Mechanical Properties

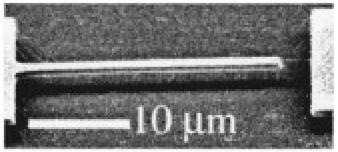
Why mechanical properties?

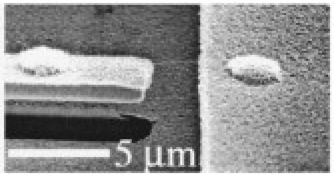
Many materials, when in service, are subjected to forces or loads; examples include….

e.g. materials used in building bridges that hold up automobiles, pedestrians…

materials for skyscrapers in the Windy City…

materials for NASA exploration…





materials for and designing MEMs and NEMs…

Space elevators?

Issues to address...

- Stress and strain
- Elastic behavior
- Plastic behavior
- Strength, ductility, resilience, toughness, hardness
- Mechanical behavior of different classes

of materials

CONCEPTS OF STRESS AND STRAIN

ress: Pressure due to applied load.

e.i.: tension, compression, shear, torsion, and combination.

$$stress = \sigma = \frac{force}{area}$$

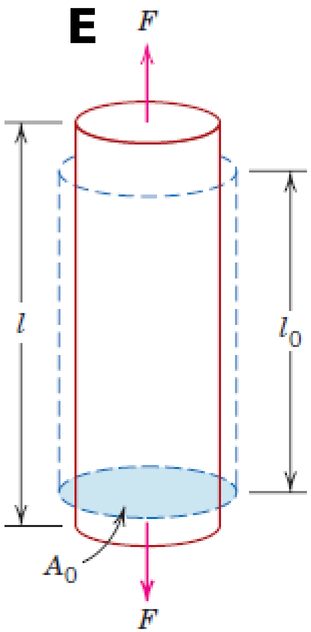
Strain: **response of the material to stress**
(i.e. Physical deformation such as elongation due to tension).

CONCEPTS OF STRESS AND STRAIN

ess: Pressure due to applied l **Strain: response of the material to stress**

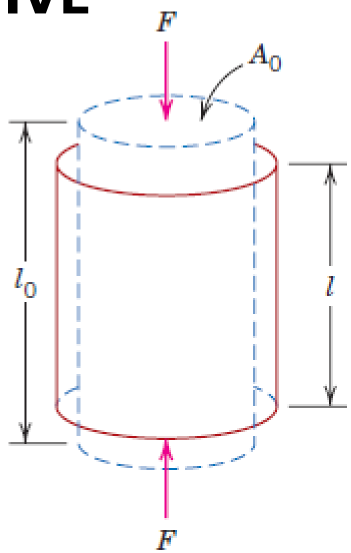
Schematic illustration of different kinds of stresses & responded strains

TENSILE



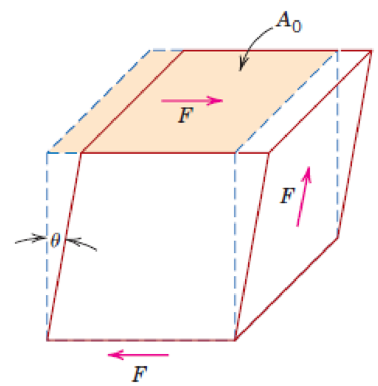
how a tensile load produces an elongation and positive linear strain. Dashed lines represent the shape before deformation; solid lines, after

COMPRESSIVE



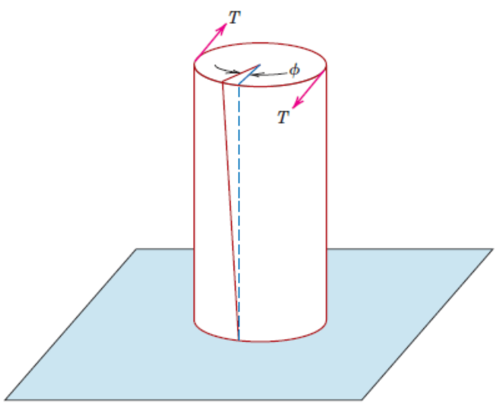
how a compressive load produces contraction and a negative linear strain.

SHEAR



shear strain γ , where
$\gamma = \tan \theta$

TORSION



torsional deformation (i.e., angle of twist Ø) produced by an applied torque *T*.

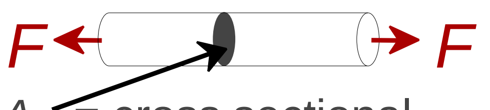
CONCEPTS OF STRESS AND STRAIN

ess: Pressure due to applied l

Strain: response of the material to stress

COMMON STATES OF STRESS

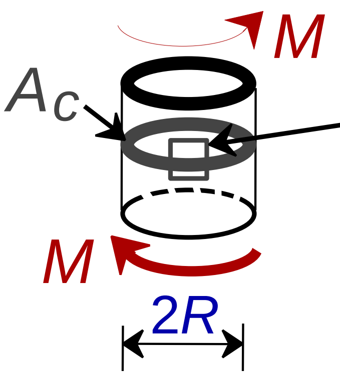
- **Simple tension: cable**

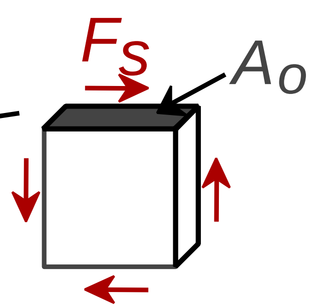


A_o = cross sectional area (when unloaded)

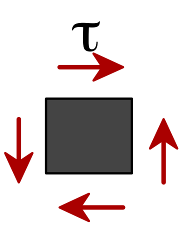
$$\sigma = \frac{F}{A_o}$$

- **Torsion (a form of shear): drive shaft**





$$\tau = \frac{F_s}{A_o}$$



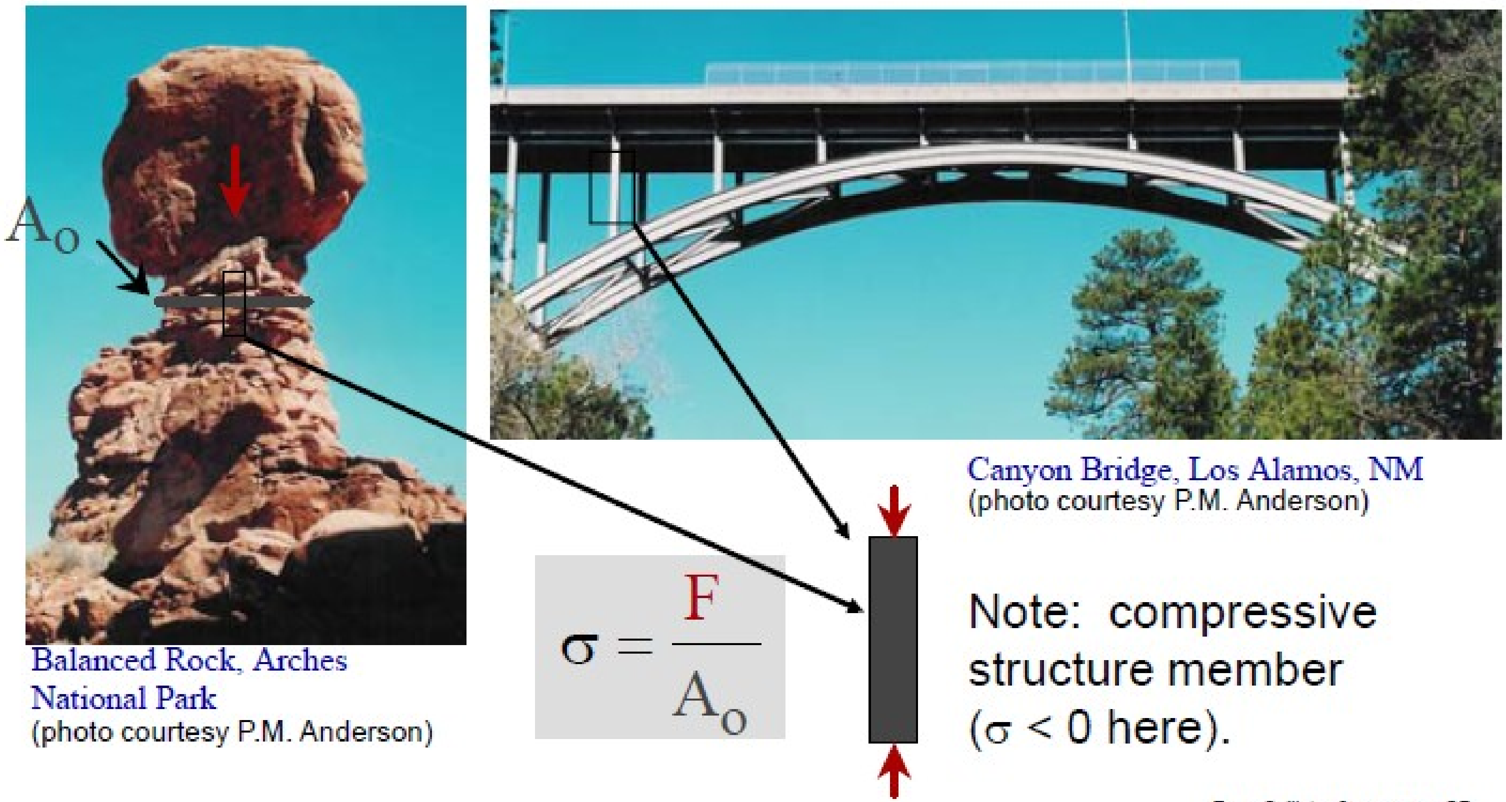
Note: $\tau = M/A_cR$ here.

CONCEPTS OF STRESS AND STRAIN

ess: Pressure due to applied l **Strain: response of the material to stress**

COMMON STATES OF STRESS

- Simple compression:



Balanced Rock, Arches National Park
(photo courtesy P.M. Anderson)

Canyon Bridge, Los Alamos, NM
(photo courtesy P.M. Anderson)

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

Note: compressive structure member ($\sigma < 0$ here).

From Callister 6e resource CD.

CONCEPTS OF STRESS AND STRAIN

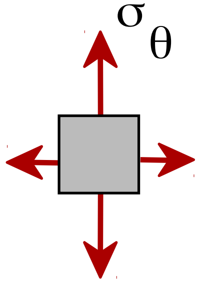
ess: **Pressure due to applied l**

Strain: **response of the material to stress**

COMMON STATES OF STRESS

- **Bi-axial tension:**

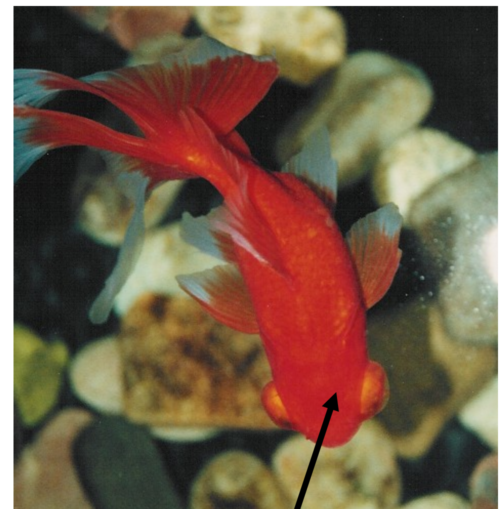
Pressurized tank



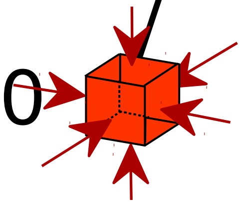
$\sigma_\theta > 0$

$\sigma_z > 0$

- **Hydrostatic compression:**



Fish under water



$\sigma_h < 0$

Also called as isostatic

CONCEPTS OF STRESS AND STRAIN

ess: Pressure due to applied l

Strain: response of the material to stress

Tension and Compression

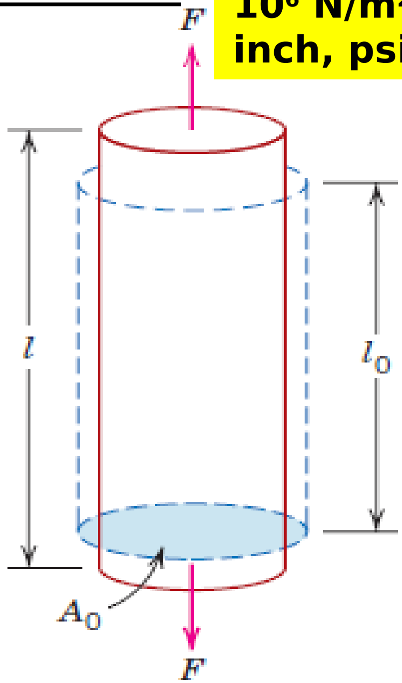
Tension

megapascals, MPa (SI) (where 1 MPa= 10^6 N/m²), and pounds force per square inch, psi

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

Newton (N) or pounds force (ıbf)

m² or in²



Engineering strain = $\varepsilon = \dfrac{l_i - l_o}{l_o} = \dfrac{\Delta l}{l_o}$

A_o = original cross sectional area

l_i = instantaneous length

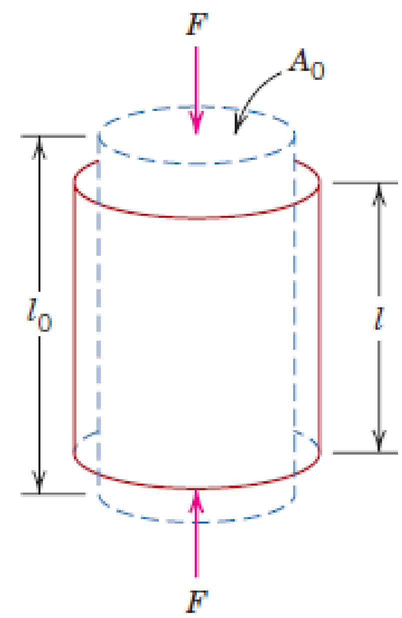
l_o = original length

Note: strain is unitless.

Compression

Same as tension but in the opposite direction (stress and strain defined in the same manner).

By convention, stress and strain are negative for compression.

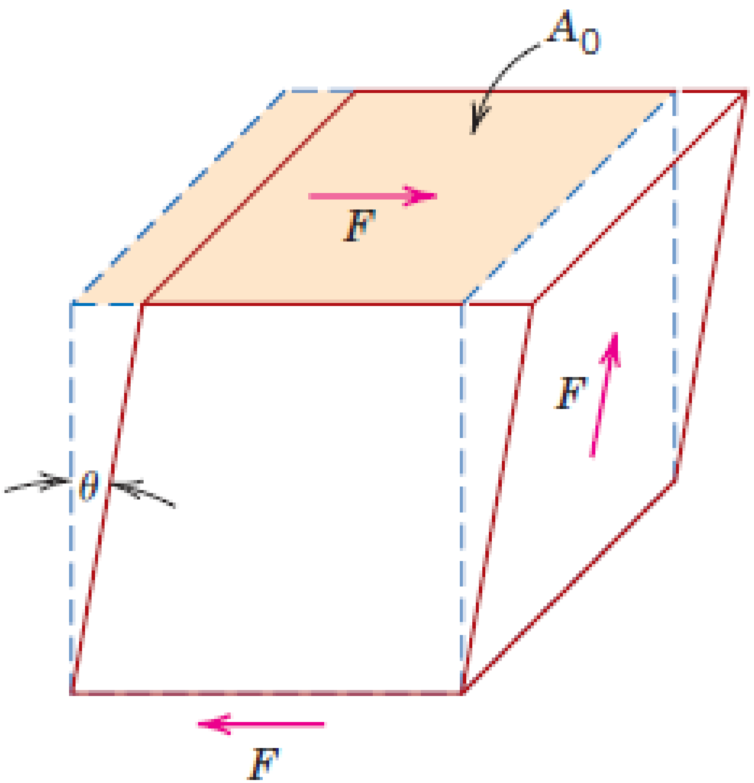


CONCEPTS OF STRESS AND STRAIN

ess: Pressure due to applied l

Strain: response of the material to stress

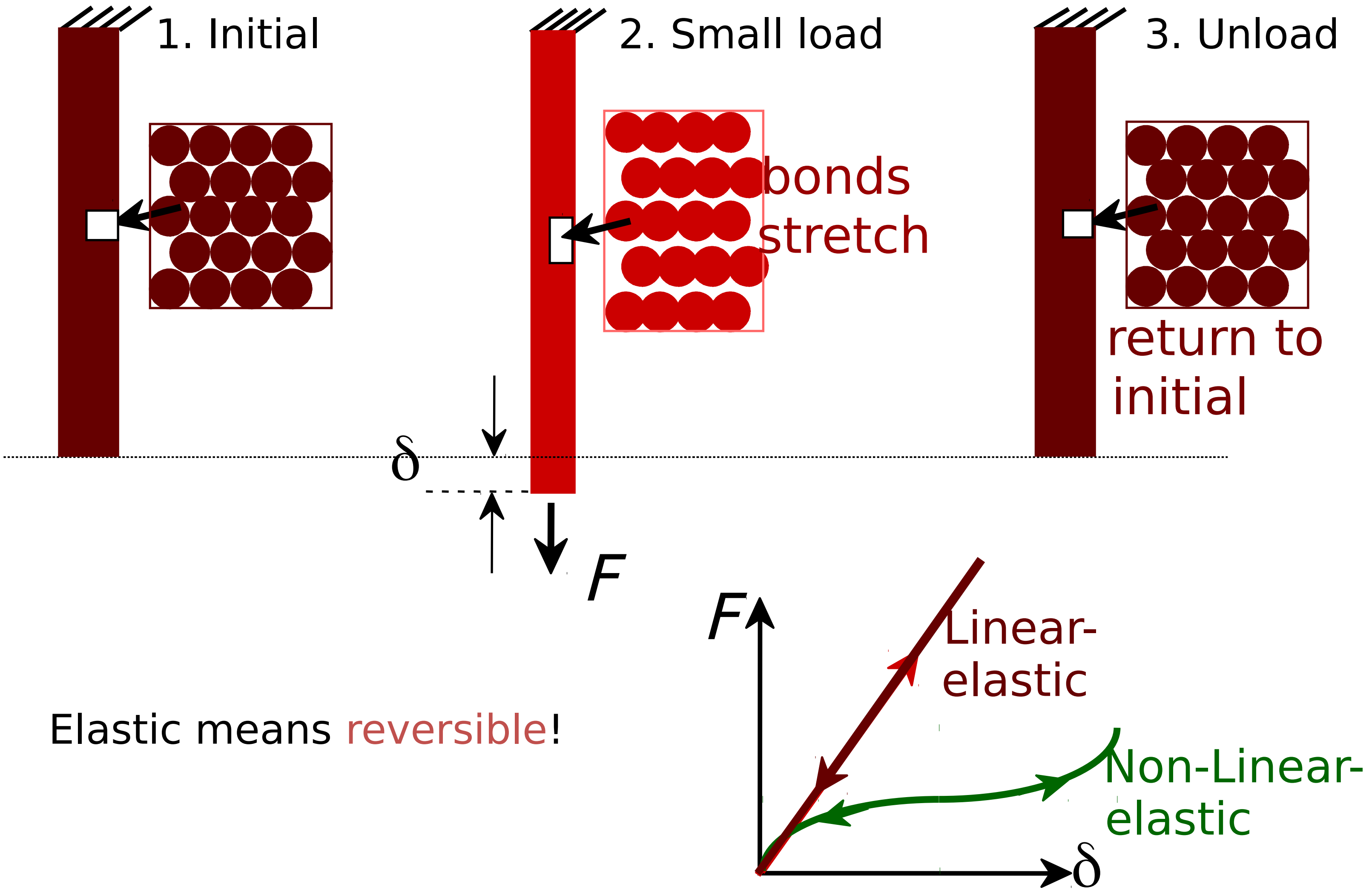
Shear



Pure shear stress = $\tau = \dfrac{F}{A_o}$

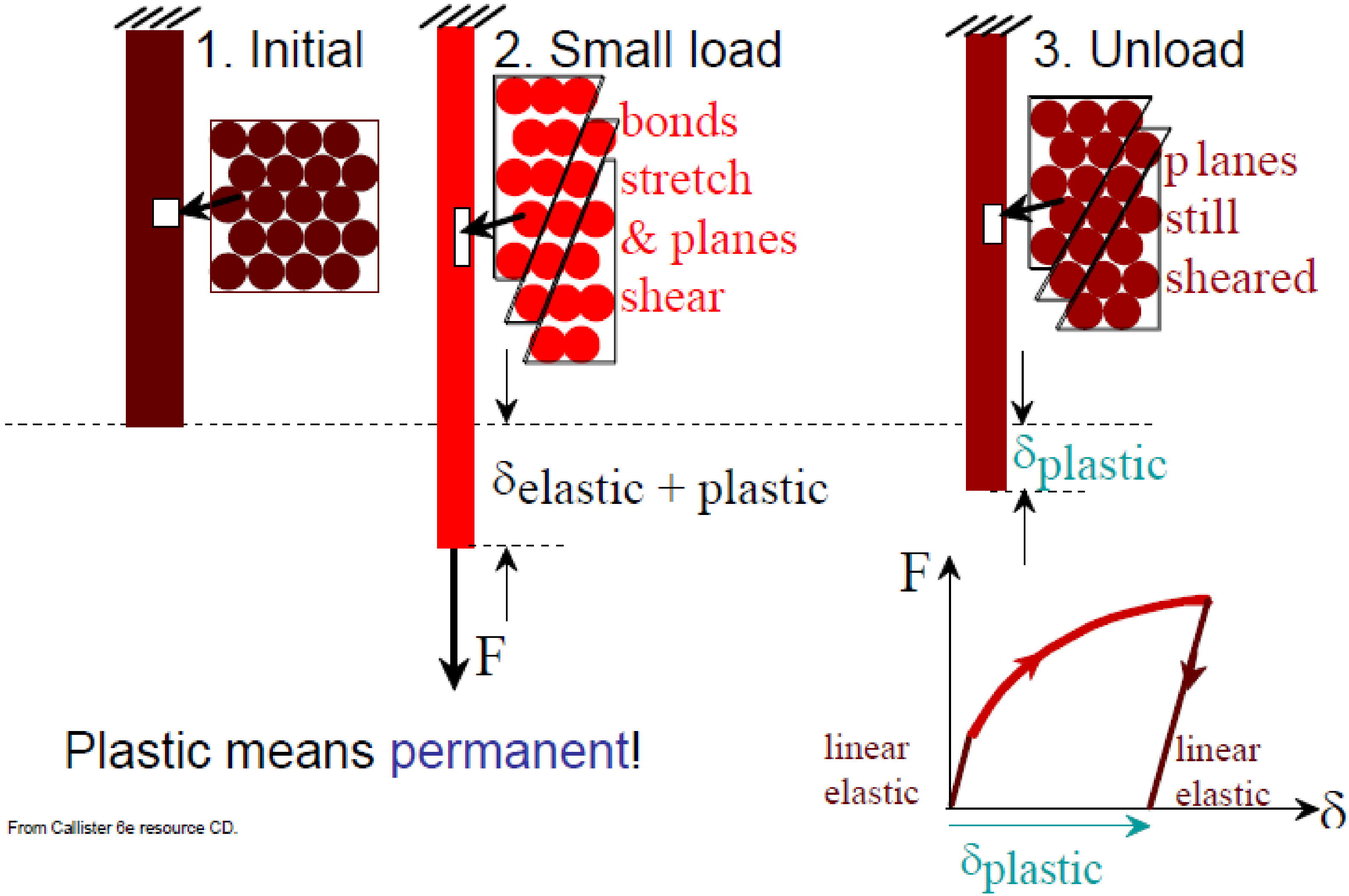
Pure shear strain = $\gamma = \tan\theta$

Elastic Deformation



Elastic means reversible!

Plastic Deformation



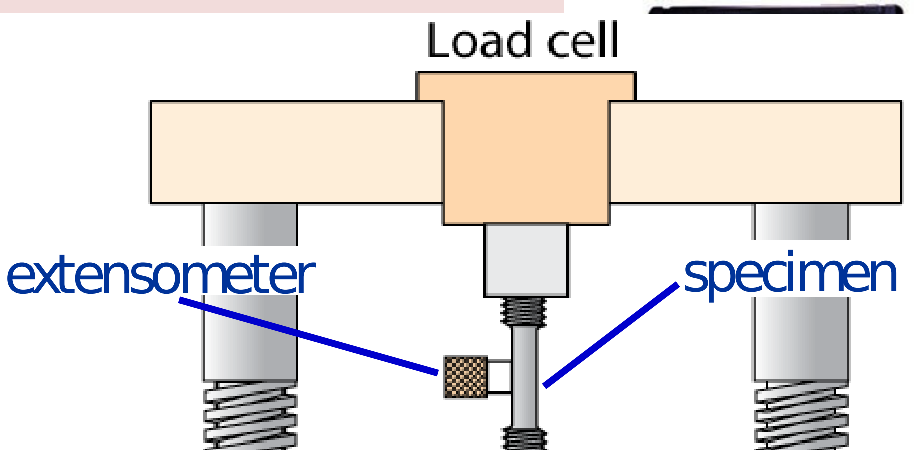
Plastic means permanent!

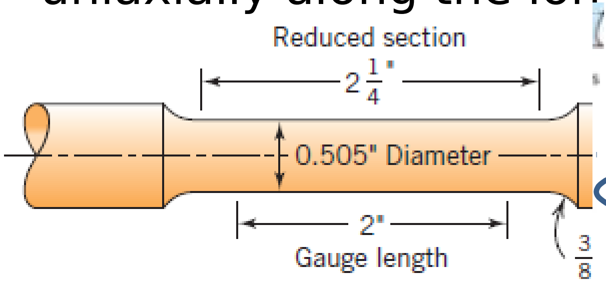
From Callister 6e resource CD.

Tension Tests

One of the most common mechanica
strain tests

- be used to ascertain several m materials that are important in d
- A specimen is deformed, usua gradually increasing tensile uniaxially along the long axis of a

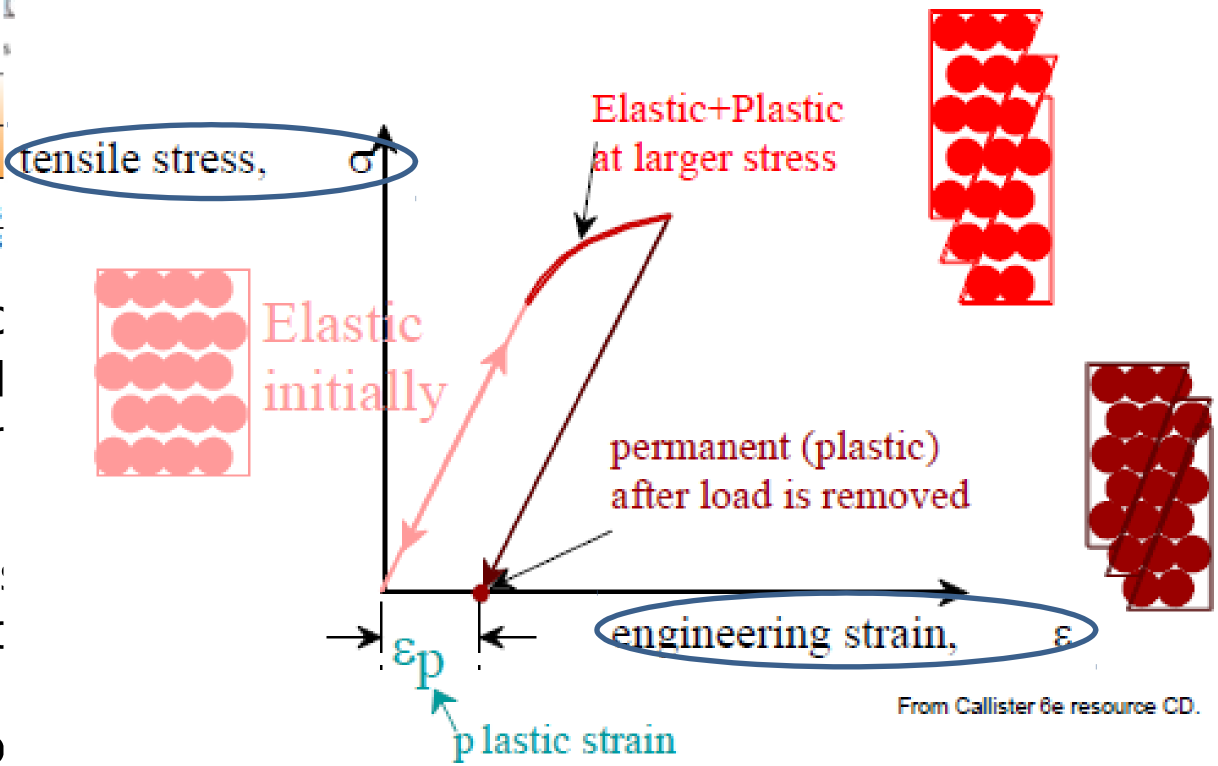




A standard tensile sp

The cross section is circul rectangular specimens ar used

The output of such a ten recorded (usually on a co load or force versus elongatio



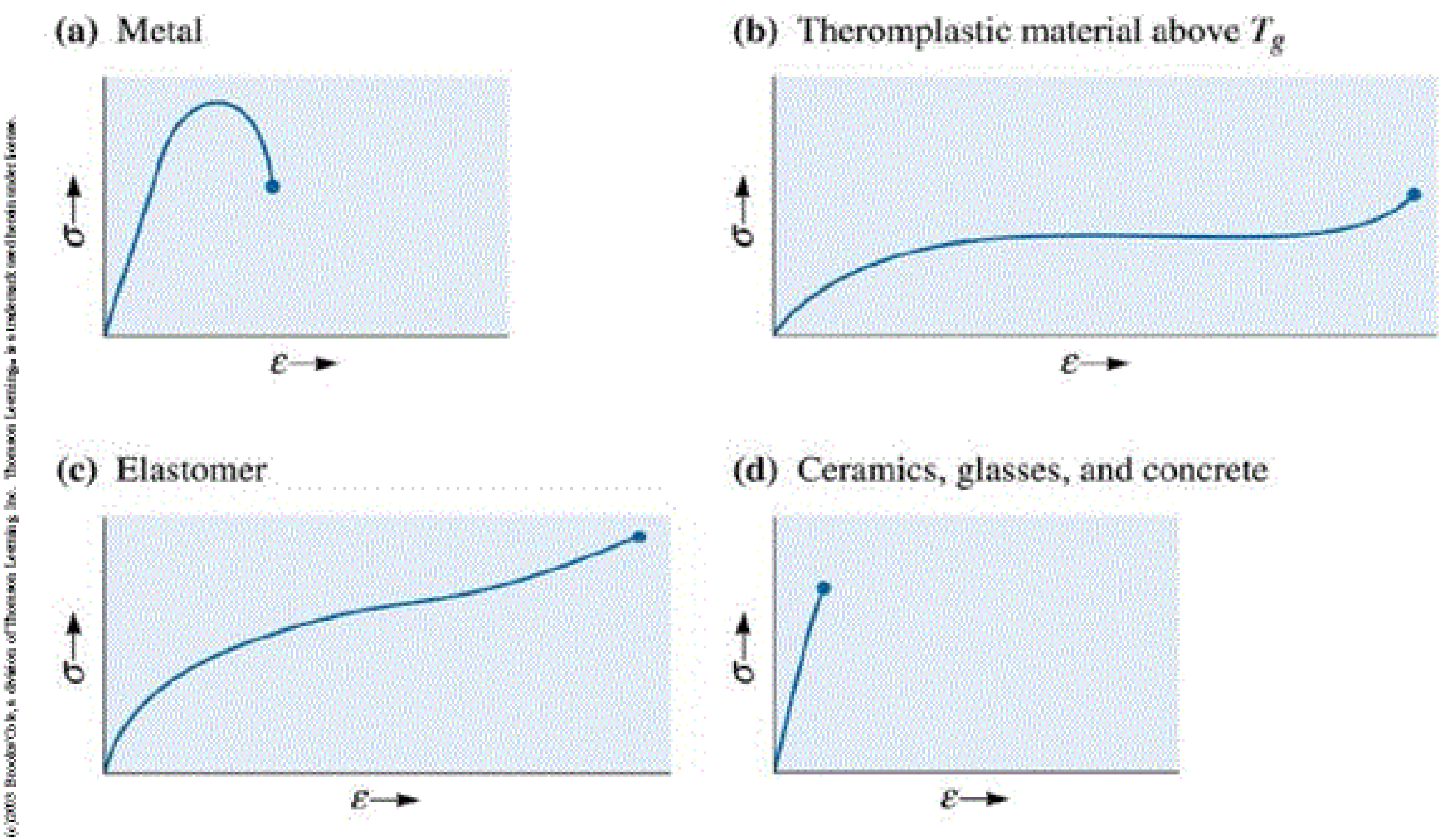


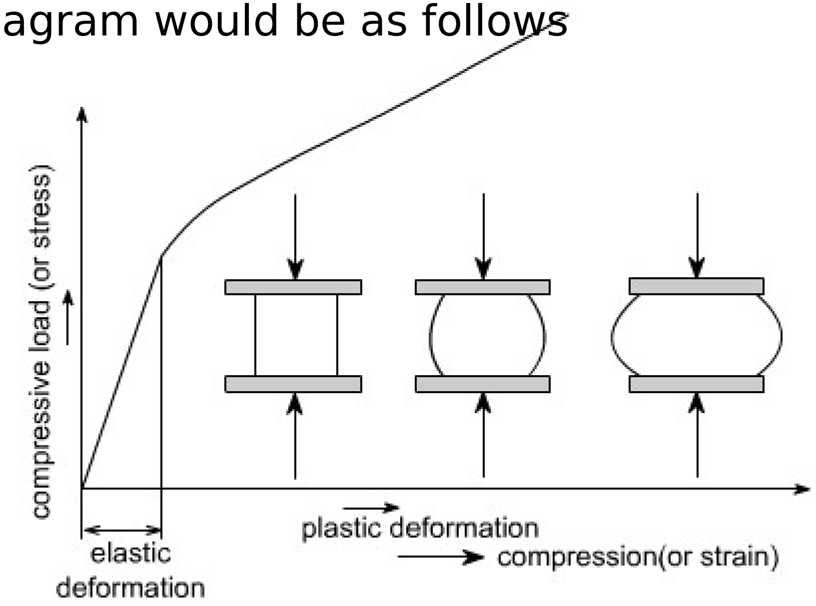
Figure 6.9 Tensile stress-strain curves for different materials. Note that these are qualitative

Compression Tests

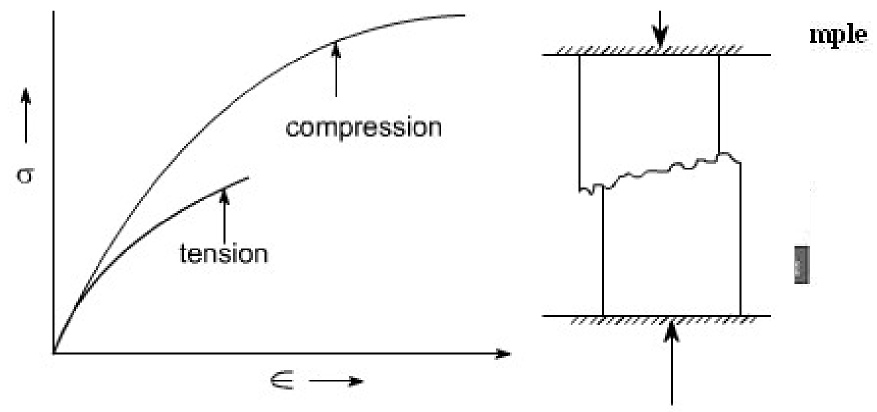
- Compression stress–strain tests may be conducted if in-service forces are of this type.

- 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.

Ductile materials: For ductile material such as mild steel, the load vs compression diagram would be as follows



Brittle materials in compression behave elastically up to certain load, and then fail suddenly by splitting or by craking



Torsional Tests

- Torsion test is not widely accepted as much as tensile test.
- Torsion tests are made on materials to determine such properties as the modulus of elasticity in shear, the torsion yield strength and the modulus of rupture.
- Often used for testing brittle materials and can be tested in full sized parts, i.e., shafts, axles and twi

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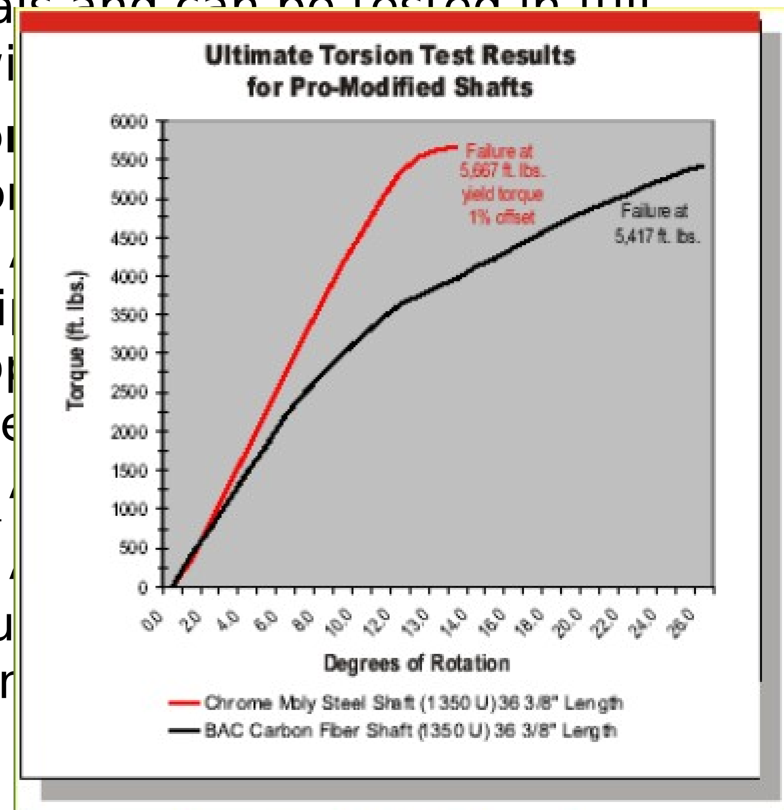
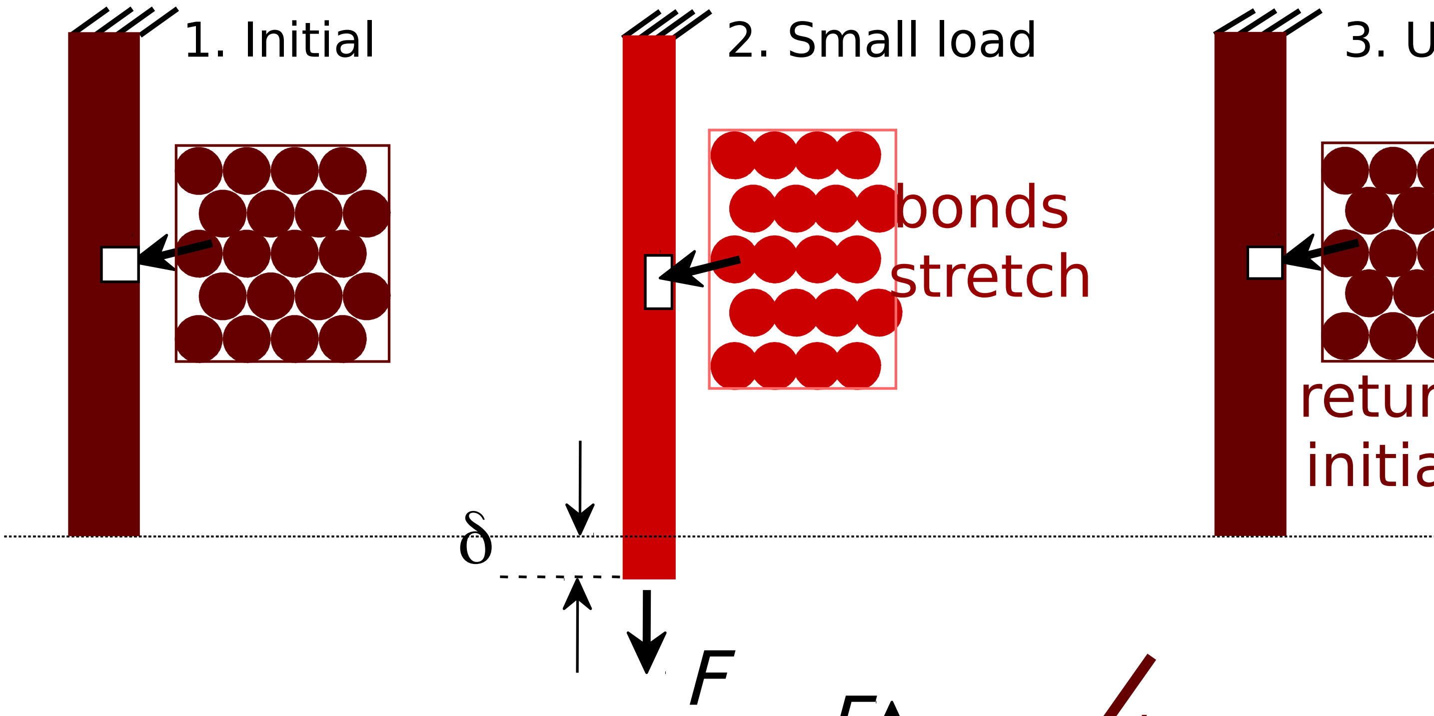


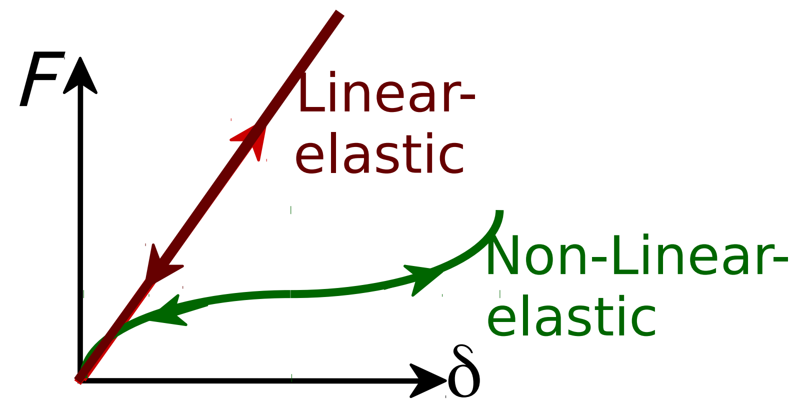
Torque-degree of rotation diagram

Determination is made of the angu
displacement (or degree of rotation
of
a point near one end of the test
section of
the specimen with respect to a point
on

hin-walled tubular specimen
iently used.

Elastic Deformation

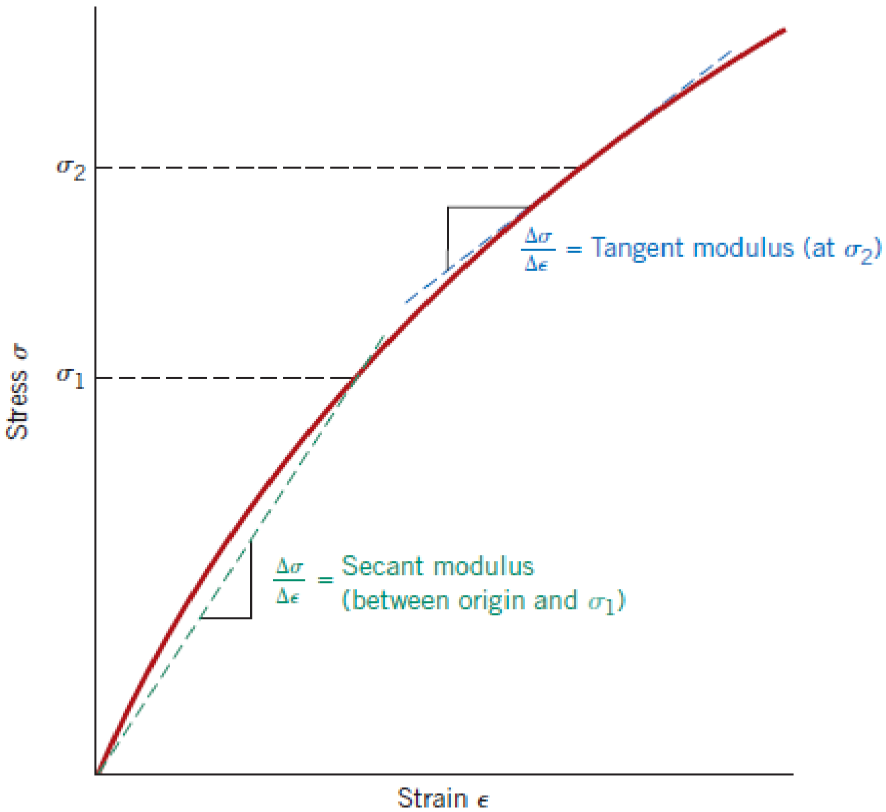




Elastic means reversible!

Elastic Deformation

-a non-permanent deformation where the material completely recovers to its original state upon release of the applied stress



There are some materials (e.g., gray cast iron, concrete, and many polymers) for which this elastic portion of the stress–strain curve is not linear.

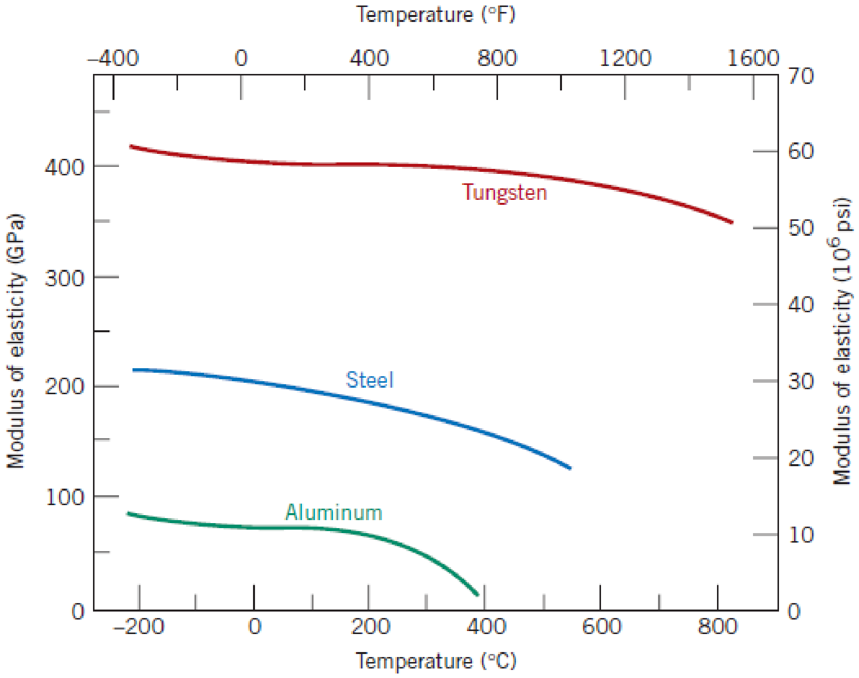
For this nonlinear behavior, either *tangent* or *secant modulus* is normally used. Tangent modulus is taken as the slope of the stress–strain curve at some specified level of stress, whereas secant modulus represents the slope of a secant drawn from the origin to some given point of the curve.

Elastic Deformation

materials are elastically anisotropic – dependent to orientation

Table 3.3 Modulus of Elasticity Values for Several Metals at Various Crystallographic Orientations

	Modulus of Elasticity (GPa)		
Metal	*[100]*	*[110]*	*[111]*
Aluminum	63.7	72.6	76.1
Copper	66.7	130.3	191.1
Iron	125.0	210.5	272.7
Tungsten	384.6	384.6	384.6



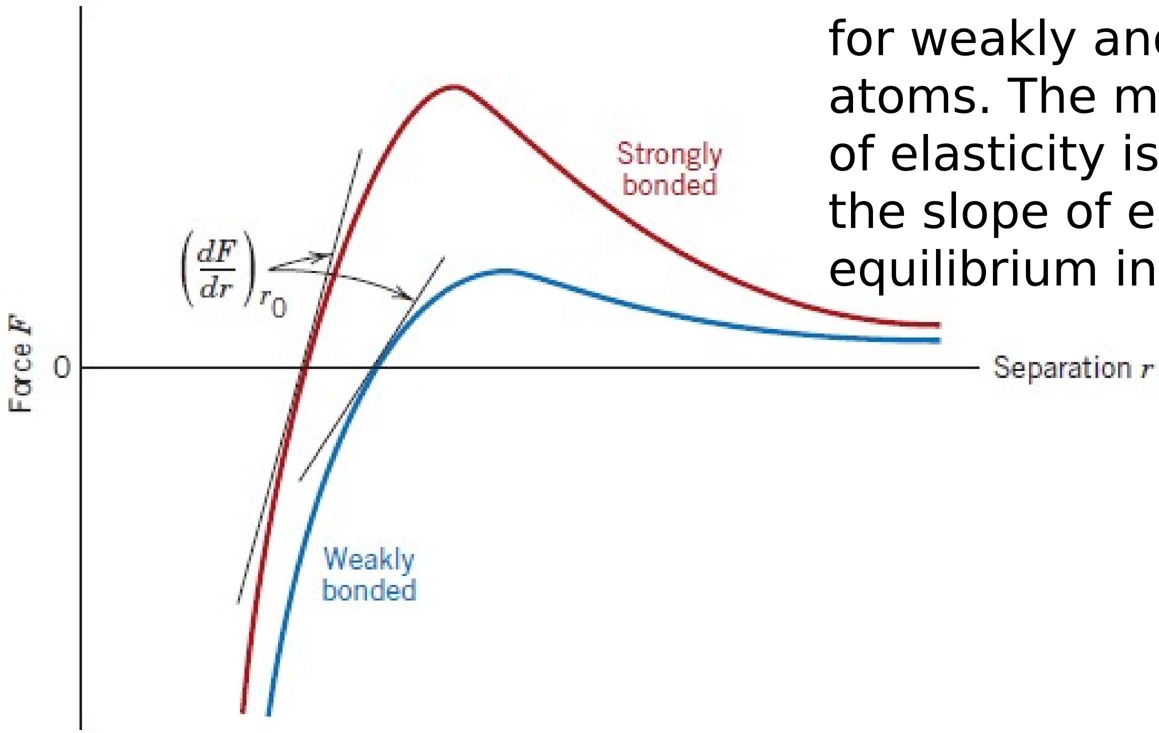
Because the grain orientation is random in most polycrystalline materials, these may be considered to be isotropic; inorganic ceramic glasses are also isotropic (independent to orientation).

with increasing temperature, the modulus of elasticity diminishes

Elastic Deformation

On an atomic scale, macroscopic elastic strain is manifested as small changes in the interatomic spacing and the stretching of interatomic bonds.

As a consequence, the magnitude of the modulus of elasticity is a measure of the resistance to separation of adjacent atoms, that is, the interatomic bonding forces



Force versus interatomic separation for weakly and strongly bonded atoms. The magnitude of the modulus of elasticity is proportional to the slope of each curve at the equilibrium interatomic separation *r*0.

$$E \propto \left(\frac{dF}{dr}\right)_{r_0}$$

Elastic Deformation

The Comparision of modulus of elasticity (Young's Moduli)

Table 6.1 Room-Temperature Elastic and Shear Moduli, and Poisson's Ratio for Various Metal Alloys

	Modulus of Elasticity		*Shear Modulus*		
Metal Alloy	*GPa*	*10^6 psi*	*GPa*	*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

Silicon (single crystal)	120 - 190 (depends on crystallographic direction)
Glass (pyrex)	70
SiC (fused or sintered)	207 - 483
Graphite (molded)	~12
High modulus C-fiber	400
Carbon Nanotubes	**~1000**

If we normalize to density: ~20 times that of steel wire.
Density normalized strength is ~56X that of steel wire.

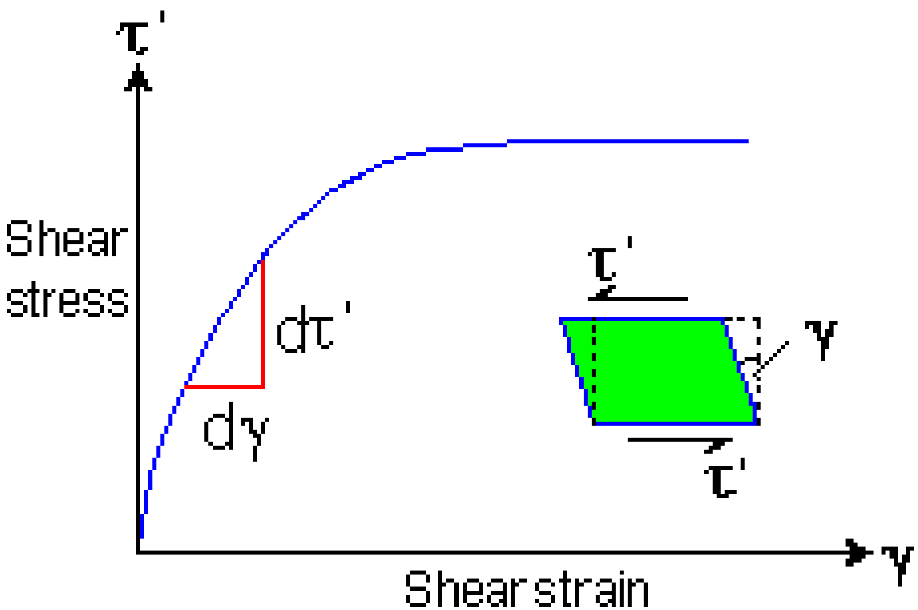
Elastic Deformation

Shear stress and strain are proportional to each other through the expression

$$\tau = G\gamma$$

Shear stress **Shear strain**

shear modulus

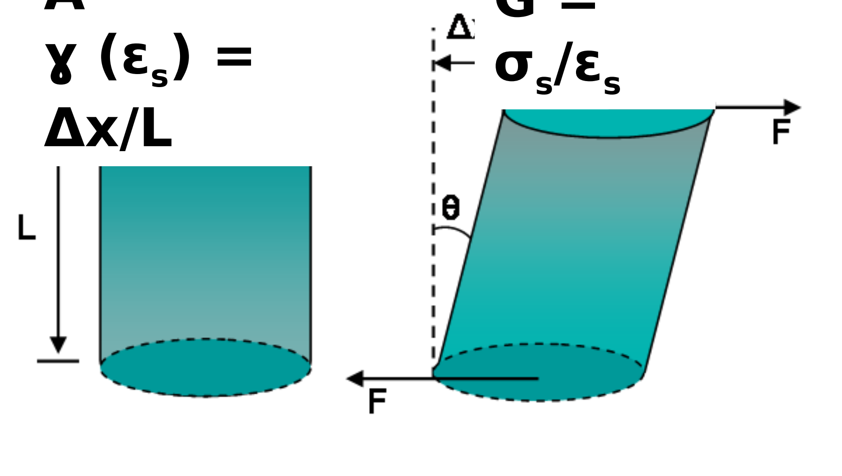


$\tau\ (\sigma_s) = F/A$

$\gamma\ (\varepsilon_s) = \Delta x/L$

$G = \tau/\gamma$

$G = \sigma_s/\varepsilon_s$



<u>Example:</u> Elongation (Elastic) Computation

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

Because the deformation is elastic, strain is dependent on stress according to Hooke's Law: **$\sigma = E\varepsilon$ and $\varepsilon = \Delta l / l_0$**

σ =276 Mpa

l_0=305mm

$$\Delta l = \frac{\sigma l_0}{E}$$

Table 6.1 Room-Temperature Elastic and Shear Moduli and Poisson's Ratio for Various Metal A

$$\Delta l = \frac{(276\ \text{MPa})(305\ \text{mm})}{110 \times 10^3\ \text{MPa}} = 0.77\ \text{mm}\ (0.03\ \text{in.})$$

	Modulus Elastici				
Metal Alloy	*GPa*	*10^6 psi*	*GPa*	*10^6 psi*	*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
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Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

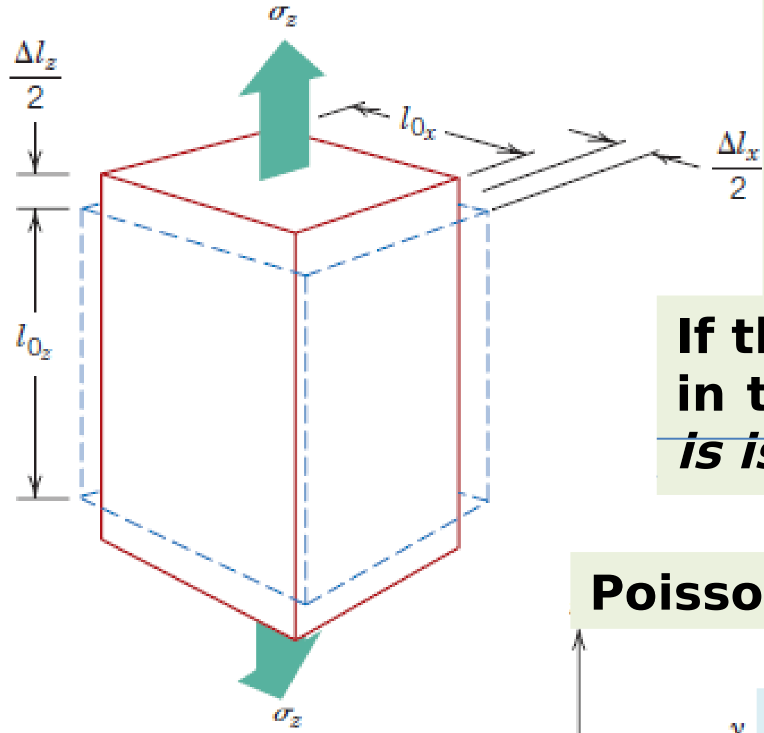
Elastic Deformation

Poisson Ratio

So far, we've considered stress only along one dimension…

But in reality;

Due to the elongation (z), there will be constrictions in the lateral (*x and y) directions perpendicular to the applied* stress; => the compressive strains ε_x *and* ε_y



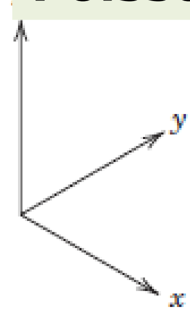
$$\frac{\epsilon_z}{2} = \frac{\Delta l_z/2}{l_{0_z}}$$

$$-\frac{\epsilon_x}{2} = \frac{\Delta l_x/2}{l_{0_x}}$$

If the applied stress is uniaxial (only in the *z direction), and the material is isotropic =>* $\varepsilon_x = \varepsilon_y$

Poisson's ratio

$$\nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z}$$



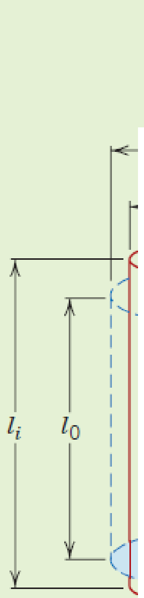
For isotropic materials, shear and elastic moduli are related to each other:

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

EXAMPLE: **Computation of Load to Produce Specified Diameter Change**

A tensile stress is to be applied along the long axis of a cylindrical brass rod that has a diameter of 10 mm. Determine the magnitude of the load required to produce a 2.5×10^{-3} mm change in diameter if the deformation is entirely elastic.

Solution



d_0: 10mm

$\Delta d_x = 2.5 \times 10^{-3}$ mm

Table 6.1 Room-Temperature Elastic and Shear Moduli and Poisson's Ratio for Various Metal Alloys

	Modulus of Elasticity		Shear Modulus		Poisson's Ratio
Metal Alloy	*GPa*	*10^6 psi*	*GPa*	*10^6 psi*	
Aluminum	69				
Brass	97				
Copper	110				
Magnesium	45				
Nickel	207				
Steel	207				
Titanium					
Tungsten					

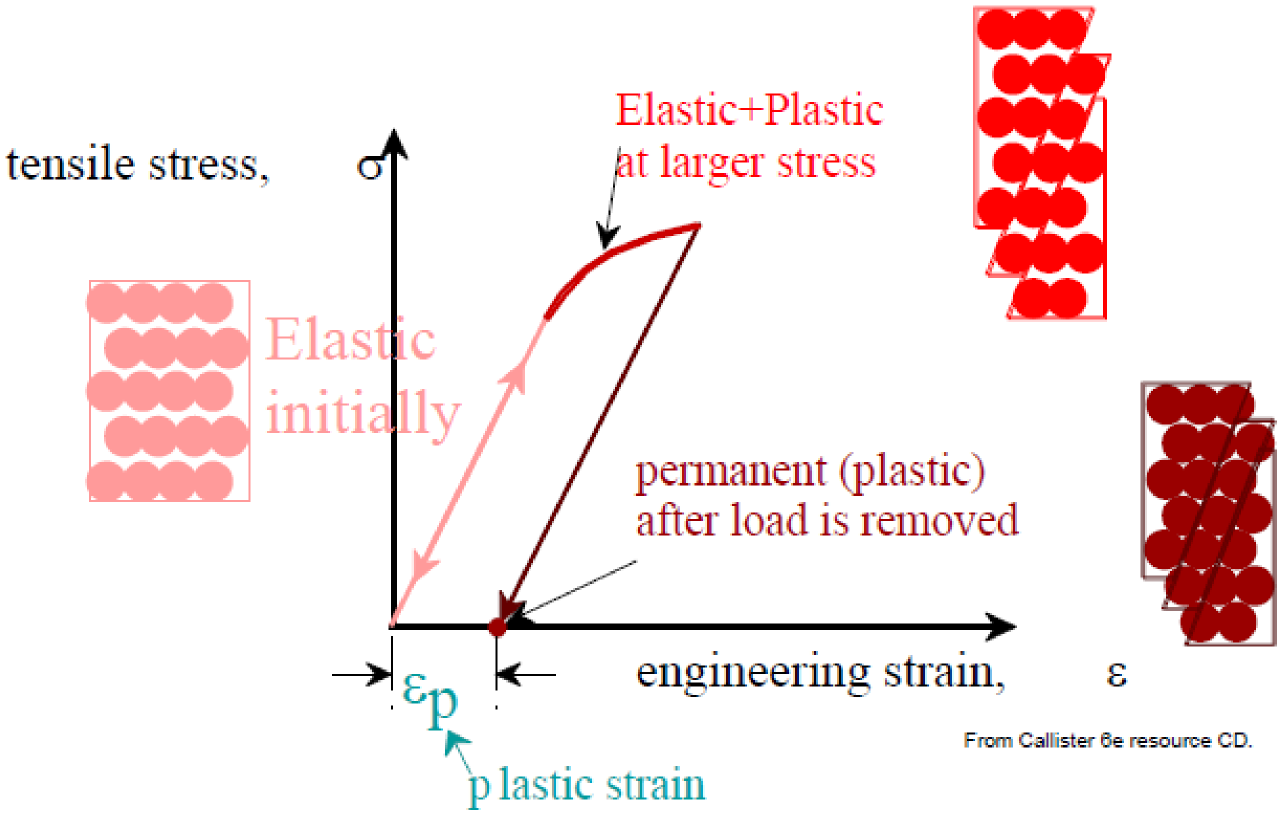
$$F = \sigma A_0 = \sigma \left(\frac{d_0}{2}\right)^2 \pi$$

$$= (71.3 \times 10^6\ \mathrm{N/m^2}) \left(\frac{10 \times 10^{-3}\ \mathrm{m}}{2}\right)^2 \pi$$

F = 5600 N

PLASTIC Deformation

A permanent deformation (upon removal of the stress they do not return to their original positions.**)**



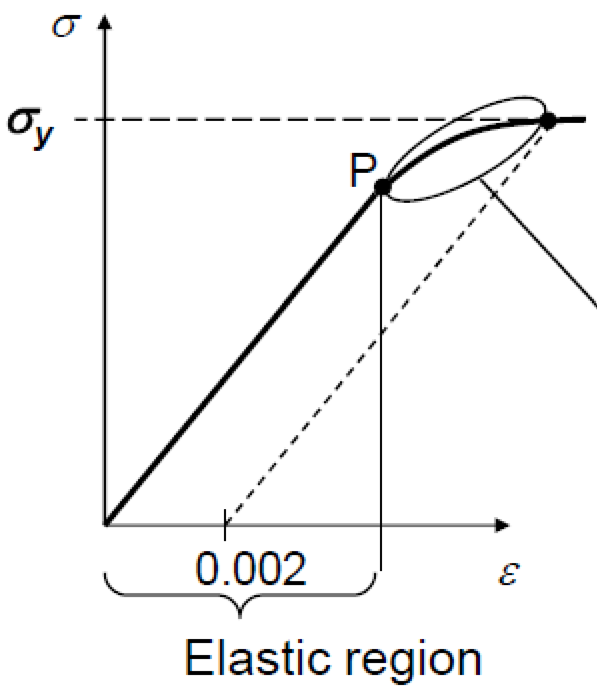
- **Atoms break bonds and form new ones.**
- **In metals, plastic deformation occurs typically at strain ≥0.005.**

PLASTIC Deformation

A. Yield strength (σ_y): ***the strength required to produce*** **a very slight yet specified amount of plastic deformation (**the stress level at which plastic deformation begins**)**

hat is the specified amount of strain?

Strain offset method



1. Start at 0.002 strain (for most metals).
2. Draw a line parallel to the linear region.
3. σ_y = where the dotted line crosses the stress-strain curve.

P = proportional limit (beginning of deviation from linear behavior.

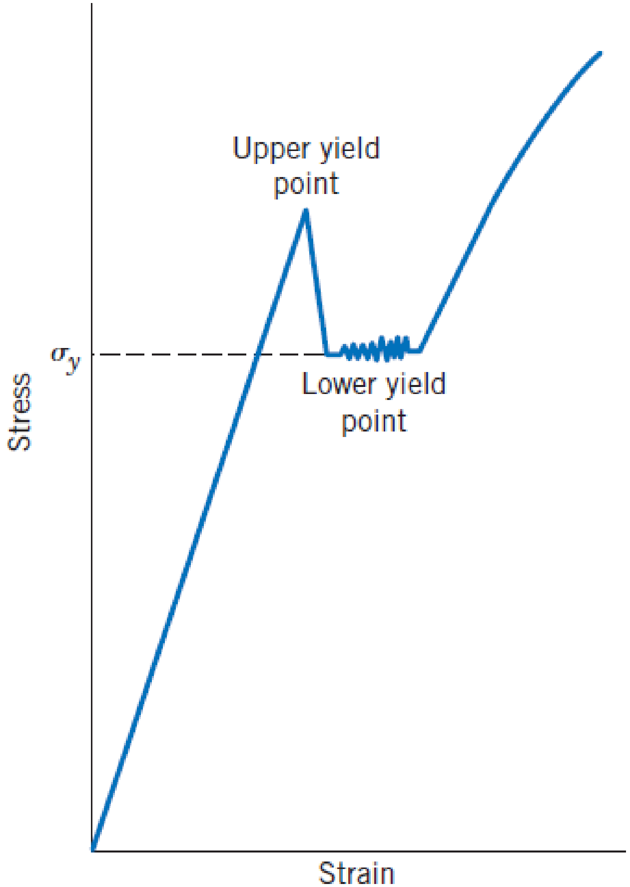
Mixed elastic-plastic behavior

For materials with nonlinear elastic region: σ_y is defined as stress required to produce specific amount of strain (e.g. ~0.005 for most metals).

PLASTIC Deformation

A. Yield strength (σ_y):

***Yield point phenomenon** occurs when elastic-plastic transition is well-defined and abrupt. (e.i.* Some steels and ot



offset methods required here!!!

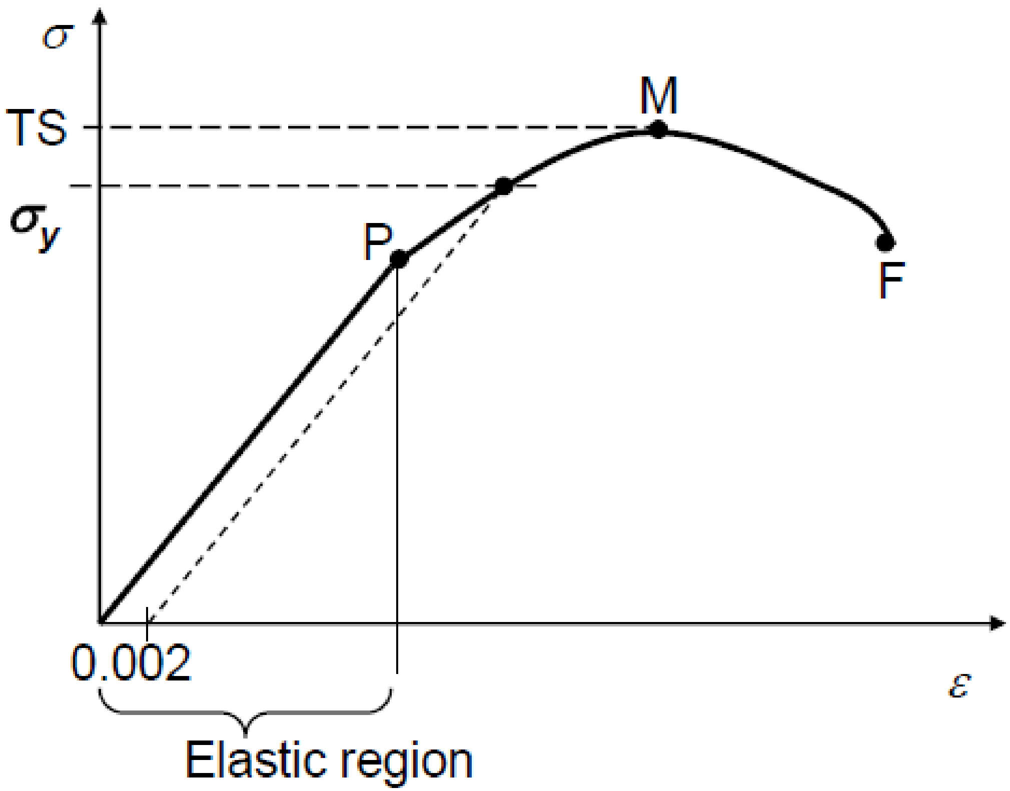
At the upper yield point, plastic deformation
is initiated with an apparent decrease in engineering stress. Continued deformation fluctuates slightly about some constant stress value, termed the lower yield point; stress subsequently rises with increasing strain.

- ***if σ_y is high, material is resistant to plastic deformation***

For metals:
35 MPa – 1400 MPa

PLASTIC Deformation

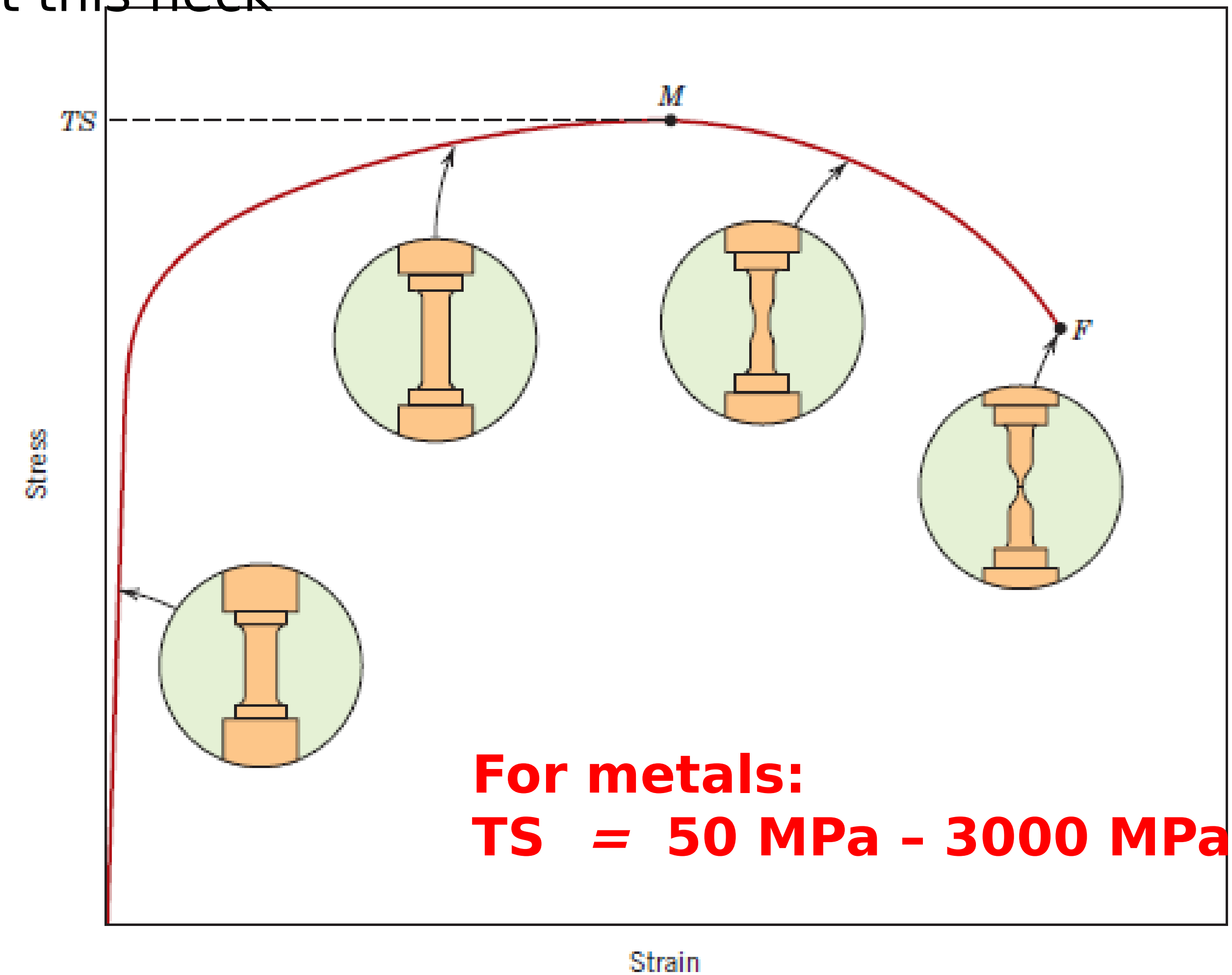
B. Tensile Strength (TS): stress at the maximum of stress-strain curve. (the maximum stress that can be sustained by a structure in tension)



P = proportional limit
σ_y = yield strength
TS = tensile strength
M = max. stress
F = fracture point

PLASTIC Deformation

Necking: at this maximum stress, a small constriction or neck begins to form at some point, and all subsequent deformation is confined at this neck



For metals:
TS = 50 MPa – 3000 MPa

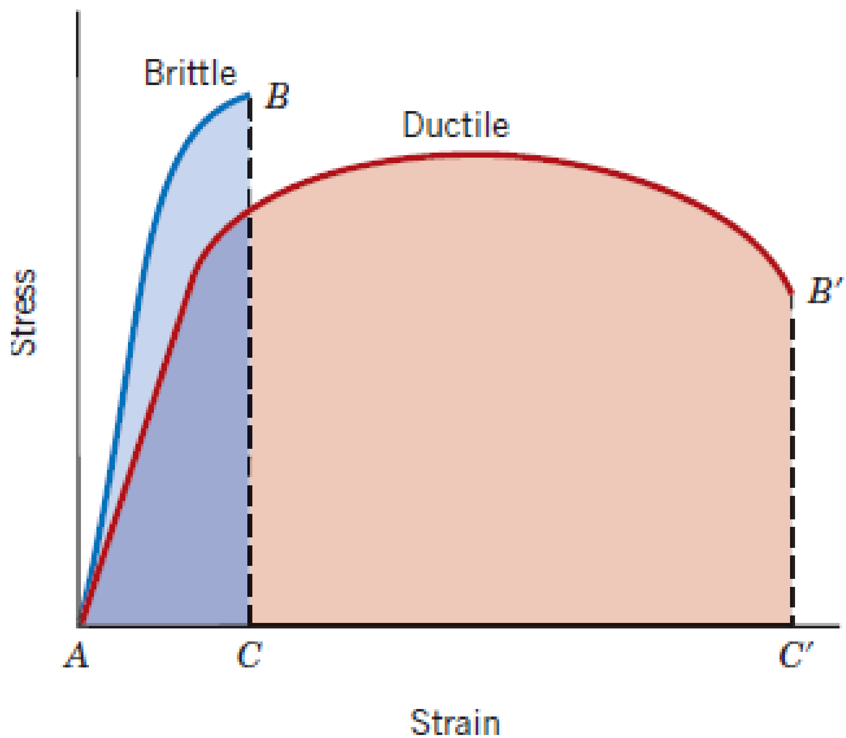
fracture ultimately occurs at the neck

PLASTIC Deformation

C. Ductility: measure of degree of plastic deformation that has been sustained at fracture.

- **<u>Ductile materials</u>** can undergo significant plastic deformation before fracture.

- **Brittle materials** can tolerate only very small plastic



<u>A knowledge of the ductility of materials is important:</u>

1- it indicates to a designer the degree to which a structure will deform plastically before fracture.

2- it specifies the degree of allowable deformation during fabrication operations.

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

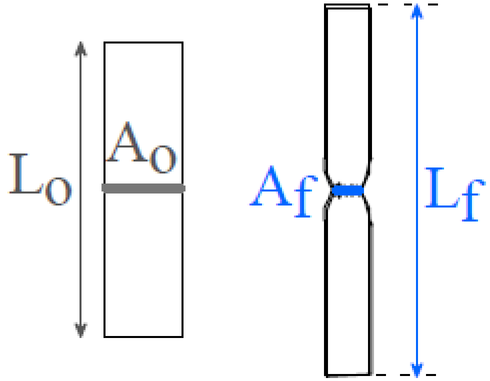
PLASTIC Deformation

Measure of ductility

Ductility may be expressed quantitatively as either *percent elongation or percent reduction in area.*

$$\% \text{ elongation} = \frac{l_f - l_o}{l_o} \times 100\%$$

$$\% \text{ reduction in area} = \frac{A_o - A_f}{A_o} \times 100\%$$



A_o and l_o are initial.
A_f and l_f are at fracture.

- **Note: % AR and % EL are often different.**

--Reason: crystal slip does not change material volume.
--%AR > %EL possible if internal voids form in neck.

Typically, materials are considered: brittle if %EL < 5%

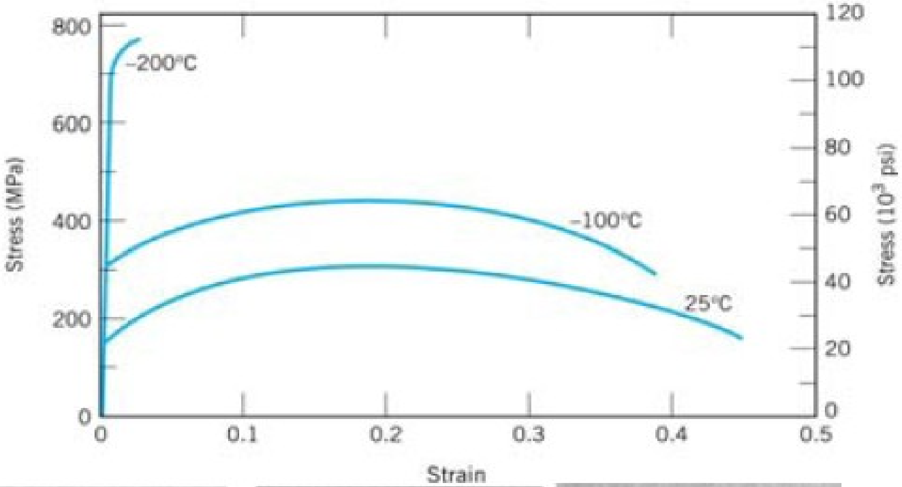
ductile if %EL > 5%

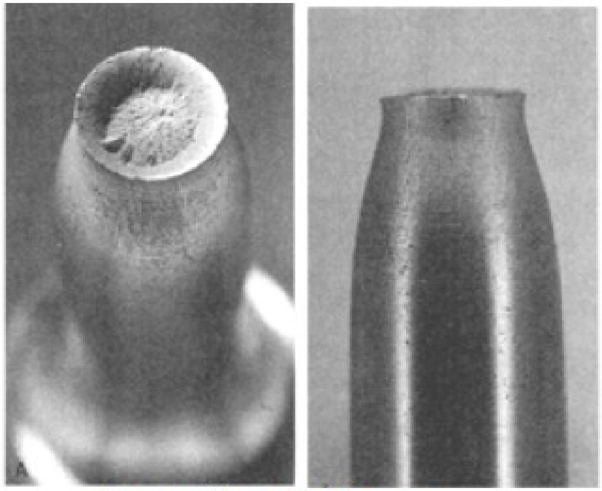
PLASTIC Deformation

C. Ductility:

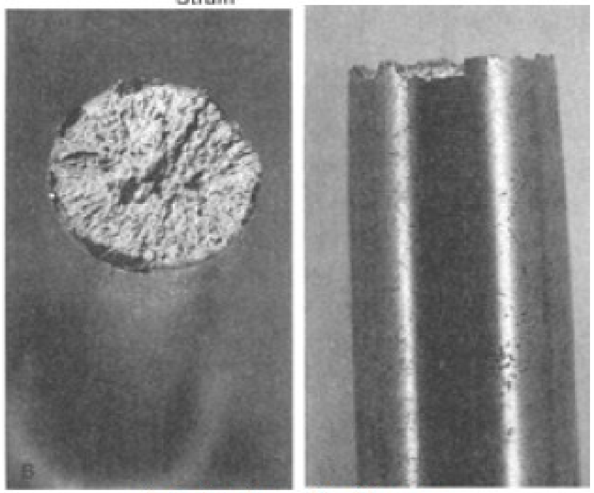
Note: most metals are ductile at RT, but can become brittle at low T

FIGURE 6.14
Engineering stress–strain behavior for iron at three temperatures.





Ductile failure

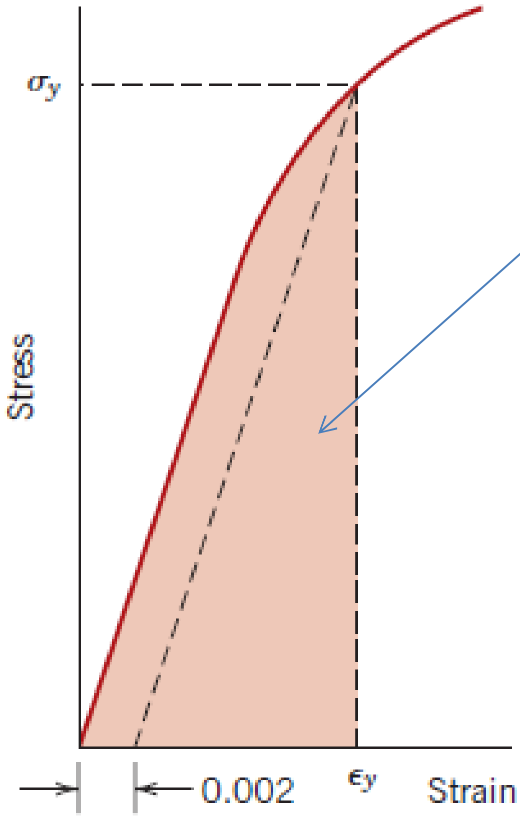


Brittle failure

PLASTIC Deformation

D. Resilience: the capacity to absorb energy when deformed elastically and to have the absorbed energy recovered upon unloading.

U_r= modulus of resilience *(Area under* the elastic



$$U_r = \int_0^{\epsilon_y} \sigma \, d\epsilon$$

J/m³ or Pa

Assuming a linear elastic region,

$$U_r = \frac{1}{2}\sigma_y \epsilon_y = \frac{1}{2}\sigma_y\left(\frac{\sigma_y}{E}\right) = \frac{\sigma_y^2}{2E}$$

Modulus of resilience for linear elastic behavior, and incorporating Hooke's law

Resilient materials have large yield strength and small elastic modulus. *Such alloys would be used in spring applications.*

PLASTIC Deformation

E. Toughness: the ability of a material to absorb energy u

The general are:

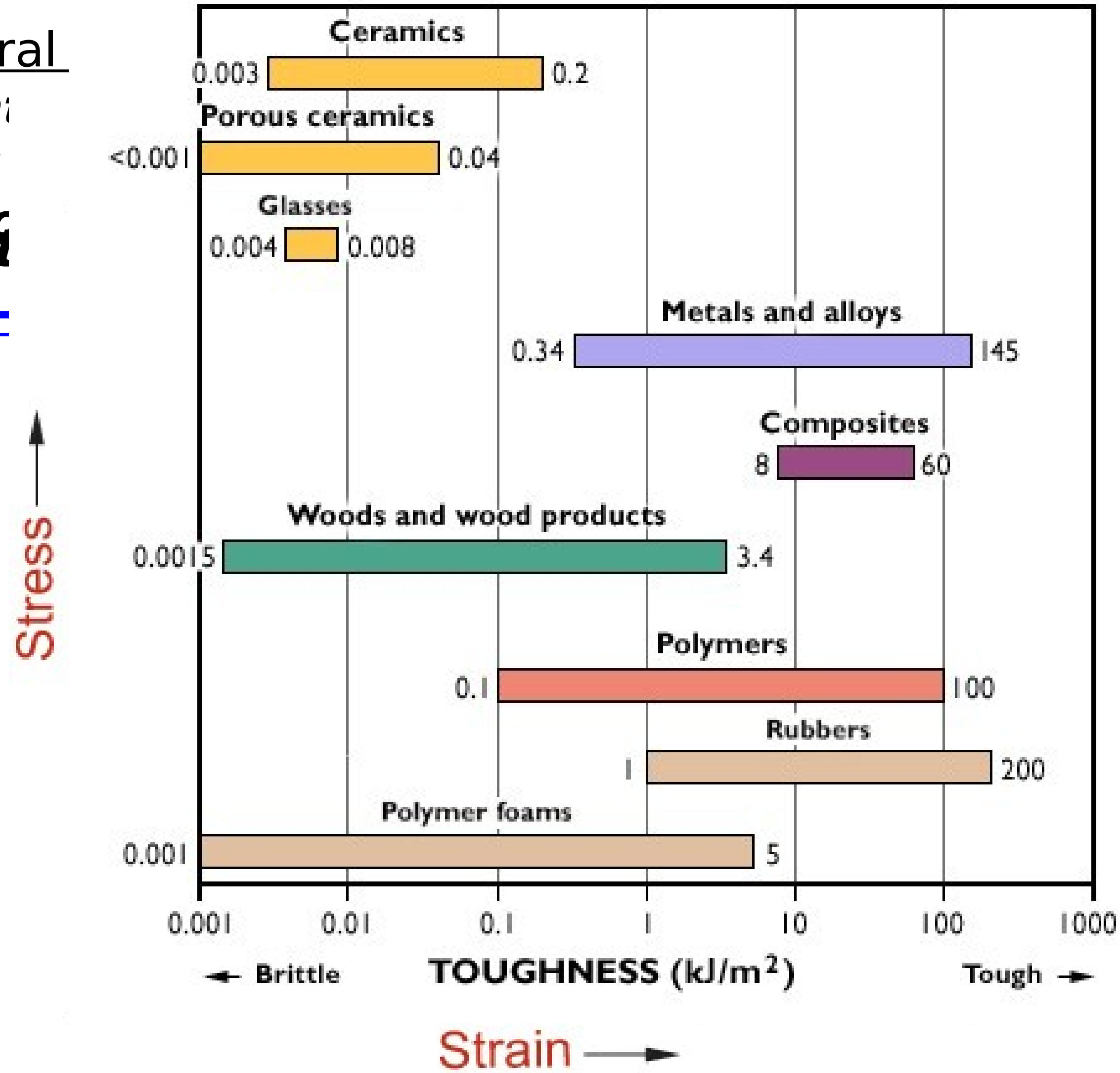
tempera strength and

ductility centration

(notch) c

Fracture t ow the curve

on strain-



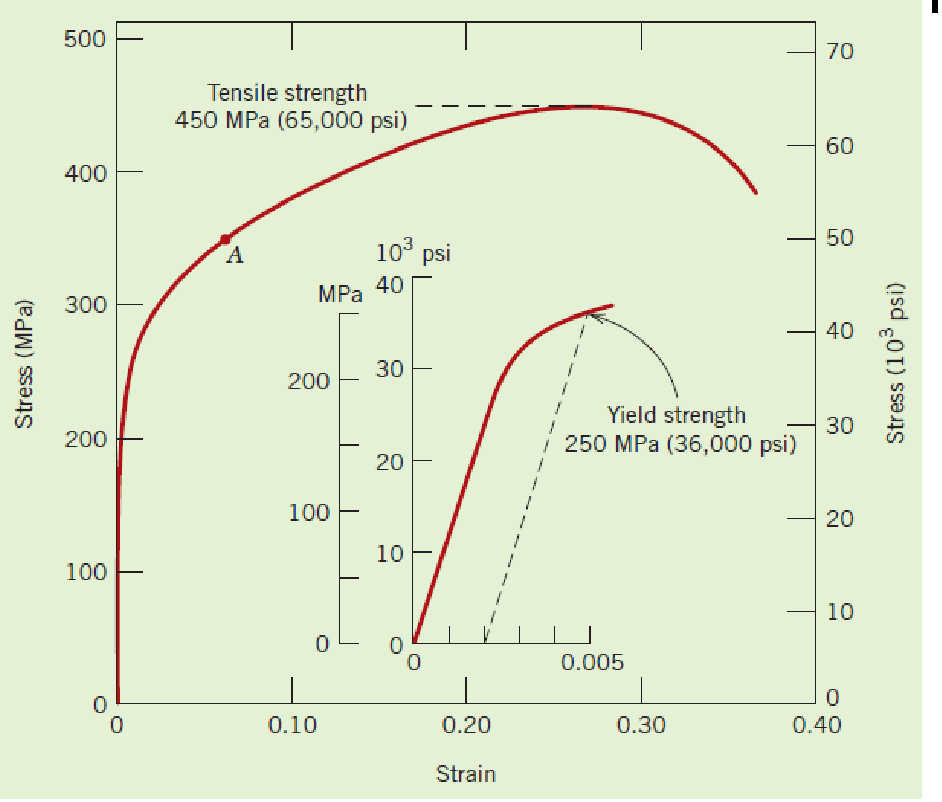
for the brass specimen shown in Figure, determine the following properties:

(a) The modulus of elasticity,

(b) The yield strength at a strain offset of 0.002,

(c) The maximum load that can be sustained by a cylindrical specimen having an original diameter of 12.8 mm,

(d) The change in length of a specimen originally 250 mm long that is subjected to a tensile stress of 345 MPa.



a) $$E = \text{slope} = \frac{\Delta\sigma}{\Delta\epsilon} = \frac{\sigma_2 - \sigma_1}{\epsilon_2 - \epsilon_1}$$ $$E = \frac{(150 - 0)\ \text{MPa}}{0.0016 - 0} = 93.8\ \text{GPa}$$

b) 0.002 strain offset line corresponds to yield strength value of 250 MPa.

c) Maximum stress can be achieved at tensile strength value (450 MPa).

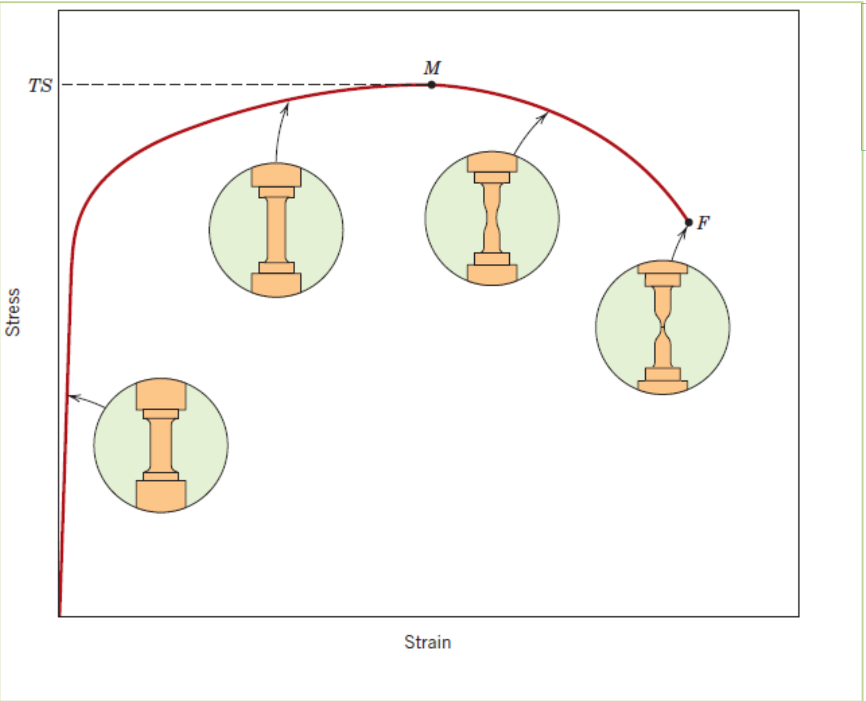
$$F = \sigma A_0 = \sigma\left(\frac{d_0}{2}\right)^2 \pi$$

$$= (450 \times 10^6\ \text{N/m}^2)\left(\frac{12.8 \times 10^{-3}\ \text{m}}{2}\right)^2 \pi = 57{,}900\ \text{N}$$

d) Point A corresponds to the 345 MPa tensile strength value. This corresponds to 0.06 strain value.

$$\Delta l = \epsilon l_0 = (0.06)(250\ \text{mm}) = 15\ \text{mm}$$

TRUE STRESS AND STRAIN



Typical engineering stress–strain behavior to fracture point

the decline in the stress necessary to continue deformation past the maximum, point *M, seems to indicate that the metal is becoming weaker. This* is not at all the case; as a matter of fact, it is increasing in strength.

The cross-sectional area is decreasing rapidly within the neck region.

The engineering stress is based on the original crosssectional area before any deformation and it does not take into account this reduction in area at the neck

$$\sigma = \frac{F}{A_0}$$ **engineering stress**

more meaningful to use a true stress–true strain scheme.

$$\sigma_T = \frac{F}{A_i}$$

$$\epsilon_T = \ln\frac{l_i}{l_0}$$

ε $_T$: true strain

True stress (σ_T) is defined as the load F divided by the instantaneous cross-sectional area A_i over which deformation is occurring.

TRUE STRESS AND STRAIN

If no volume change occurs during deformati $A_i l_i = A_o l_o$
is, if
true and engineering stress and strain are re ***to***

$$\sigma_T = \sigma(1 + \epsilon)$$

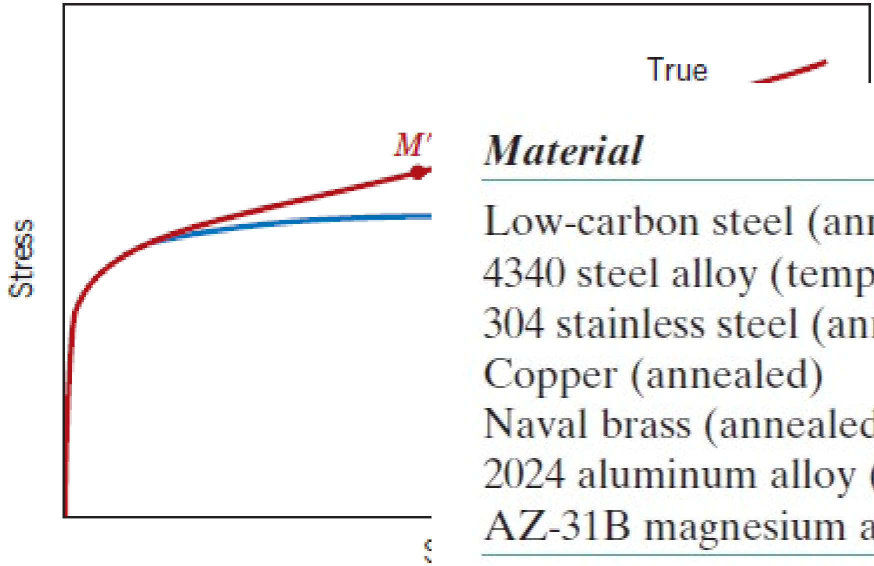
$$\epsilon_T = \ln(1 + \epsilon)$$

True stress–true strain relationship in plastic region of deformation (to point of necking)

$$\sigma_T = K\epsilon_T^n$$

K, n constants
n strain hardening exponent

- valid only to the onset of necking; beyond this point true stress and strain should be computed from actual load, cross-sectional area, and gauge length measurements.

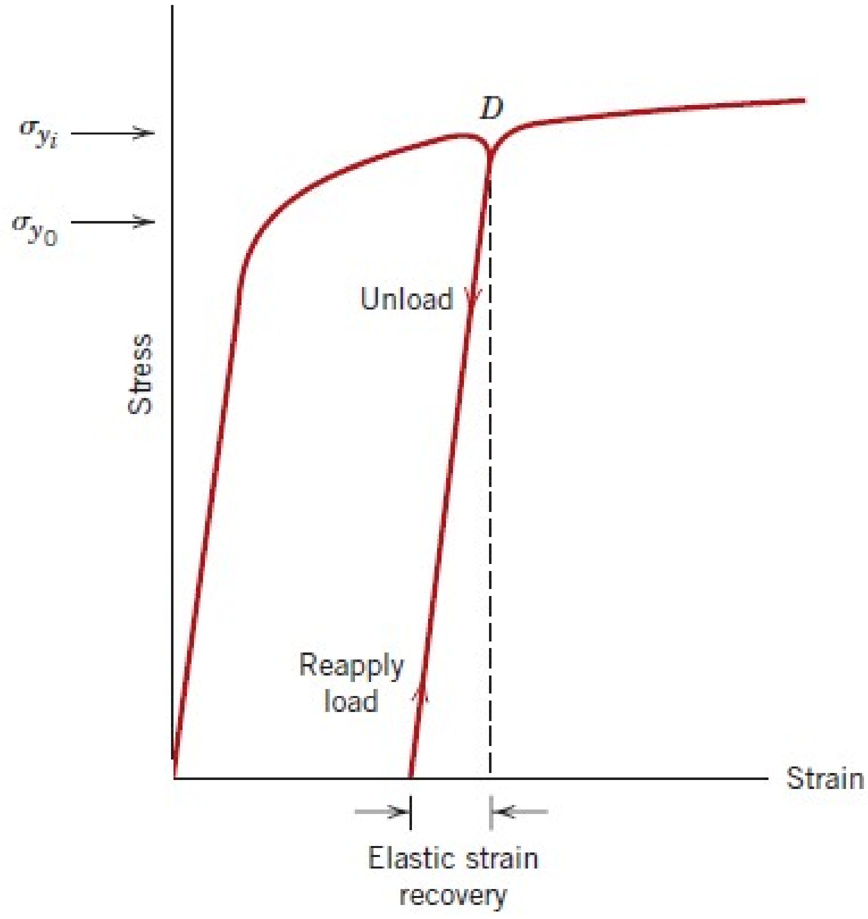


Material	*n*	*K/MPa*
Low-carbon steel (annealed)	0.21	600
4340 steel alloy (tempered @ 315°C)	0.12	2650
304 stainless steel (annealed)	0.44	1400
Copper (annealed)	0.44	530
Naval brass (annealed)	0.21	585
2024 aluminum alloy (heat-treated—T3)	0.17	780
AZ-31B magnesium alloy (annealed)	0.16	450

account the complex stress state

ELASTIC RECOVERY AFTER PLASTIC DEFORMATION

Upon release of the load during the course of a stress–strain test, some fraction of the total deformation is recovered as elastic strain



In plastic deformation region, relasing loading (D)=> the curve traces a near straight-line path from the point of unloading (point D),virtually identical or parallel to the modulus of elasticity curve.

If the load is reapplied, the curve will traverse essentially the same linear portion
in the direction opposite to unloading.

Problem: A cylindrical specimen of steel having an original diameter of 12.8 mm is tensile-tested to fracture and found to have an engineering fracture strength of 460 MPa. If its cross-sectional diameter at fracture is 10.7 mm, determine:

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

(b) The true stress at fracture.

(a)

$$\%\text{RA} = \frac{\left(\dfrac{12.8\text{ mm}}{2}\right)^2\pi - \left(\dfrac{10.7\text{ mm}}{2}\right)^2\pi}{\left(\dfrac{12.8\text{ mm}}{2}\right)^2\pi} \times 100$$

$$= \frac{128.7\text{ mm}^2 - 89.9\text{ mm}^2}{128.7\text{ mm}^2} \times 100 = 30\%$$

b)

$$F = \sigma_f A_0 = (460 \times 10^6\ \text{N/m}^2)(128.7\ \text{mm}^2)\left(\frac{1\ \text{m}^2}{10^6\ \text{mm}^2}\right) = 59{,}200\ \text{N}$$

$$\sigma_T = \frac{F}{A_f} = \frac{59{,}200\ \text{N}}{(89.9\ \text{mm}^2)\left(\frac{1\ \text{m}^2}{10^6\ \text{mm}^2}\right)}$$

$$= 6.6 \times 10^8\ \text{N/m}^2 = 660\ \text{MPa}$$

Problem: Compute the strain-hardening exponent *n* for an alloy in which a true stress of 415 MPa produces a true strain of 0.10; assume a value of 1035 MPa for *K*.

$$\sigma_T = K\epsilon_T^n$$

$$n = \frac{\log \sigma_T - \log K}{\log \epsilon_T}$$

$$= \frac{\log(415\ \text{MPa}) - \log(1035\ \text{MPa})}{\log(0.1)} = 0.40$$

PROPERTIES OBTAINED FROM THE TENSILE TEST

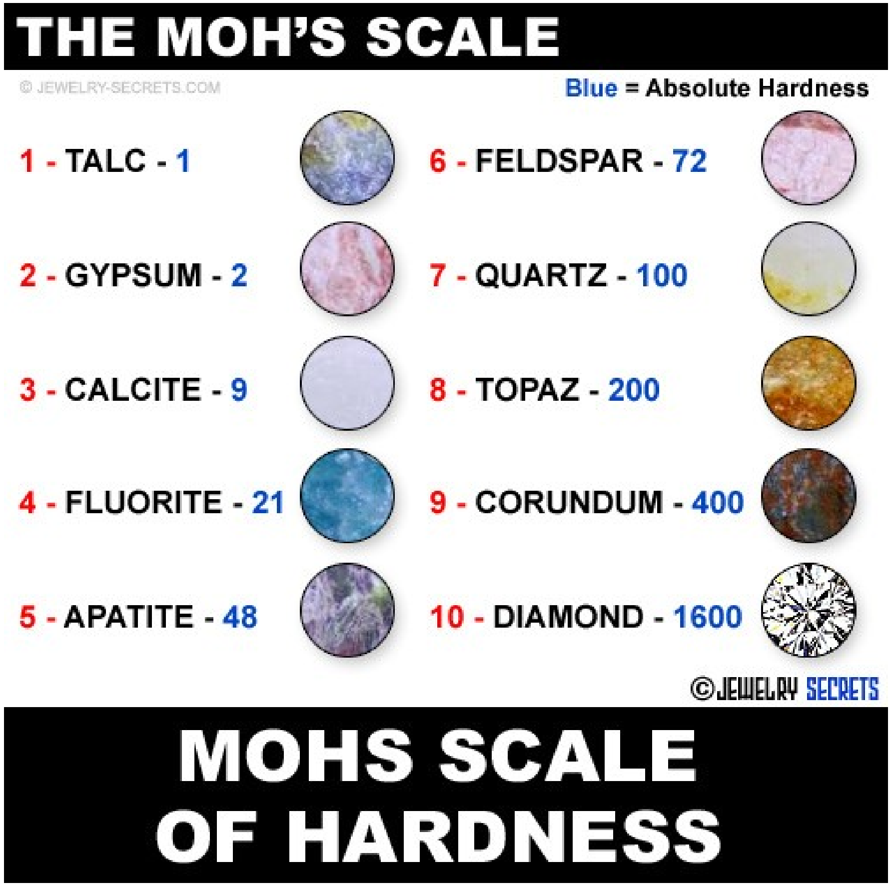
- ✓ Yield Strength
- ✓ Elastic Limit
- ✓ Tensile Strength, Necking
- ✓ Hooke’s Law
- ✓ Poisson’s Ratio
- ✓ Young’s Modulus (Modulus of Elasticity)
- ✓ Resilience
- ✓ Toughness

HARDNESS

Hardness: measure of a material's resistance to localized plastic deformation (e.g., a small dent or a scratch)

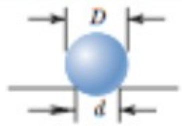
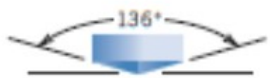
Early hardness tests were based on natural minerals with a scale constructed solely on the ability of one material to scratch another that was softer.

The Mohs Scale was developed by the German geologist Friedrich Mohs in 1812 and describe the hardness of a given mineral or gemstone.
Diamond was, at the time, the hardest material known to exist so is at the top of the list, with Talc being at the bottom.



Summary of hardness testing methods

Table 6.5 Hardness-Testing Techniques

Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid	 $l/b = 7.11$ $b/t = 4.00$		P	$HK = 14.2P/l^2$
Rockwell and superficial Rockwell	Diamond cone; $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ in diameter steel spheres				…ell

[a]For the hardness formulas given, P (…

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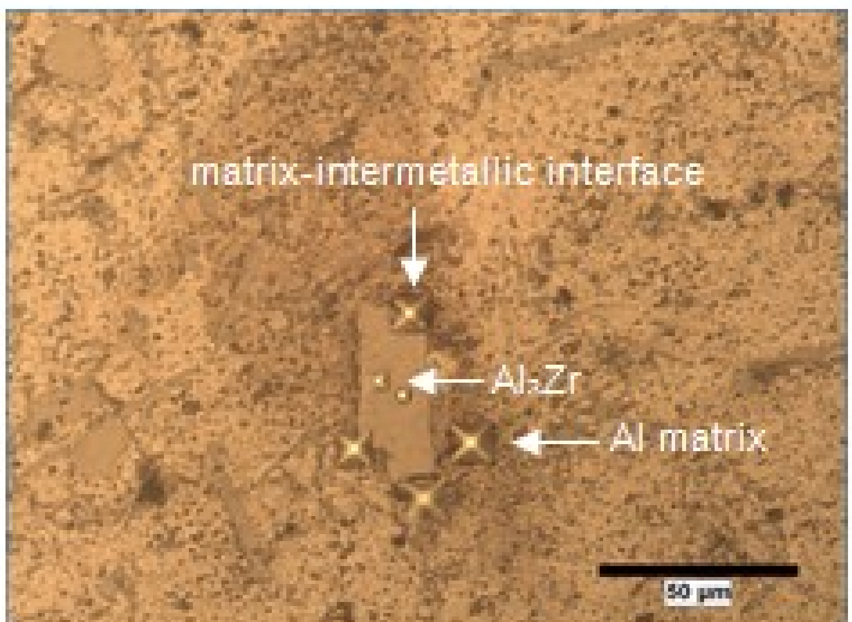

Comparison of several hardness scales.