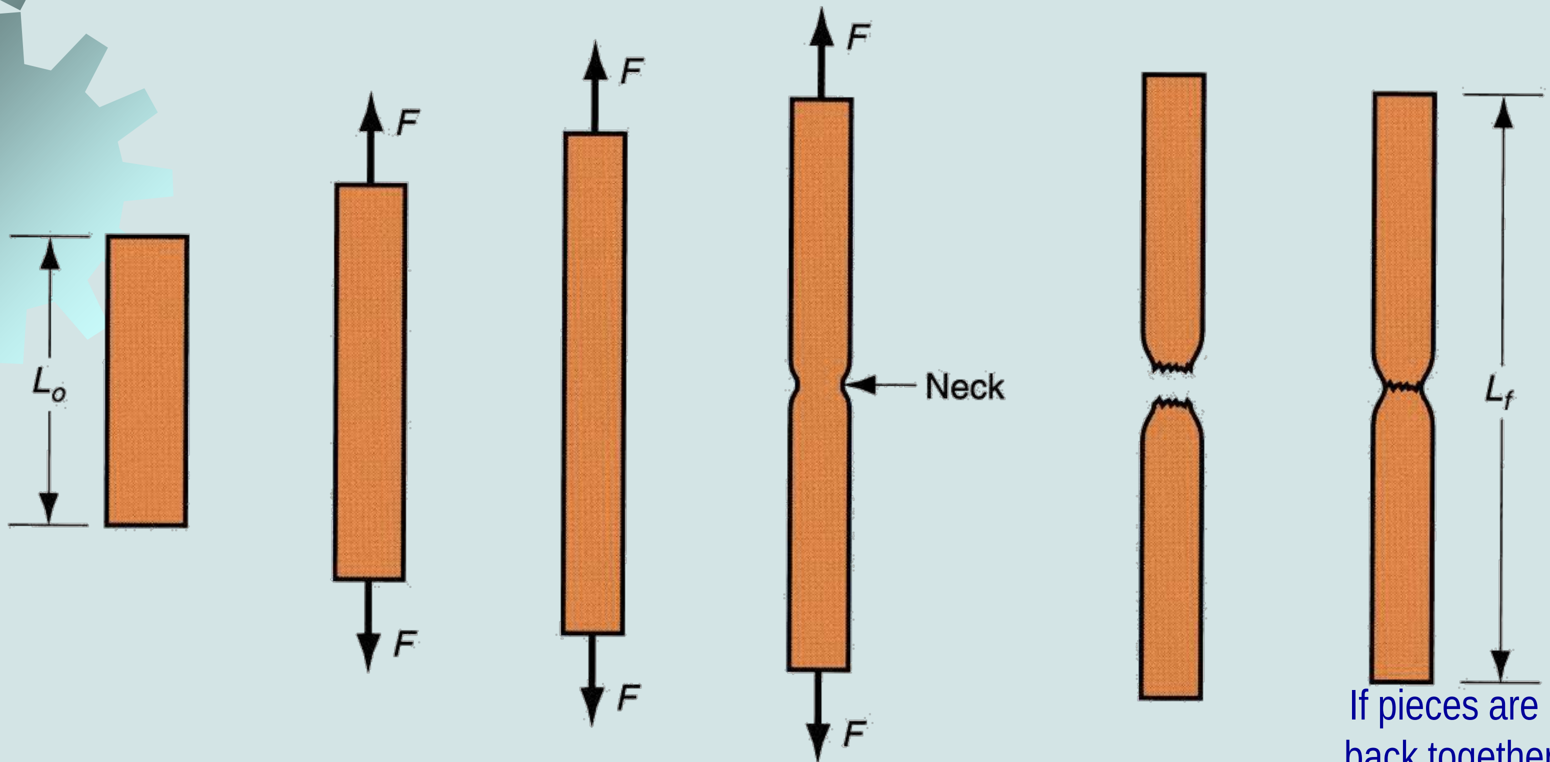
Figure 3.1 Tensile test: (b) typical test specimen

Tensile Test Setup



Tensile Test Sequence

Figure 3.2 Typical progress of a tensile test:



(1) beginning of test, no load

(2) uniform elongation and reduction of cross-sectional area

(3) continued elongation, maximum load reached

(4) necking begins, load begins to decrease

(5) fracture

If pieces are put back together as in **(6)**, final length can be measured

Tensile Test

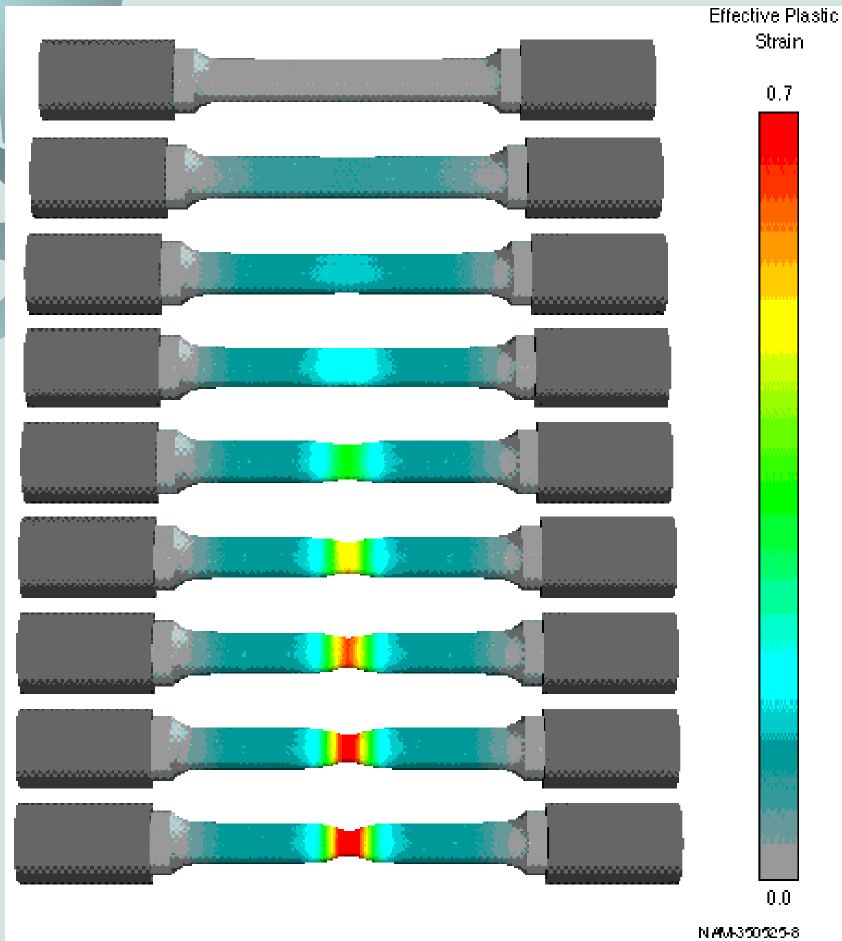
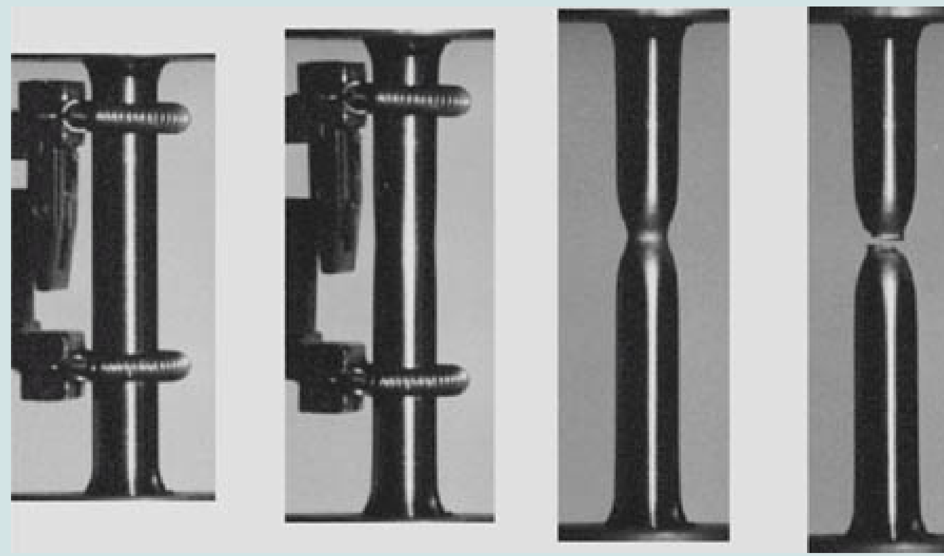


Figure WF-3. Simulation of the steel round bar tensile test including the necking behavior.



Different types of stress-strain graphs

Stress-strain curves

- Engineering → important in design
- True → important in manufacturing

Engineering Stress

Defined as force divided by original area:

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

where

σ_e = engineering stress (MPa) or Pa or psi,

F = applied force (N) or lb, and

A_o = original area of test specimen (mm^2 or m^2 or in^2)

(Remember: N/m^2 = Pa, N/mm^2 = MPa,

lb/in^2 = psi, klb/in^2 = $kips/in^2$)

Engineering Strain

Defined at any point in the test as

$$e = \frac{L - L_o}{L_o}$$

where

e = engineering strain (it has no unit);

L = length at any point during elongation; and

L_o = original gage length

Typical Engineering Stress-Strain Plot

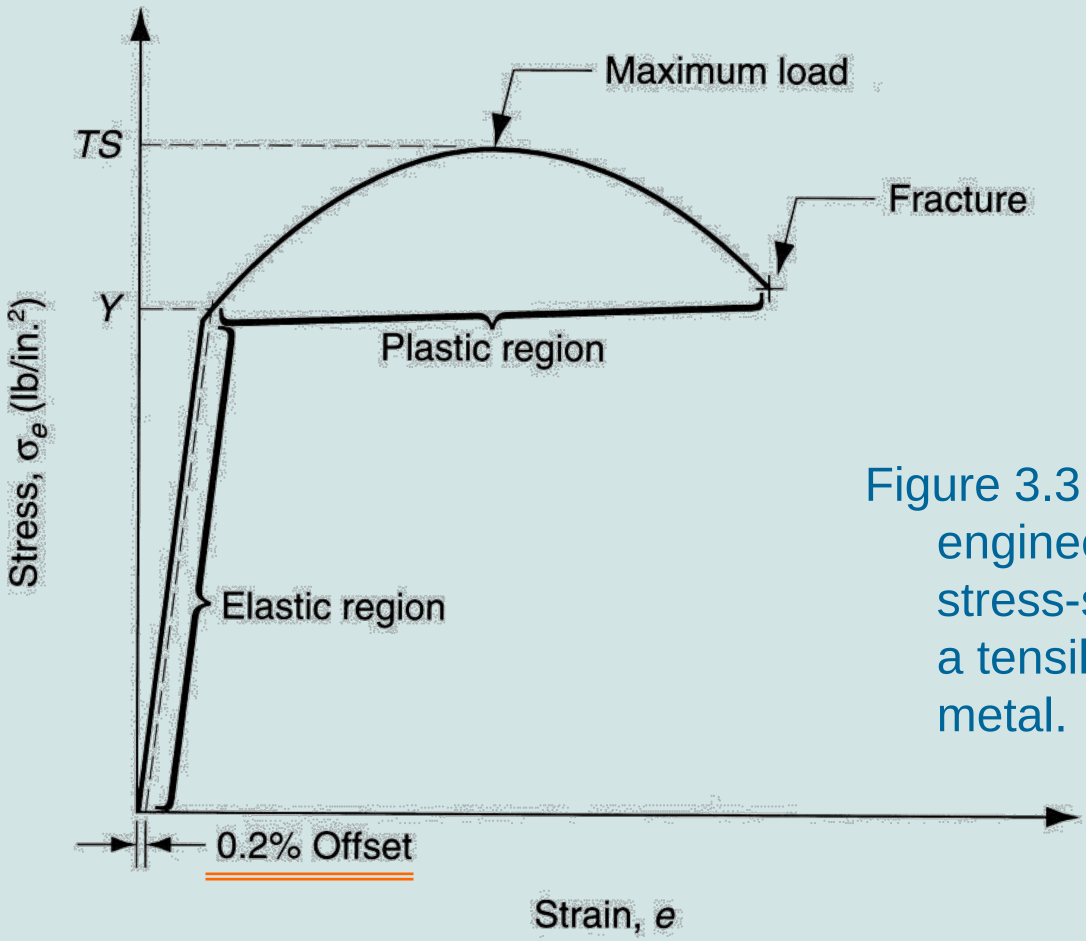


Figure 3.3 Typical engineering stress-strain plot in a tensile test of a metal.

Two Regions of Stress-Strain Curve

The two regions indicate two distinct forms of behavior:

1. Elastic region – prior to yielding of the material
2. Plastic region – after yielding of the material

Elastic Region in Stress-Strain Curve

- Relationship between stress and strain is linear
- Material returns to its original length when stress is removed

Hooke's Law: $\sigma_e = E e$

where E = *modulus of elasticity*, σ_e = *stress*, e=*strain*

- E is a measure of the inherent stiffness of a material
- Its value differs for different materials

Yield Point in Stress-Strain Curve

- As stress increases, a point in the linear relationship is finally reached when the material begins to yield
  - *Yield point Y* can be identified by the change in slope at the upper end of the linear region
  - *Y* = a strength property
  - Other names for yield point = *yield strength, yield stress, and elastic limit*

Plastic Region in Stress-Strain Curve

- Yield point marks the beginning of plastic deformation
- The stress-strain relationship is no longer guided by Hooke's Law (non-linear relationship)
- As load is increased beyond *Y*, elongation proceeds at a much faster rate than before, causing the slope of the curve to change dramatically

Tensile Strength in Stress-Strain Curve

- Elongation is accompanied by a uniform reduction in cross-sectional area, consistent with maintaining constant volume
- Finally, the applied load *F* reaches a maximum value, and engineering stress at this point is called the *tensile strength* *TS* (or ultimate tensile strength)

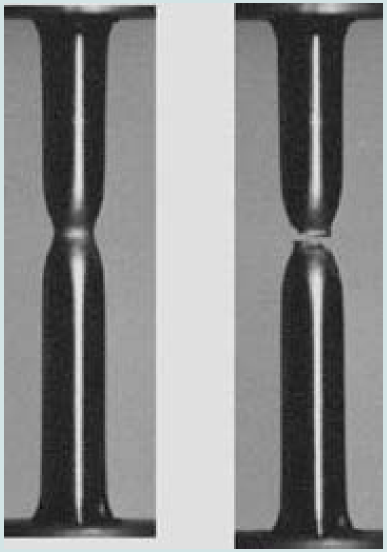
$$TS = \frac{F_{max}}{A_o}$$

Ductility in Tensile Test

Ability of a material to plastically strain without fracture

- Ductility measure = elongation *EL*

$$EL = \frac{L_f - L_o}{L_o}$$



where *EL* = elongation (*expresses as a percent*);

L_f = specimen <u>length at fracture</u>; and

L_o = original specimen length

L_f is measured as the distance between gage marks after two pieces of specimen are put back together

Area reduction

defined as

$$AR = \frac{A_0 - A_f}{A_0}$$

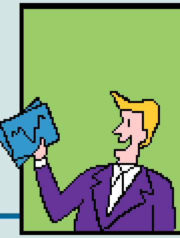
expressed as a percent, where:

A_f = area of the cross section at the point of fracture, mm^2 or in^2

A_0 = original area

Therefore, ductility is measured by elongation (EL) or area reduction (AR).

Lets compare!



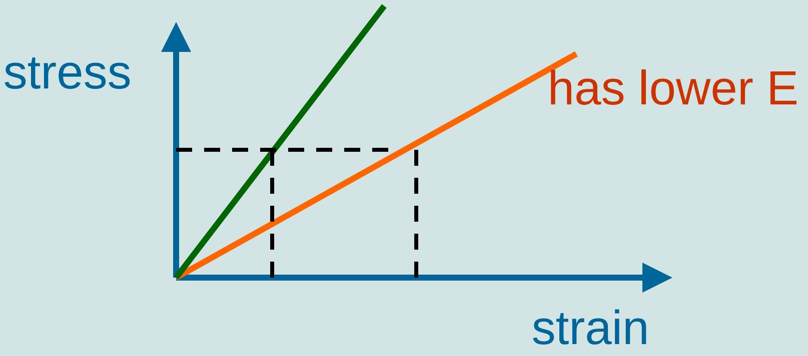
- Which material has the highest modulus of elasticity?
- Which material has the highest tensile strength?
- Which material has the highest elongational rate?

Lets compare!

LOW - > HIGH

<u>Modulus of elasticity</u> (measure of stiffness):

Polyethylene (0.03×10^6 psi), Nylon, Lead (3×10^6 psi), Magnesium, AL & Glass, Copper, Cast Iron (20×10^6 psi), Iron & Steel (30×10^6 psi), Alumina (50×10^6 psi), Tungsten, Diamond (150×10^6 psi)



For a given force, the one with lower E, deforms more in comparison with the one with higher E (which is stiffer).

Lets compare!

LOW - > HIGH

Tensile Strength:

AL (10,000psi), Copper, Cast Iron (40,000psi), Mg, Low C Steel, High C Steel(90,000psi), Stainless steel (95,000psi), Ti alloy

Elongation:

Metals: Cast Iron (0.6%), Mg, high C steel (10%), Ti, low C steel (30%), Nickel, Stainless steel (55%).

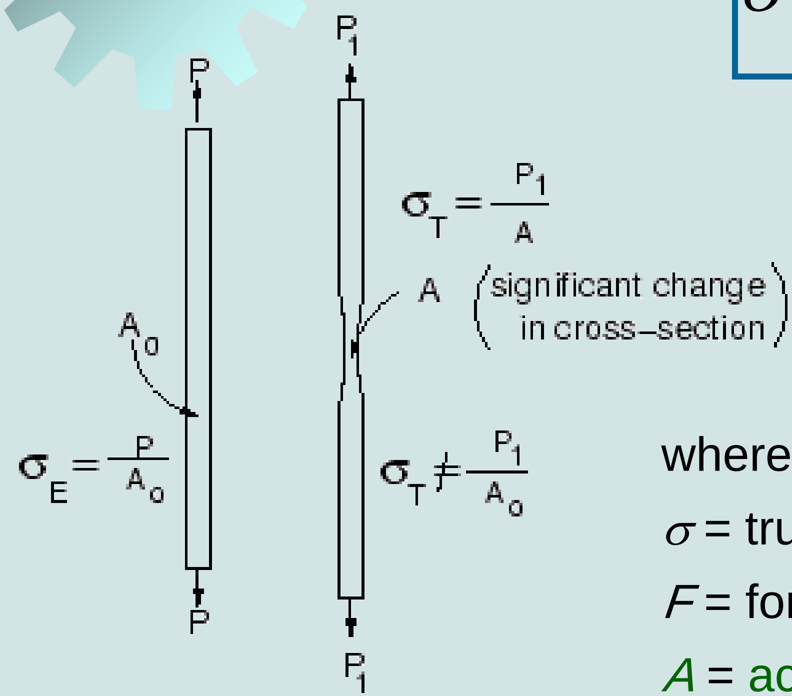
Ceramics: 0%

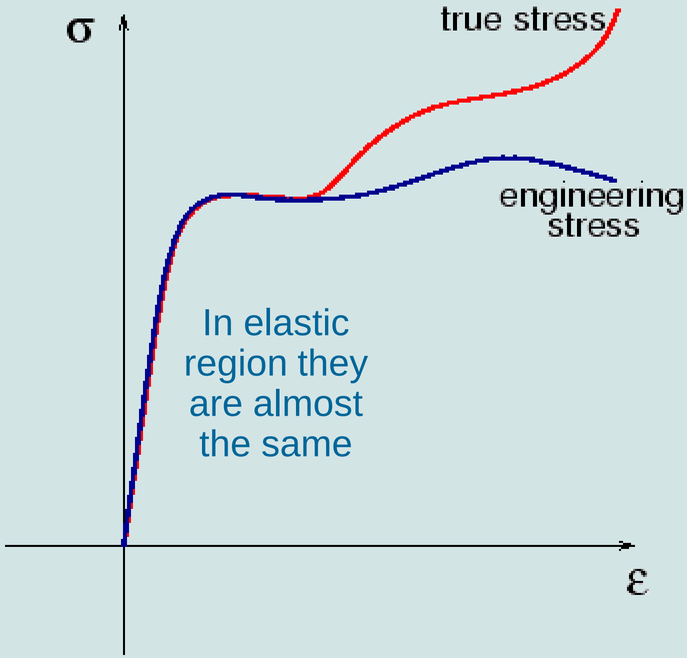
Polymers: thermosetting polymer (1%), Thermoplastic polymer (100%)

True Stress

Stress value obtained by dividing the applied load by the instantaneous area

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





where

σ = true stress;

F = force; and

A = actual (instantaneous) area resisting the load

True Strain or Hencky strain

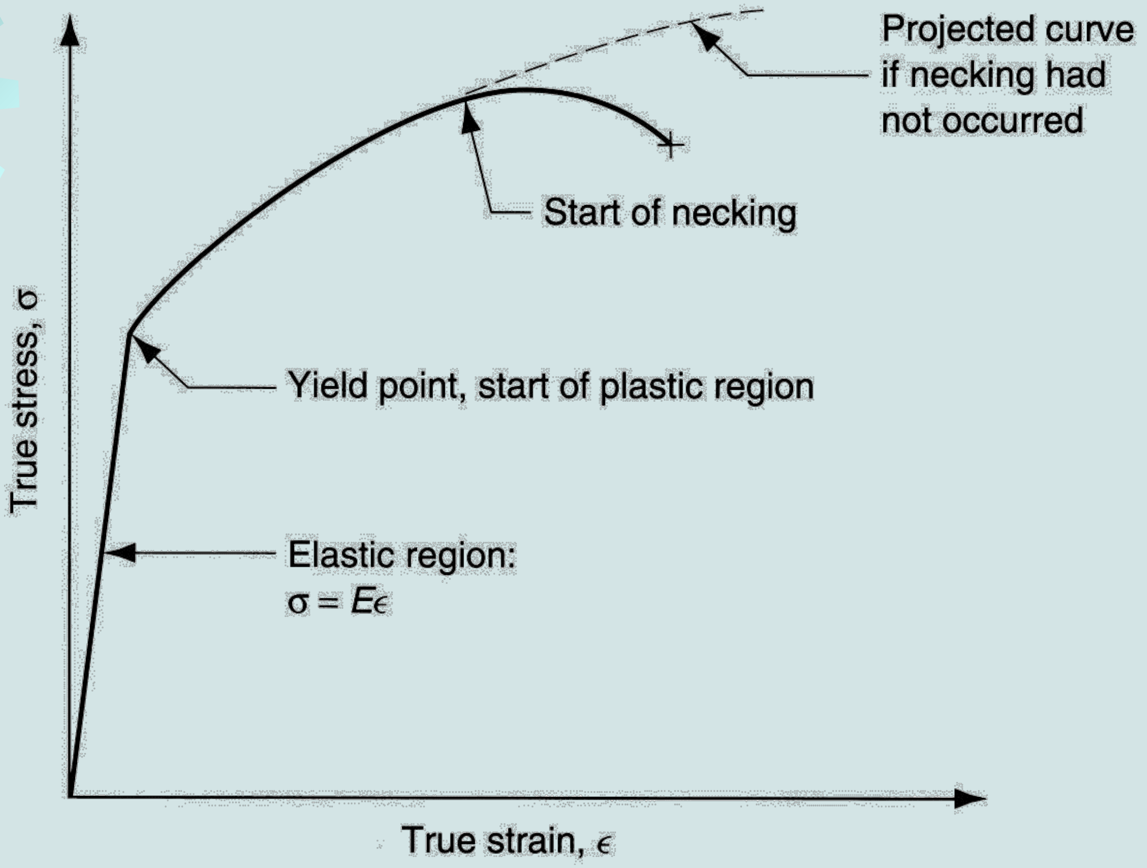
Provides a more realistic assessment of "instantaneous" elongation per unit length

$$\varepsilon = \int d\varepsilon = \int_{L_o}^{L} \frac{dL}{L} = \ln L - \ln L_0 = \ln \frac{L}{L_o}$$

$$\varepsilon = \ln \frac{L}{L_o}$$

True Stress-Strain Curve

Figure 3.4 - True stress-strain curve for the previous engineering stress-strain plot in Figure 3.3.



Strain Hardening in Stress-Strain Curve

- Note that true stress increases continuously in the plastic region until necking
  - In the engineering stress-strain curve, the significance of this was lost because stress was based on an incorrect area value

- It means that the metal is becoming stronger as strain increases
  - This is the property called *strain hardening*

True stress versus Engineering Stress

True strain can be related to the corresponding engineering strain by:

$$\varepsilon = \ln(1+e)$$

True stress and engineering stress can be related by the expression:

$$\sigma_t = \sigma_e (1+e)$$

True stress versus true strain in plastic region:

$$\sigma_t = K\varepsilon^n$$

Flow curve

K is the strength coefficient and is in MPa. n is the strain hardening exponent.

Flow Curve

True stress-strain curve a straight line in a log-log plot:

$$\sigma = K\varepsilon^n$$

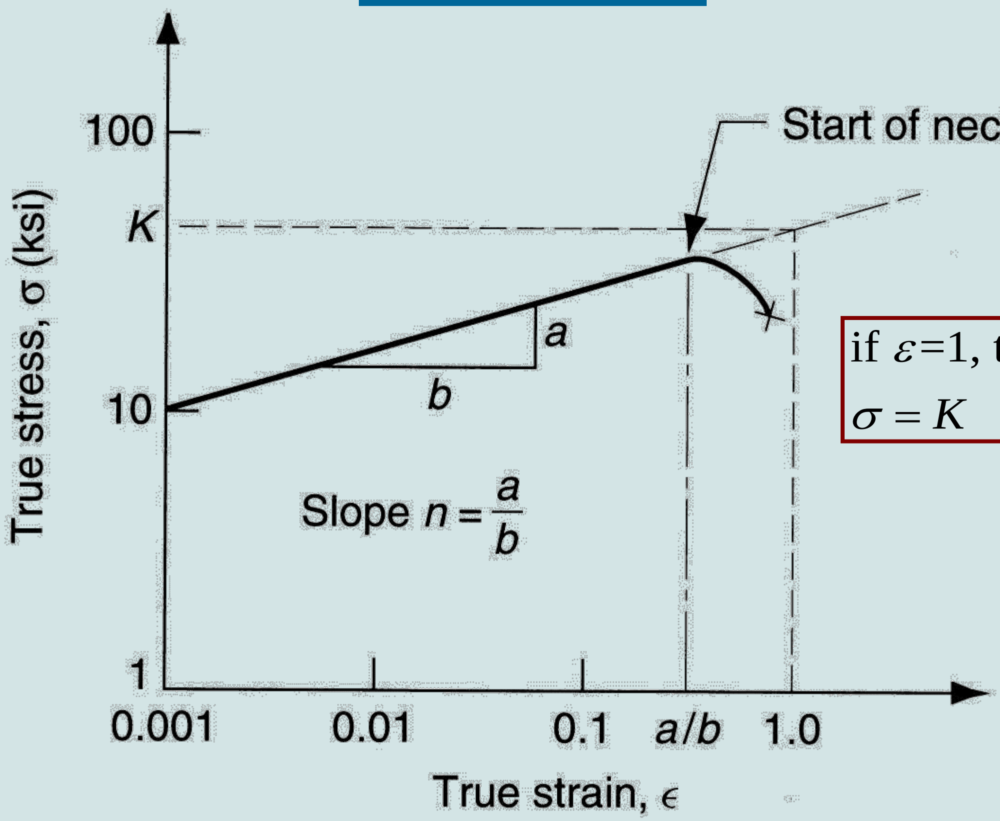
$$\ln\sigma = \ln\left(K\varepsilon^n\right)$$

$$\ln\sigma = \ln K + \ln\left(\varepsilon^n\right)$$

$$\ln\sigma = \ln K + n\ln\varepsilon$$

this is similar to:

$$Y = b + nX$$



if ε=1, then $\sigma = K$

Figure 3.5 True stress-strain curve plotted on log-log scale.

Lets compare!

Engineering Stress & strain

$\sigma_e = E\, e$

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

$$e = \frac{L - L_o}{L_o}$$

$$TS = \frac{F_{max}}{A_o}$$

Elastic region

$$\sigma_t = \sigma_e (1 + e)$$

$$\varepsilon = \ln(1 + e)$$

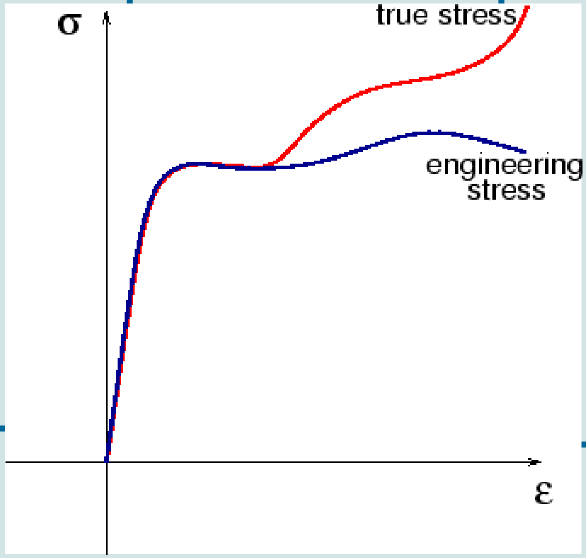
True Stress & strain

$\sigma_t = E\varepsilon$

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

$$\varepsilon = \int_{L_o}^{L} \frac{dL}{L} = \ln \frac{L}{L_o}$$

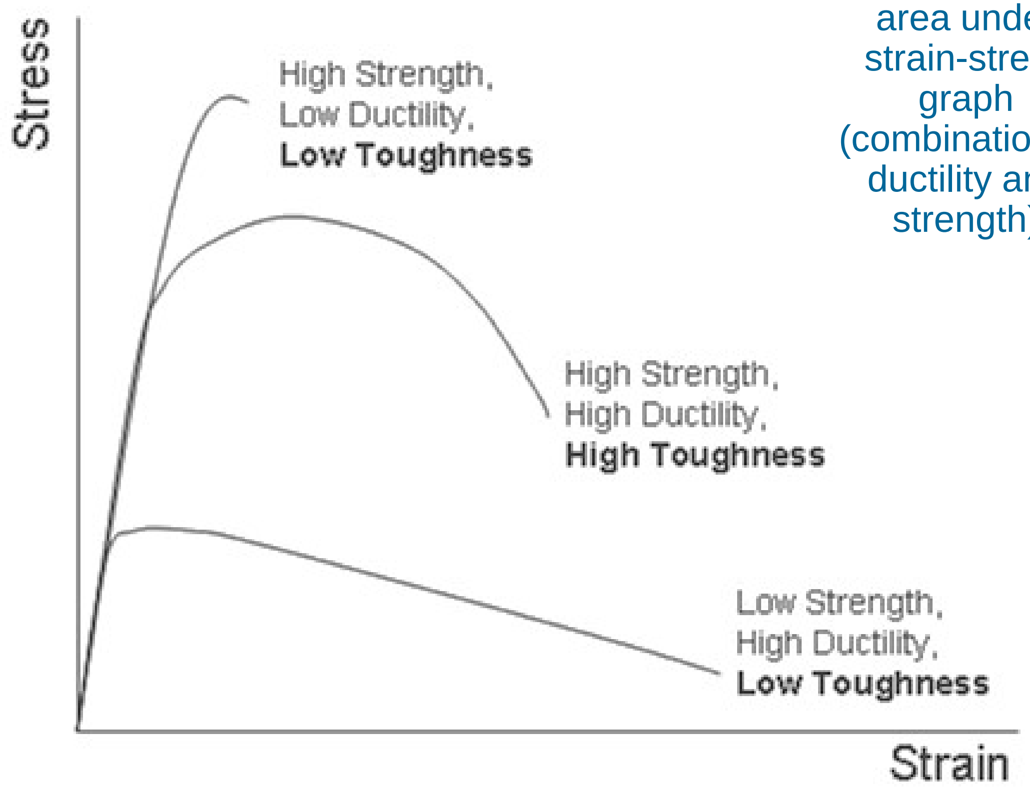
$$TS = \frac{F_{max}}{A}$$



Plastic region

$$\sigma_t = K\varepsilon^n$$

Lets compare!



Toughness: area under strain-stress graph (combination of ductility and strength)

Categories of Stress-Strain Relationship

- Perfectly elastic
- Elastic and perfectly plastic
- Elastic and strain hardening

Perfectly Elastic

- Behavior is defined completely by modulus of elasticity *E*
- Fractures rather than yielding to plastic flow
- Brittle materials: ceramics, many cast irons, and thermosetting polymers

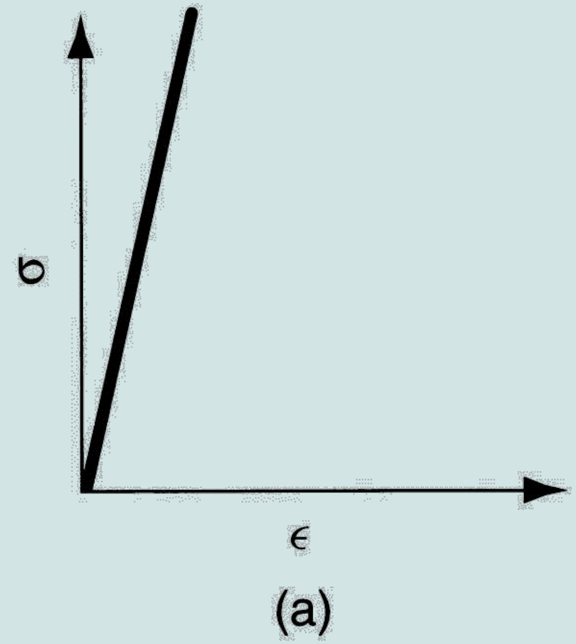


Figure 3.6 Categories of stress-strain relationship: (a) perfectly elastic.

Elastic and Perfectly Plastic

- Stiffness defined by *E*
- Once *Y* reached, deforms plastically at same stress level
- Flow curve: $K = Y$, $n = 0$
- Metals behave like this when heated to sufficiently high temperatures (above recrystallization)
- One example is Lead

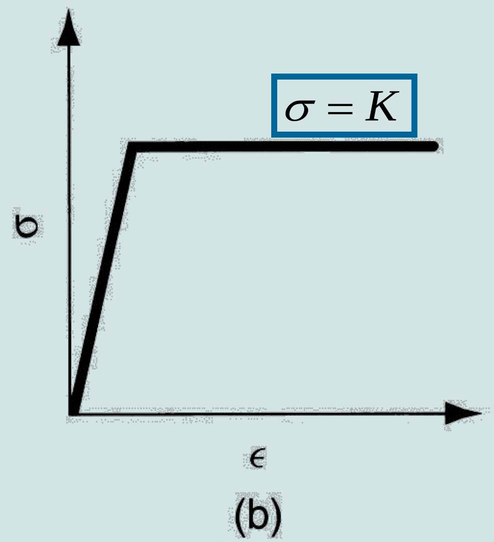


Figure 3.6 Categories of stress-strain relationship:

(b) elastic and perfectly plastic.

Elastic and Strain Hardening

- Hooke's Law in elastic region, yields at *Y*
- Flow curve: $K > Y$, $n > 0$
- Most <u>ductile metals</u> behave this way when cold worked

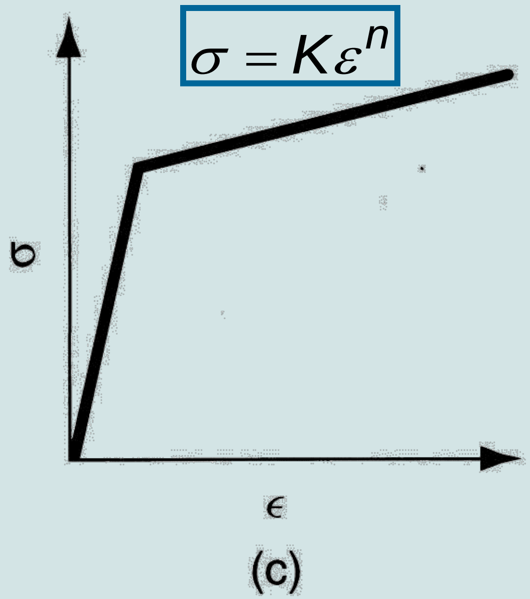


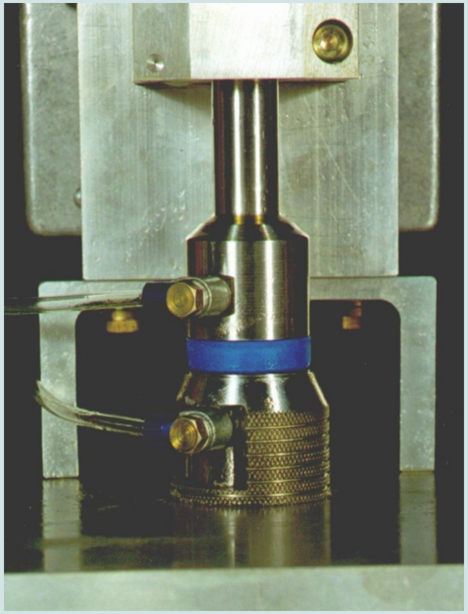
Figure 3.6 Categories of stress-strain relationship:

(c) elastic and strain hardening.

Compression test

Compression Test

Applies a load that squeezes the ends of a cylindrical specimen between two platens



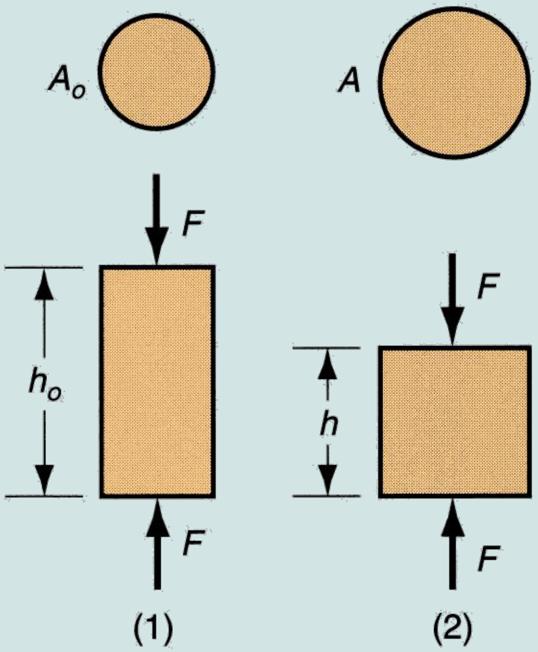
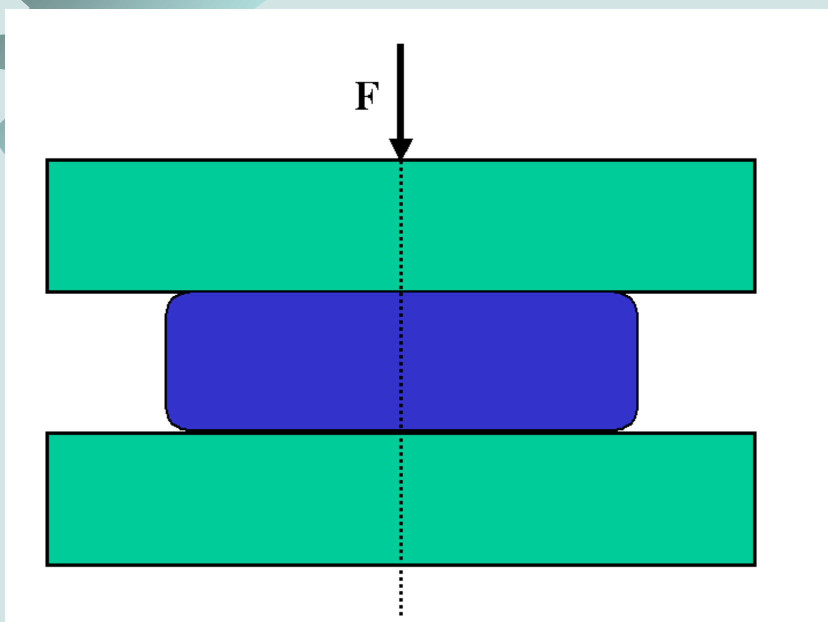
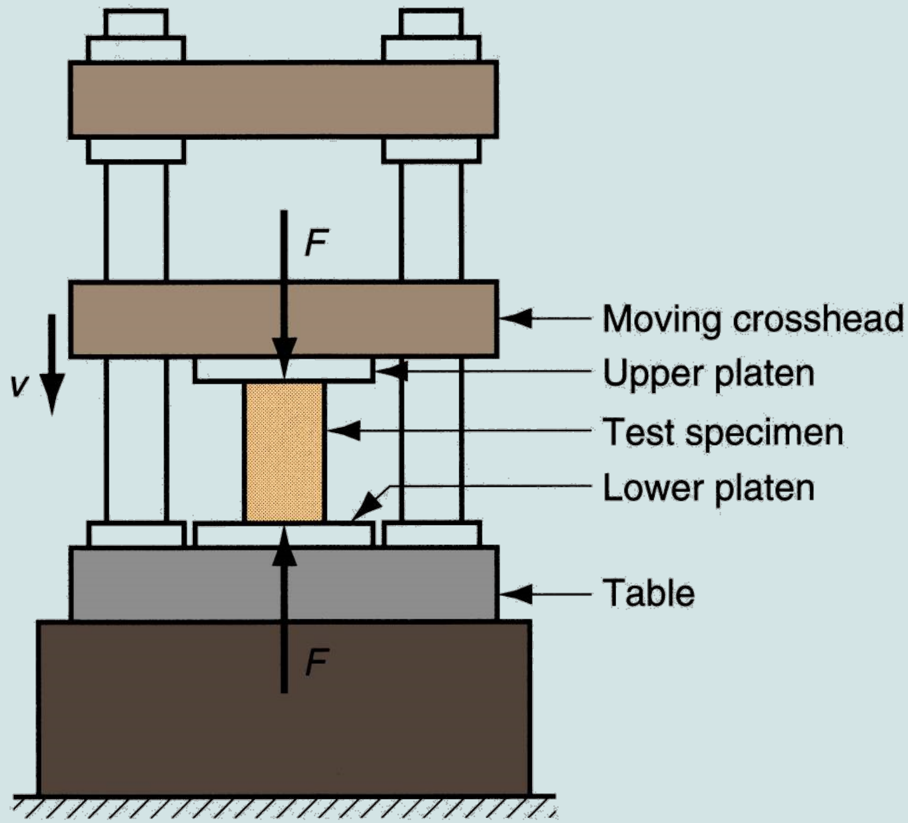


Figure 3.7 Compression test: (a) compression force applied to test piece in (1) and (2) resulting change in height.

Compression Test Setup





(b)

Engineering Stress in Compression

As the specimen is compressed, its height is reduced and cross-sectional area is increased

$$\sigma_e = -\frac{F}{A_o}$$

where

A_o = original area of the specimen

Engineering Strain in Compression

Engineering strain is defined

$$e = \frac{h - h_o}{h_o}$$

Since height is reduced during compression, value of *e* is negative

(the negative sign is usually ignored when expressing compression strain)

Stress-Strain Curve in Compression

Shape of plastic region is different from tensile test because cross section increases

Calculated value of engineering stress is higher

In comparison to the true stress

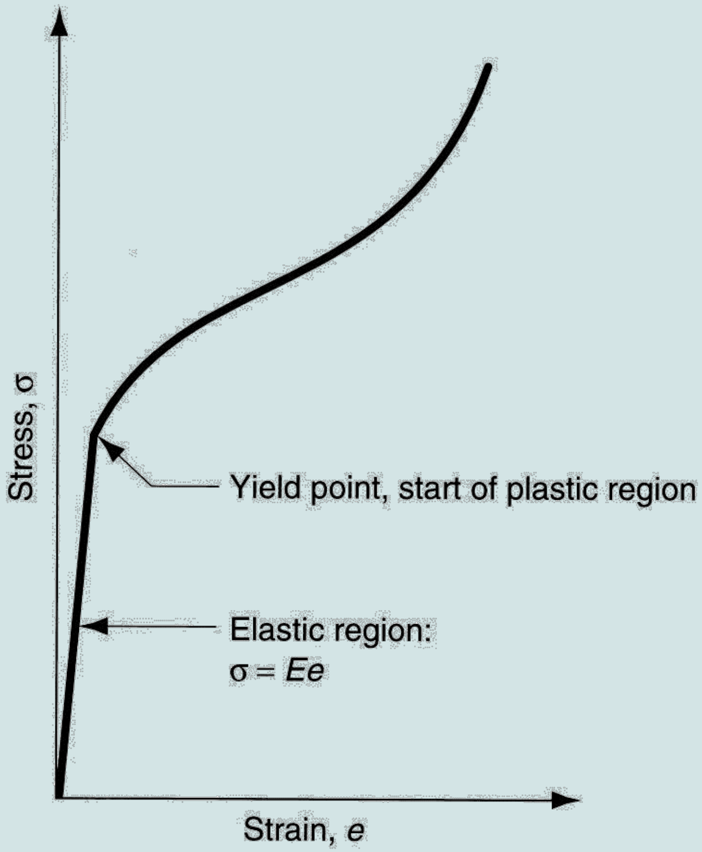


Figure 3.8 Typical engineering stress-strain curve for a compression test.

Tensile Test vs. Compression Test

- Although differences exist between engineering stress-strain curves in tension and compression, the true stress-strain relationships are nearly identical
- Since tensile test results are more common, flow curve values (K and n) from tensile test data can be applied to compression operations
- When using tensile K and n data for compression, ignore necking, which is a phenomenon peculiar to straining induced by tensile stresses
- Barreling and edge fracture happen