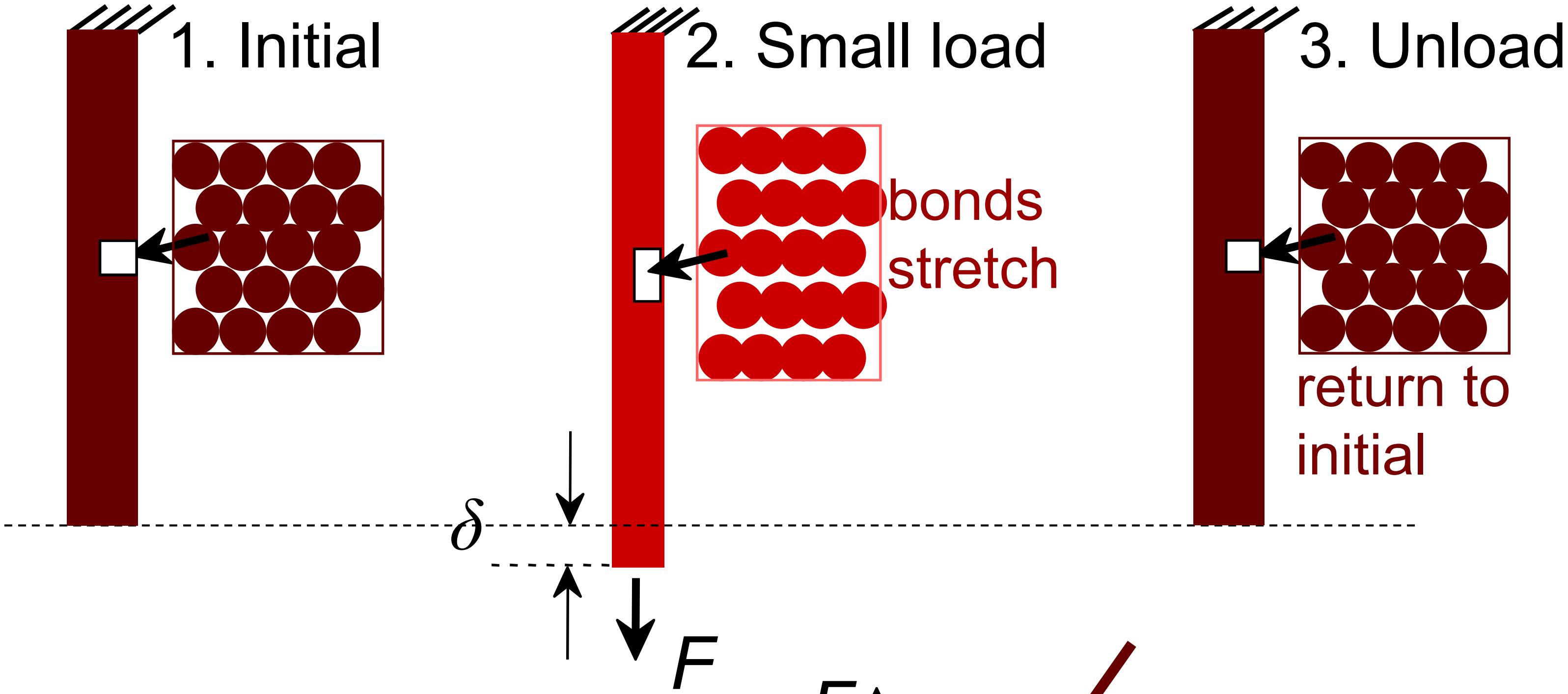
Chapter 8:
Mechanical Properties of Metals

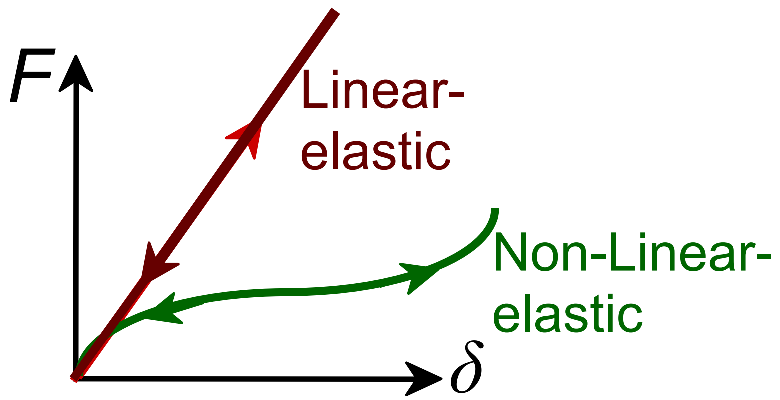
ISSUES TO ADDRESS...

- Stress and strain: What are they and why are they used instead of load and deformation?
- Elastic behavior: When loads are small, how much deformation occurs? What materials deform least?
- Plastic behavior: At what point does permanent deformation occur? What materials are most resistant to permanent deformation?
- Toughness and ductility: What are they and how do we measure them?

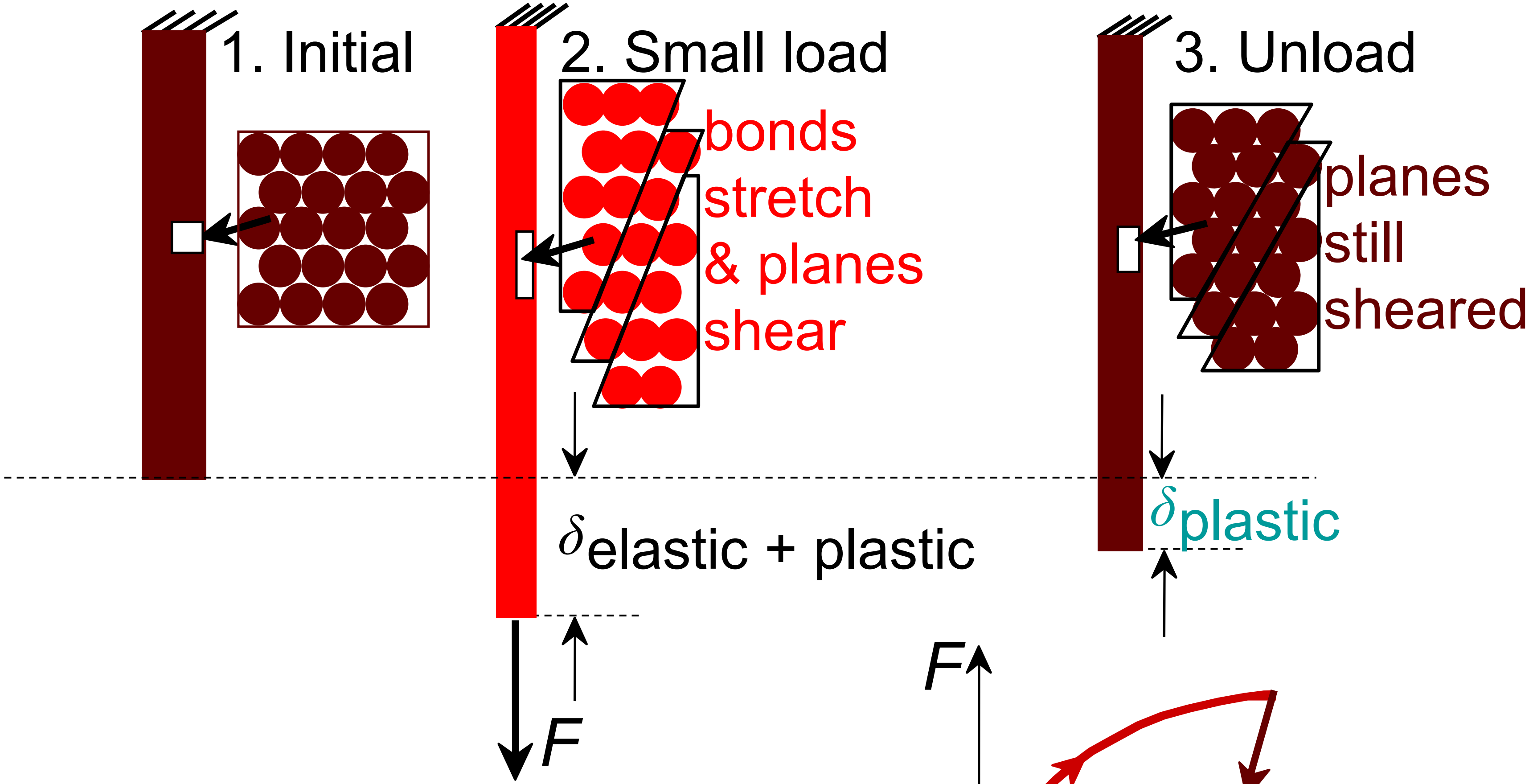
Elastic Deformation



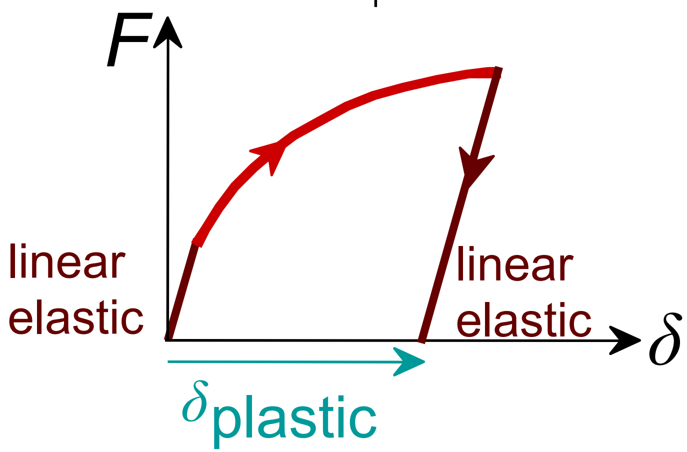
Elastic means reversible!



Plastic Deformation (Metals)

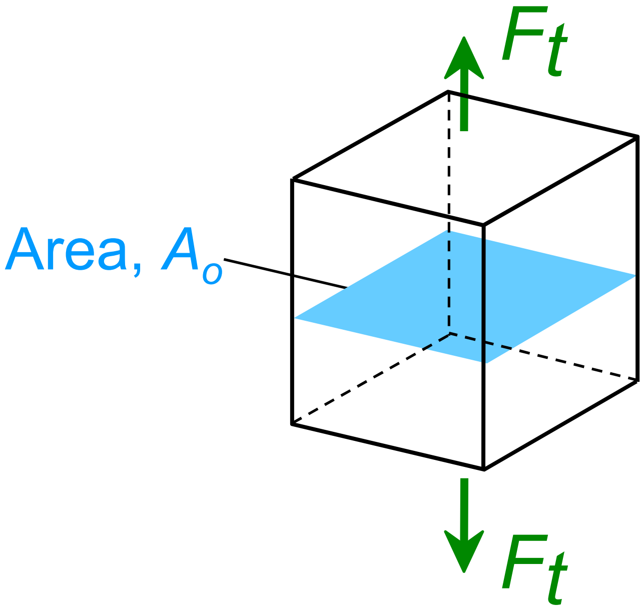


Plastic means permanent!



Engineering Stress

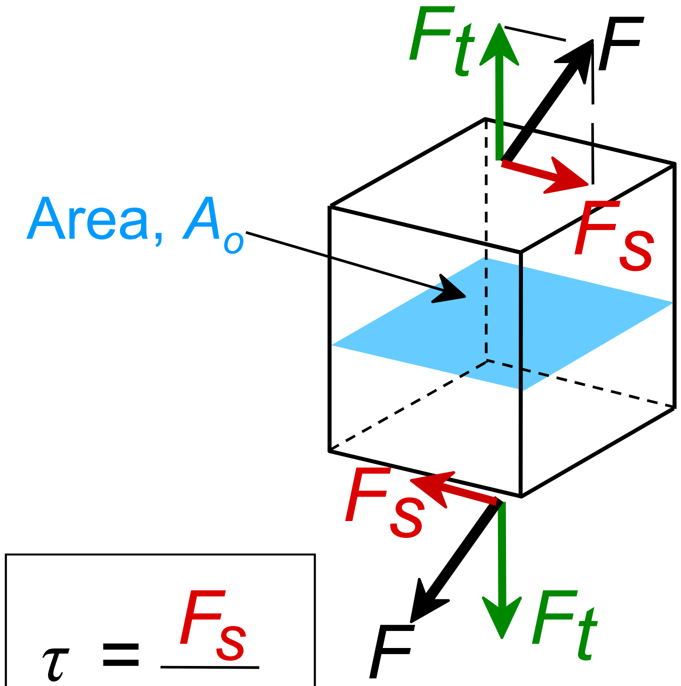
- Tensile stress, σ:



$$\sigma = \frac{F_t}{A_o} = \frac{\text{N}}{\text{m}^2}$$

original cross-sectional area before loading

- Shear stress, τ:

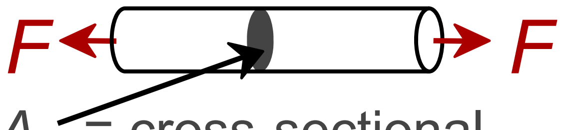


$$\tau = \frac{F_s}{A_o}$$

$\therefore$ Stress has units: N/m^2

Common States of Stress

- **Simple tension: cable**

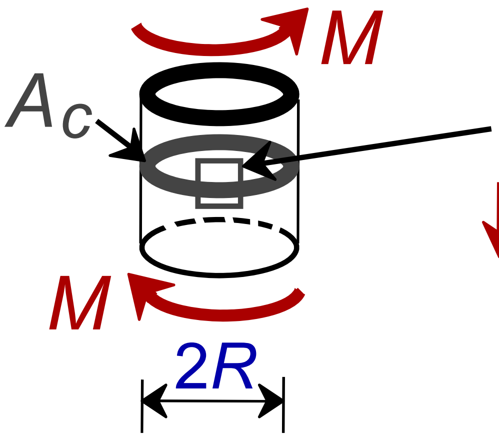


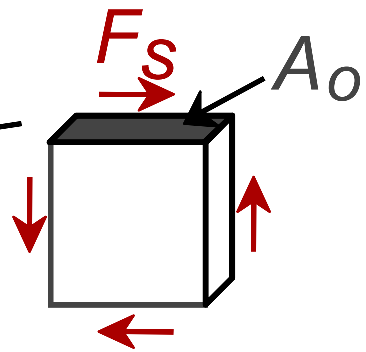
A_o = cross-sectional area (when unloaded)

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

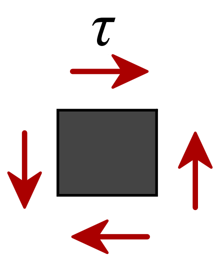
Ski lift (photo courtesy P.M. Anderson)

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



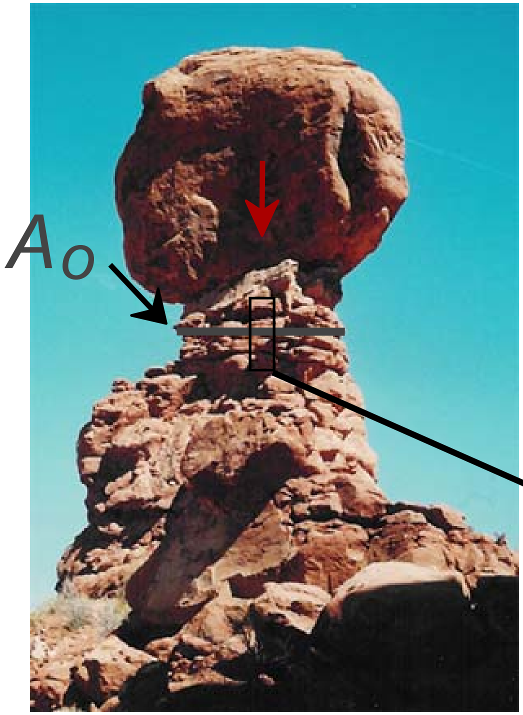


$$\tau = \frac{F_s}{A_o}$$



OTHER COMMON STRESS STATES (i)

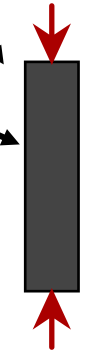
- **Simple compression:**



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

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

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



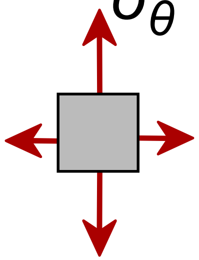
Note: compressive structure member ($\sigma < 0$ here).

OTHER COMMON STRESS STATES (ii)

- **Bi-axial tension:**

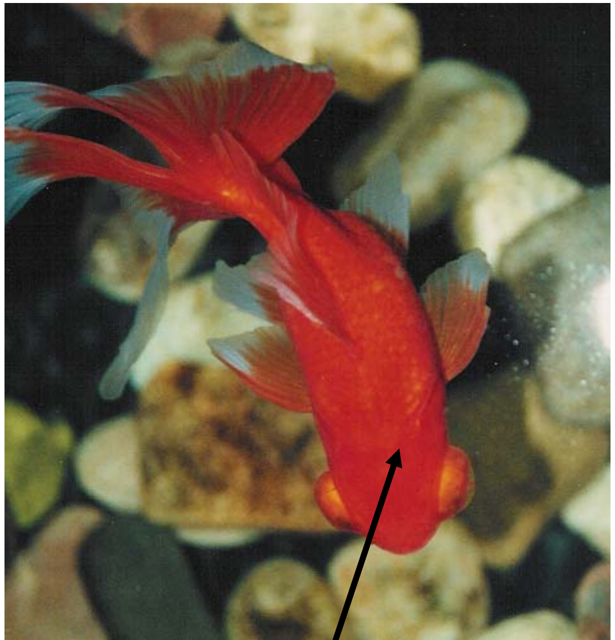
Pressurized tank
(photo courtesy
P.M. Anderson)

$\sigma_\theta > 0$



$\sigma_z > 0$

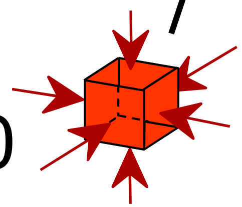
- **Hydrostatic compression:**



Fish under water

(photo courtesy
P.M. Anderson)

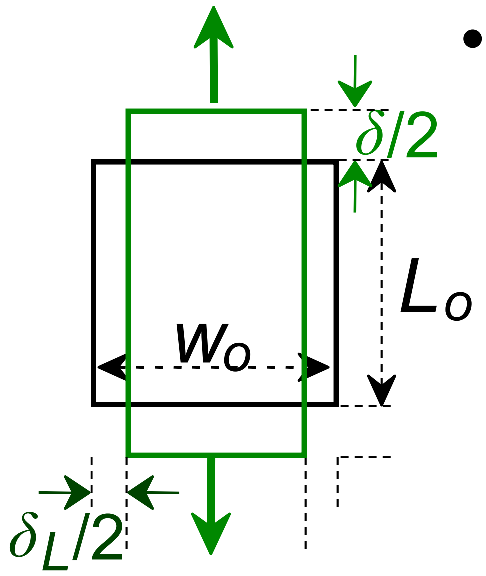
$\sigma_h < 0$



Engineering Strain

- **Tensile strain:**

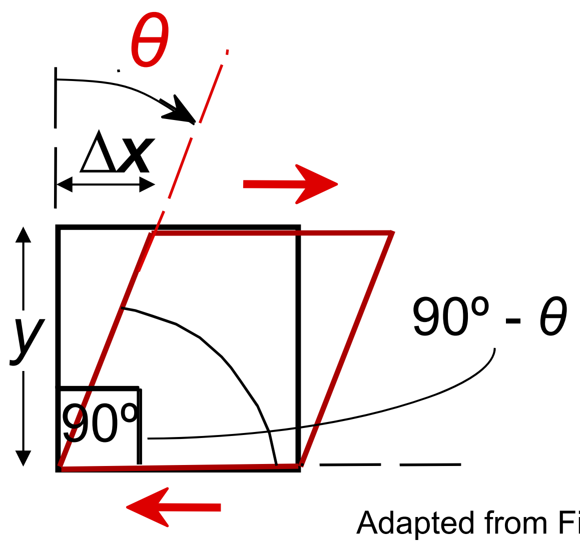
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain:**

$$\varepsilon_L = \frac{-\delta_L}{w_o}$$

- **Shear strain:**



$$\gamma = \Delta x / y = \tan\theta$$

Strain is always dimensionless.

Adapted from Fig. 8.1 (a) and (c), *Callister & Rethwisch 9e.*

Stress-Strain Testing

• **Typical tensile test machine**

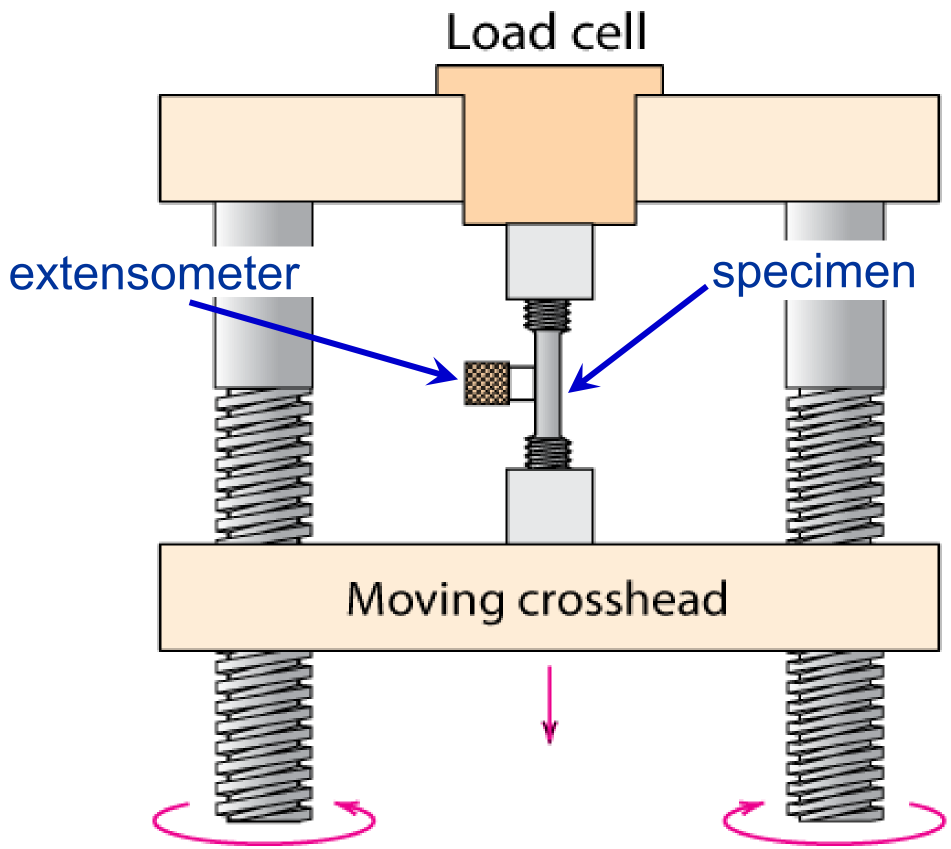


Fig. 8.3, *Callister & Rethwisch 9e.*
(Taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)

• **Typical tensile specimen**

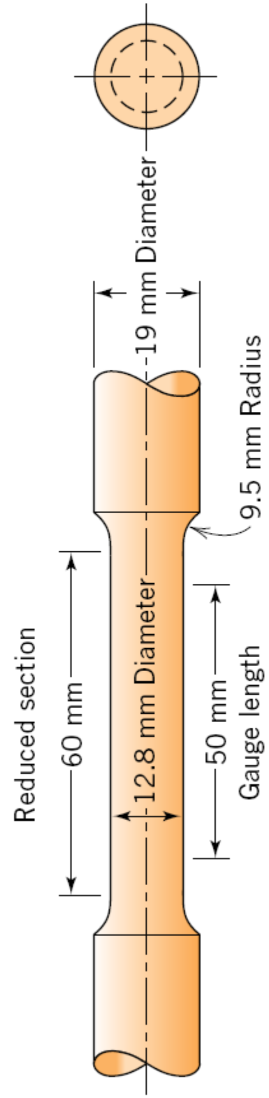


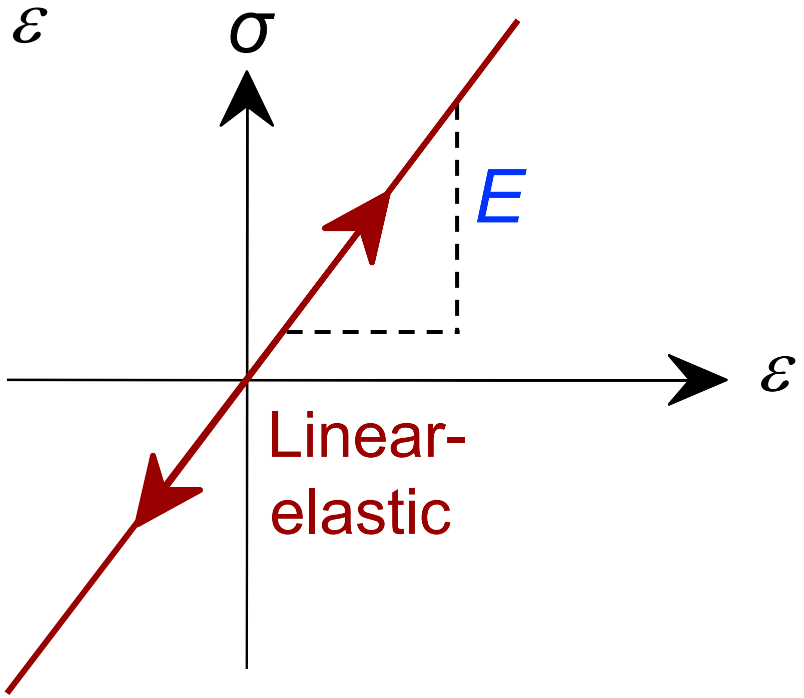
Fig. 8.2, *Callister & Rethwisch 9e.*

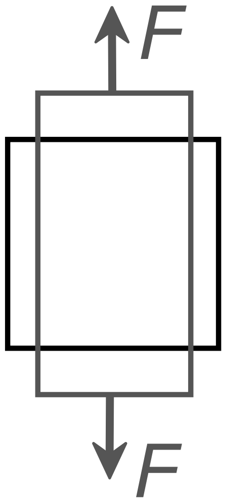
Linear Elastic Properties

- **Modulus of Elasticity, *E*:**
  (also known as Young's modulus)

- **Hooke's Law:**

$$\sigma = E\,\varepsilon$$



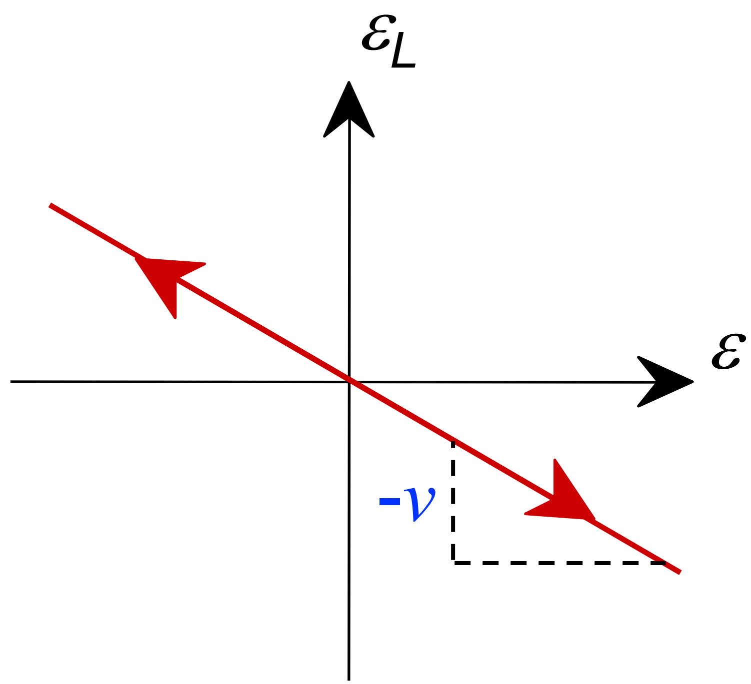


Poisson's ratio, ν

• Poisson's ratio, ν:

Ratio between radial and axial strains

$$\nu = - \frac{\varepsilon_L}{\varepsilon}$$



metals: $\nu \sim 0.33$

ceramics: $\nu \sim 0.25$

polymers: $\nu \sim 0.40$

Units:
E: [GPa] or [psi]
ν: dimensionless

$\nu > 0.50$ density increases

$\nu = 0.50$ no volume change

$\nu < 0.50$ density decreases (voids form)

Mechanical Properties

- Slope of stress strain plot (which is proportional to the elastic modulus) depends on bond strength of metal

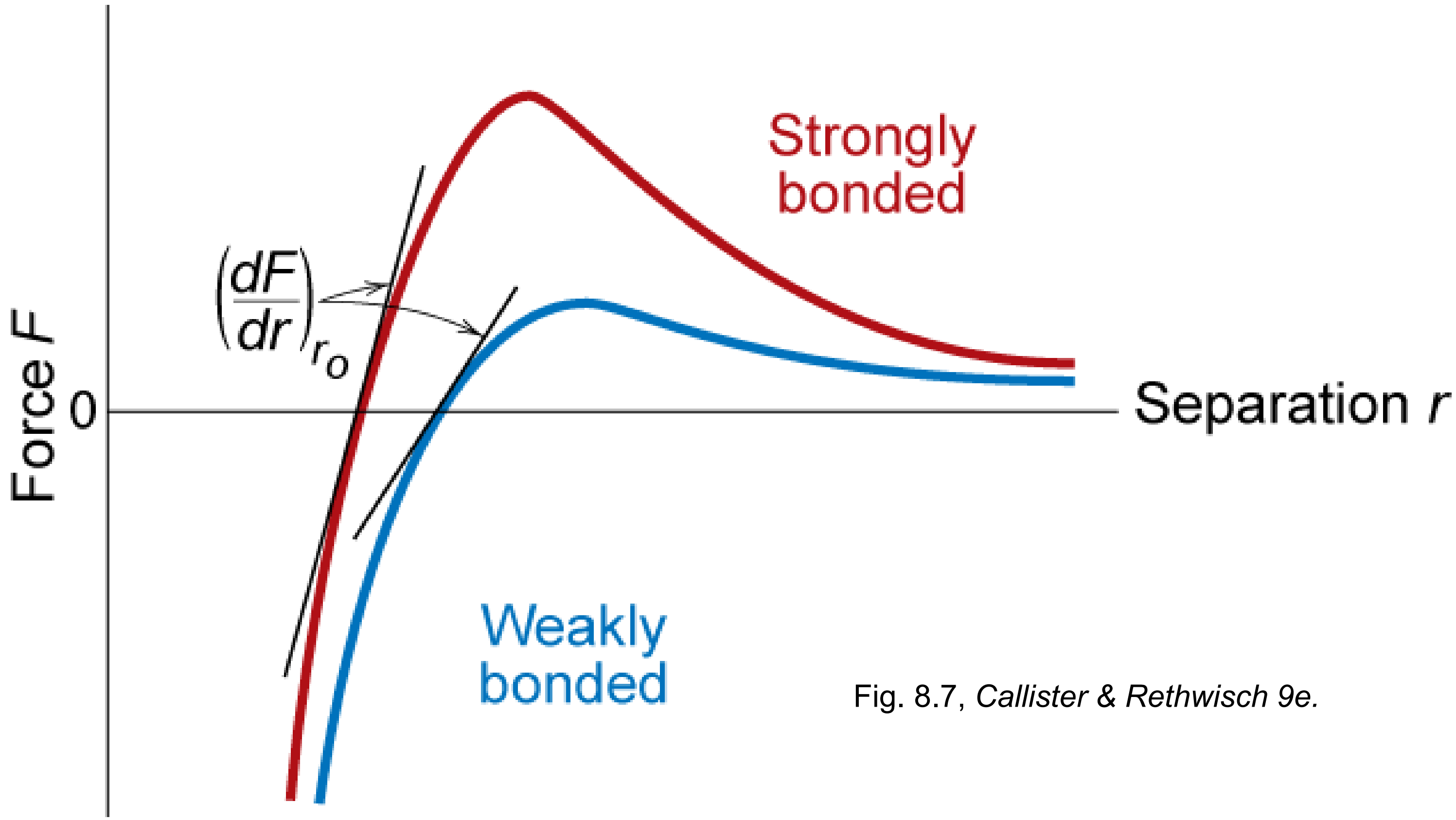
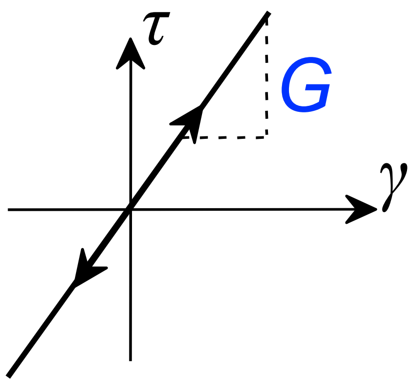


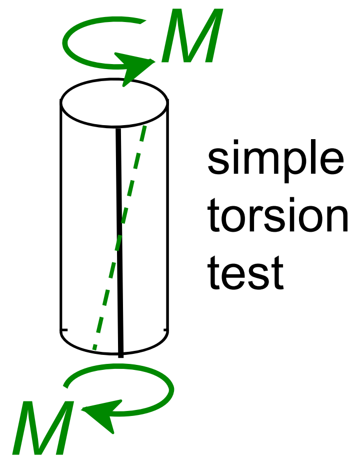
Fig. 8.7, *Callister & Rethwisch 9e.*

Other Elastic Properties

- **Elastic Shear modulus, *G*:**

$$\tau = G\,\gamma$$

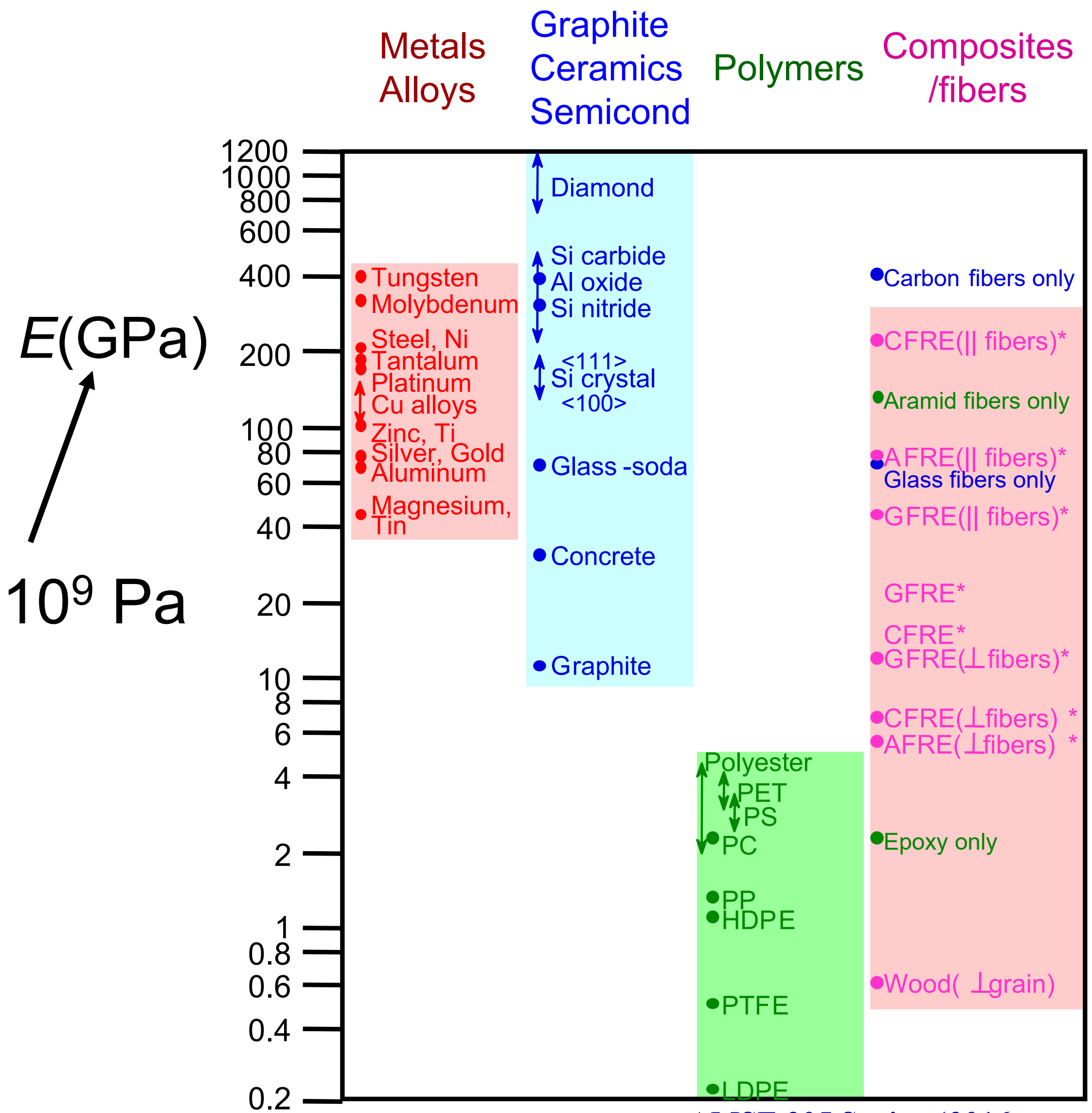




- **Special relations for isotropic materials:**

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

Young's Moduli: Comparison



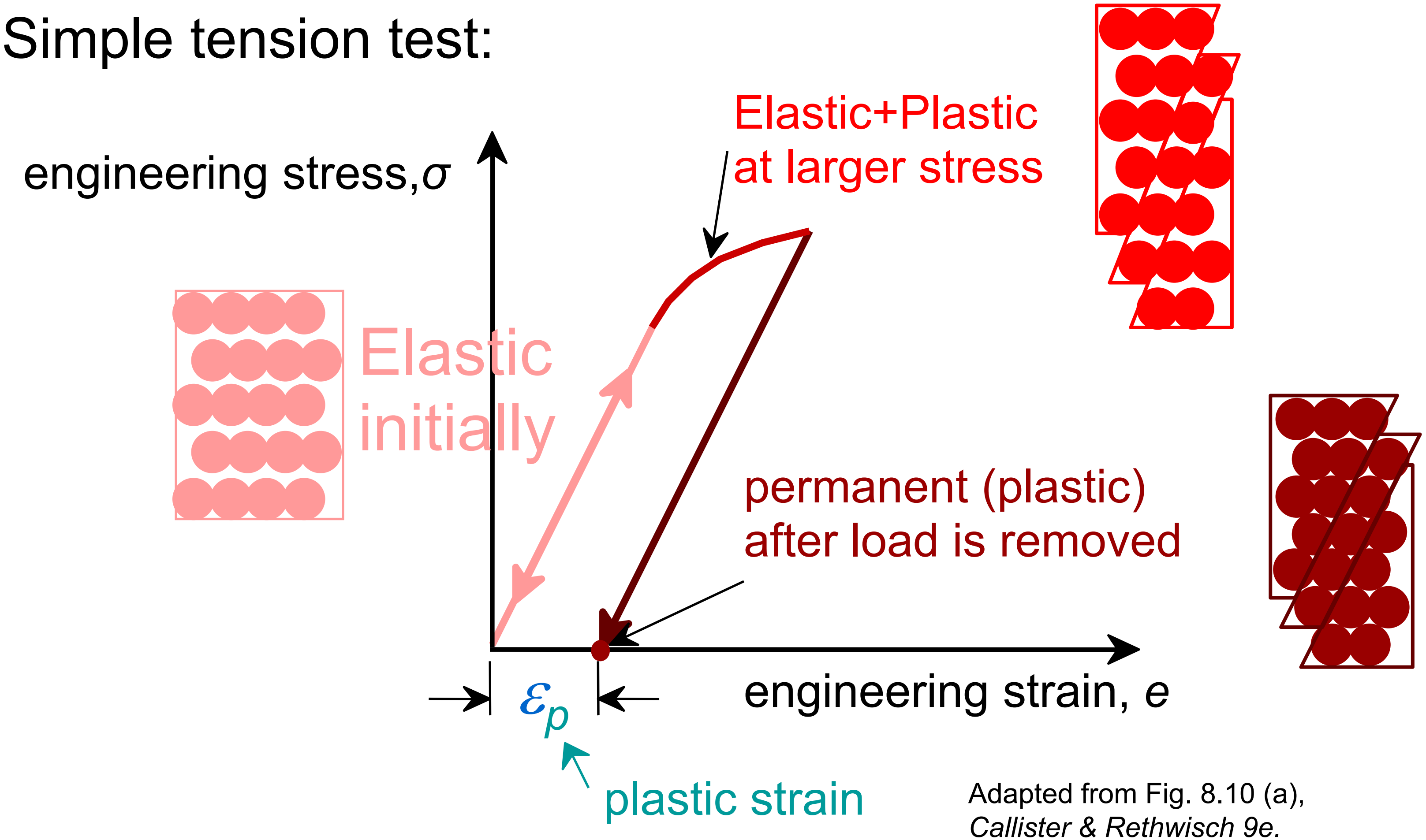
Based on data in Table B.2, *Callister & Rethwisch 9e.*

Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

Plastic (Permanent) Deformation

(at lower temperatures, i.e. $T < T_{melt}/3$)

• Simple tension test:

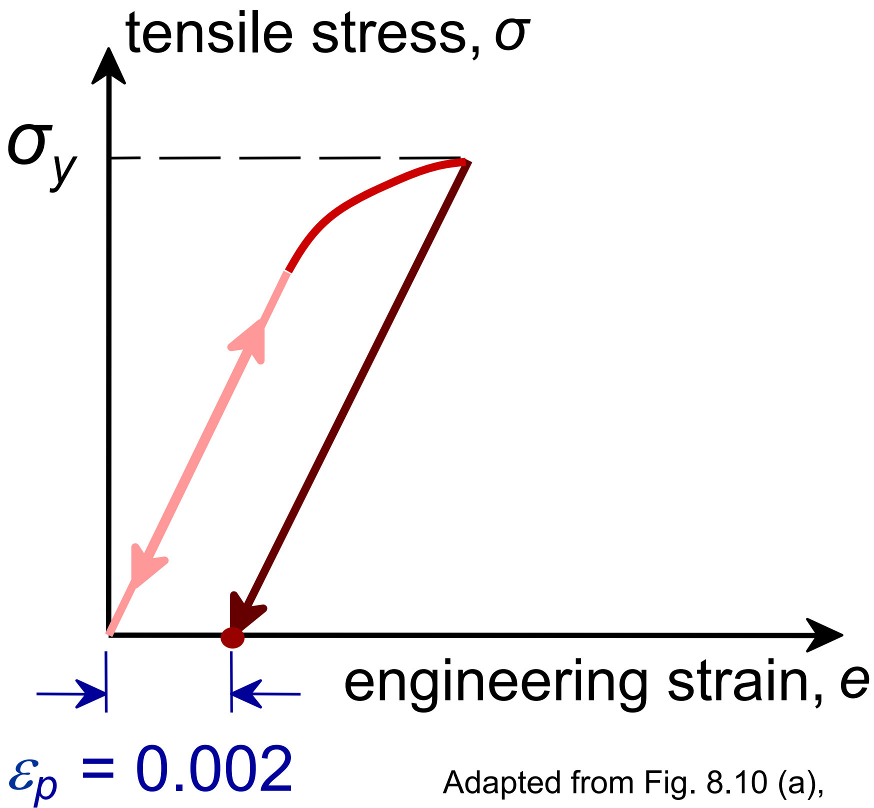


Adapted from Fig. 8.10 (a),
Callister & Rethwisch 9e.

Yield Strength, σ_y

- **Stress at which *noticeable* plastic deformation has occurred.**

when $\varepsilon_p = 0.002$



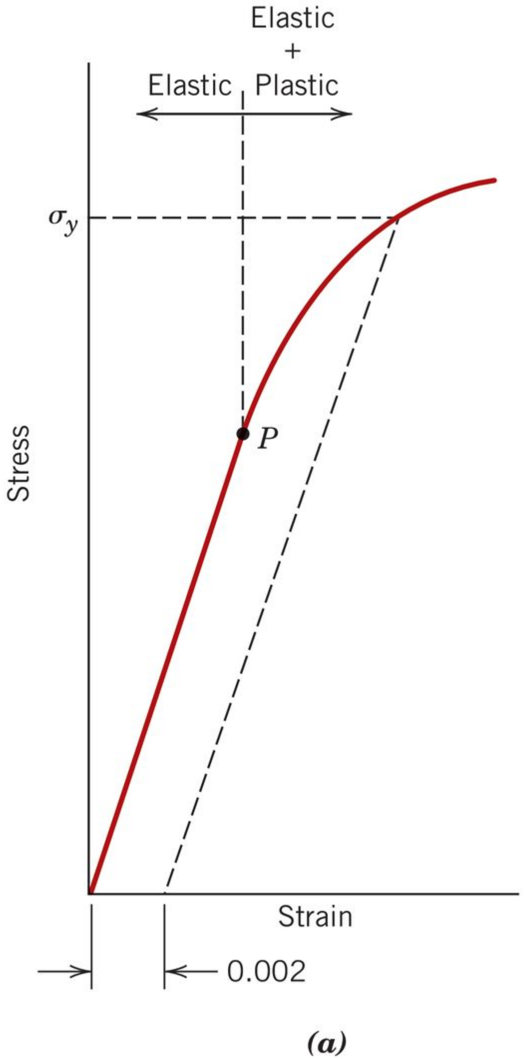
Adapted from Fig. 8.10 (a),
Callister & Rethwisch 9e.

σ_y = yield strength

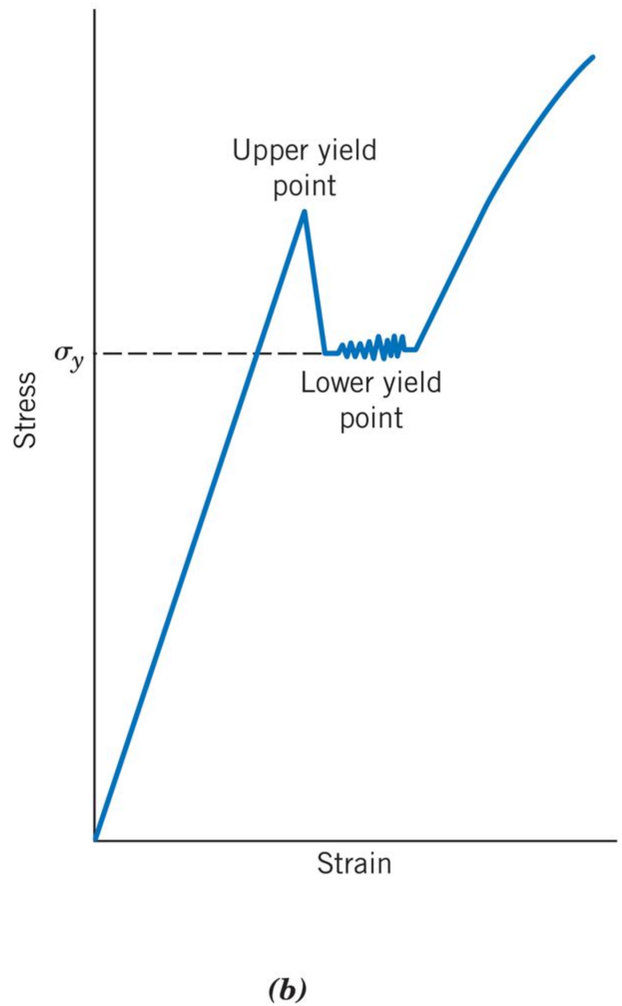
Note: for 2 inch sample

$\varepsilon = 0.002 = \Delta z/z$

$\therefore\ \Delta z = 0.004$ in

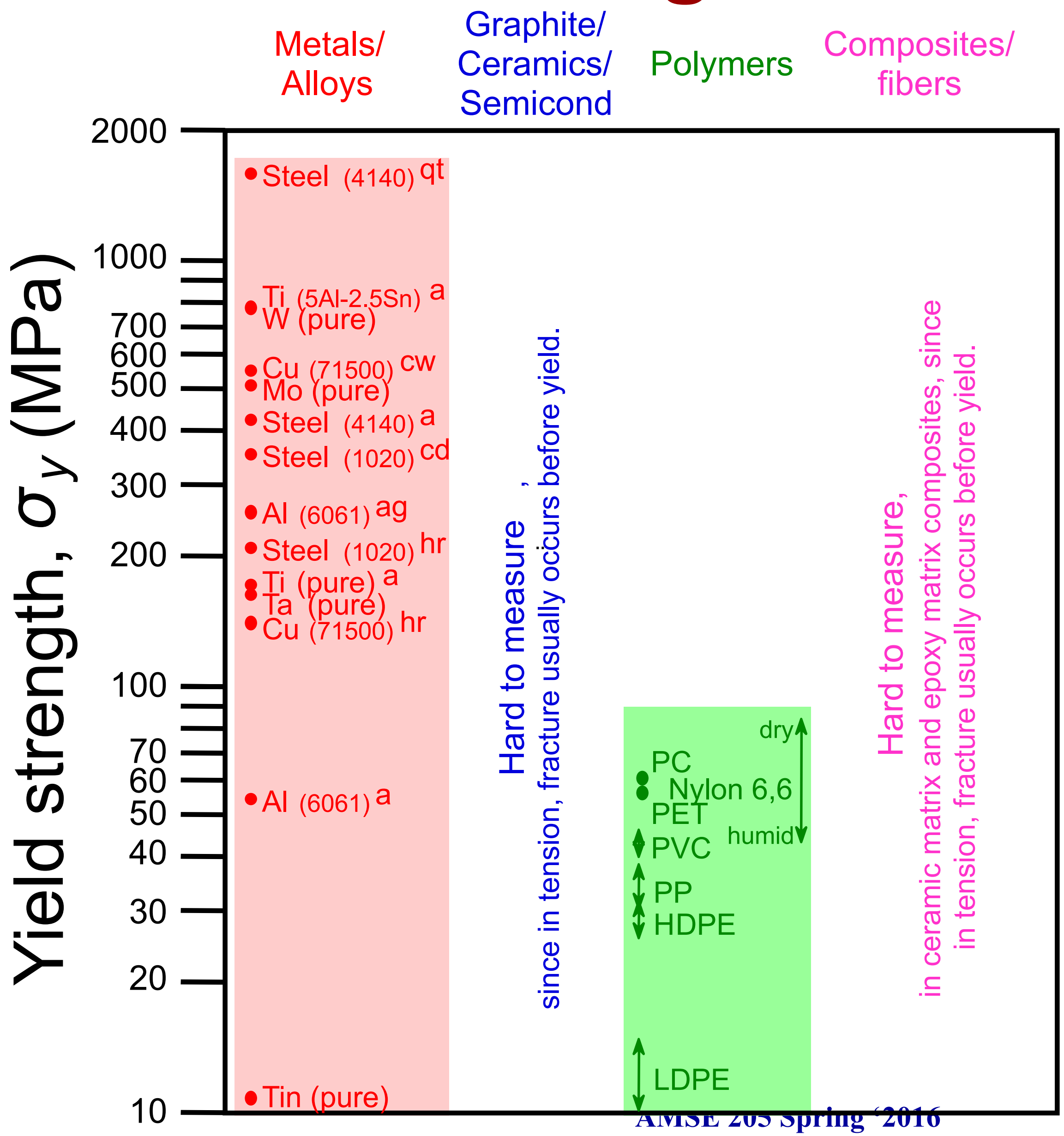


Typical stress-strain behavior for a metal



Typical stress-strain behavior for steels

Yield Strength : Comparison



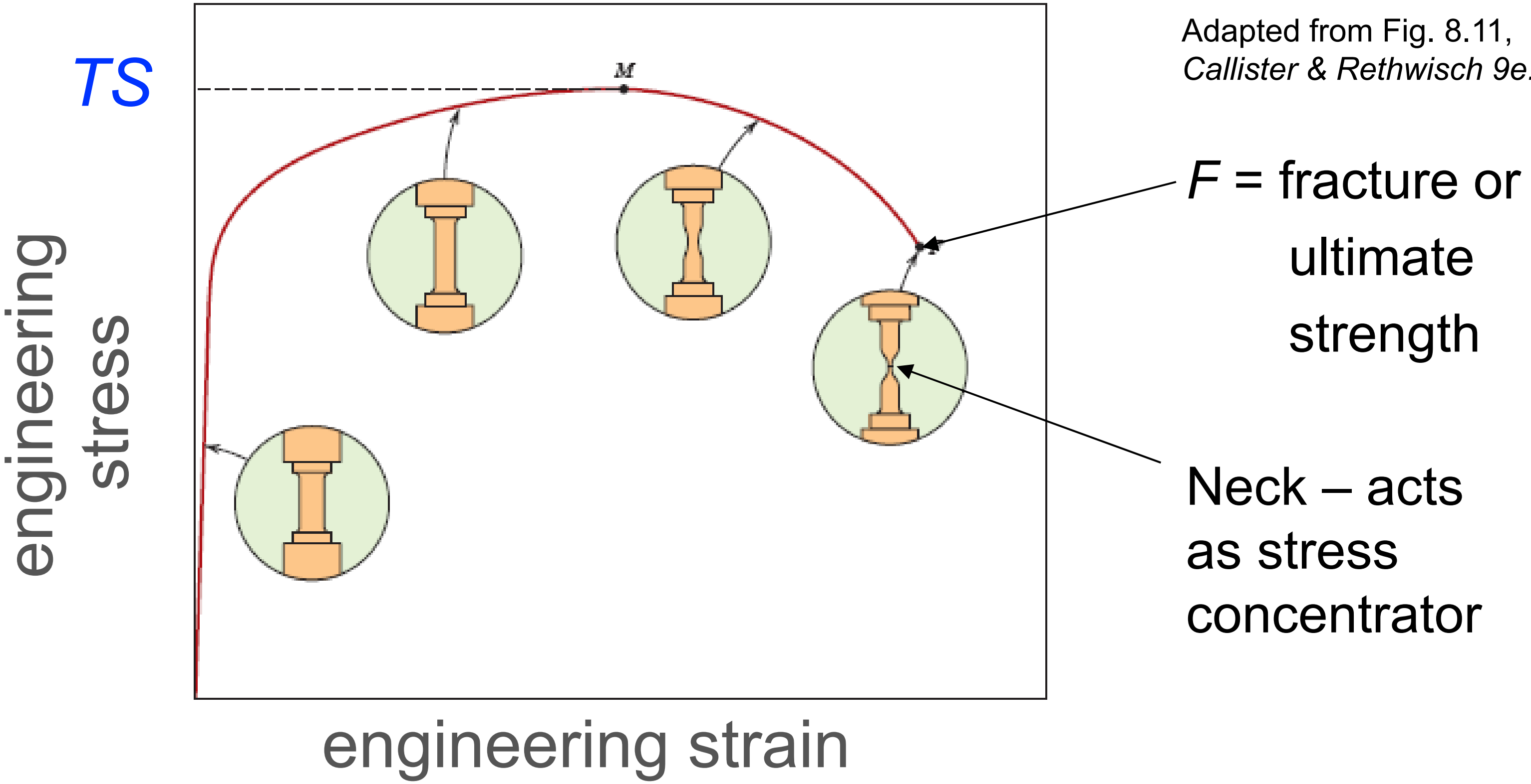
Room temperature values

Based on data in Table B.4, *Callister & Rethwisch 9e.*

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

Tensile Strength, TS

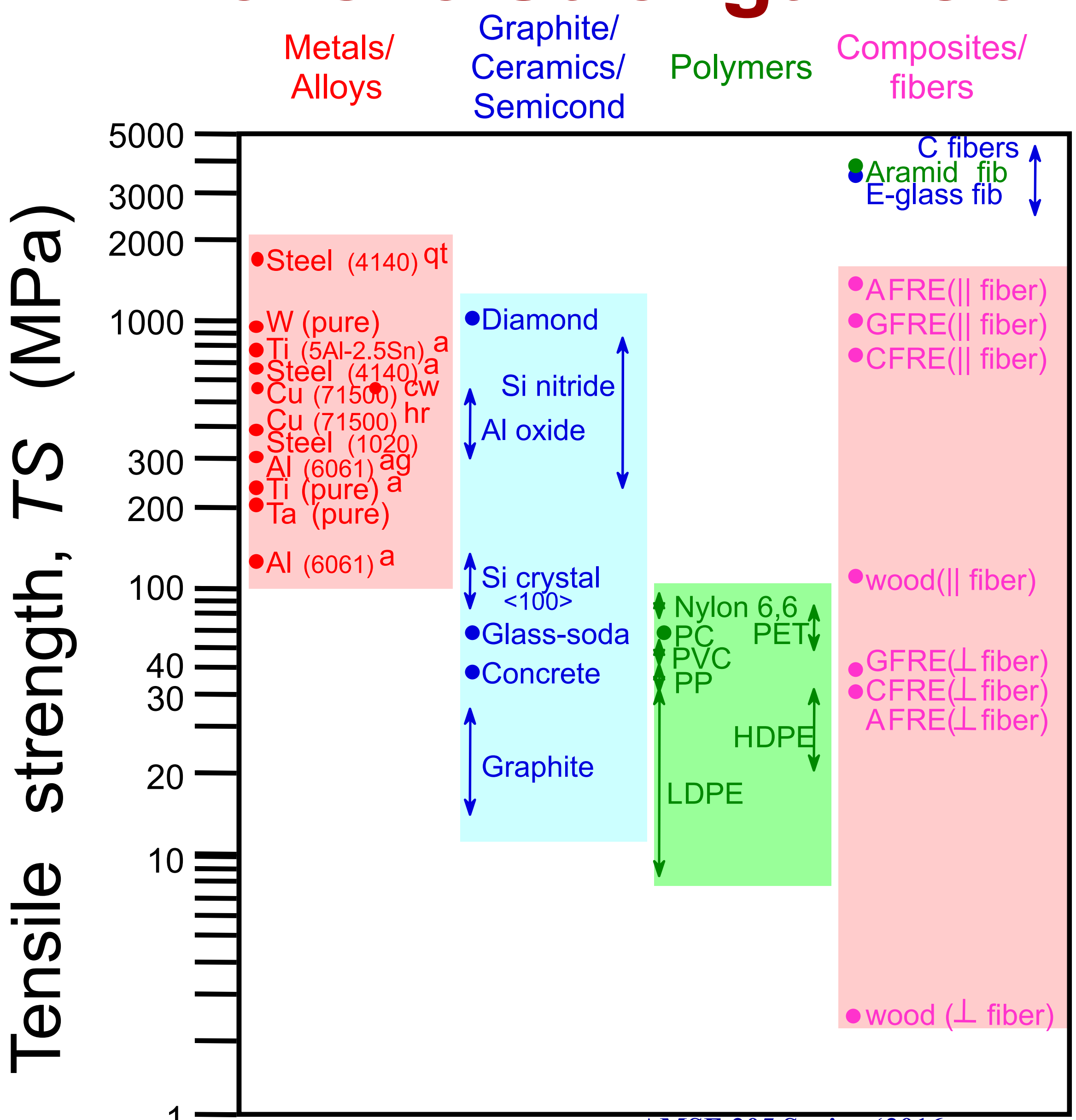
- Maximum stress on engineering stress-strain curve.



Adapted from Fig. 8.11, *Callister & Rethwisch 9e.*

- Metals: occurs when noticeable necking starts.
- Polymers: occurs when polymer backbone chains are aligned and about to break.

Tensile Strength: Comparison



Room temperature values

Based on data in Table B4, *Callister & Rethwisch 9e.*

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

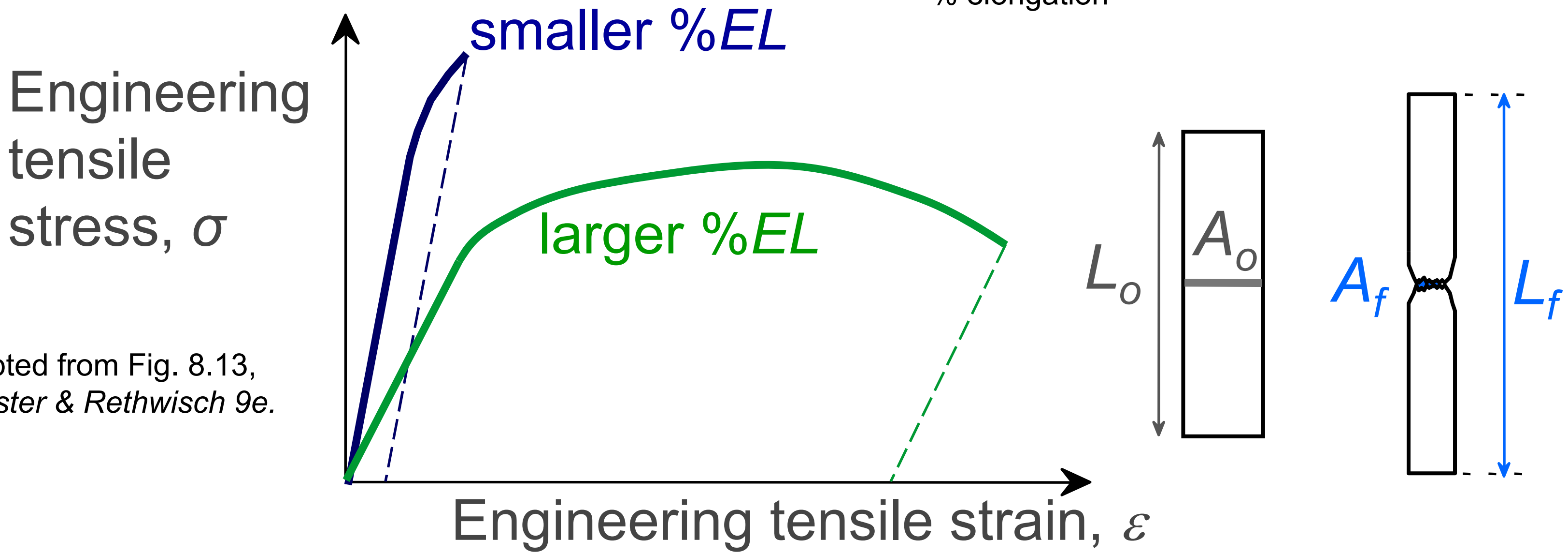
AFRE, GFRE, & CFRE = aramid, glass, & carbon fiber-reinforced epoxy composites, with 60 vol% fibers.

Ductility

- Plastic tensile strain at failure:

$$\%EL = \frac{L_f - L_o}{L_o} \times 100$$

% elongation



Adapted from Fig. 8.13, *Callister & Rethwisch 9e.*

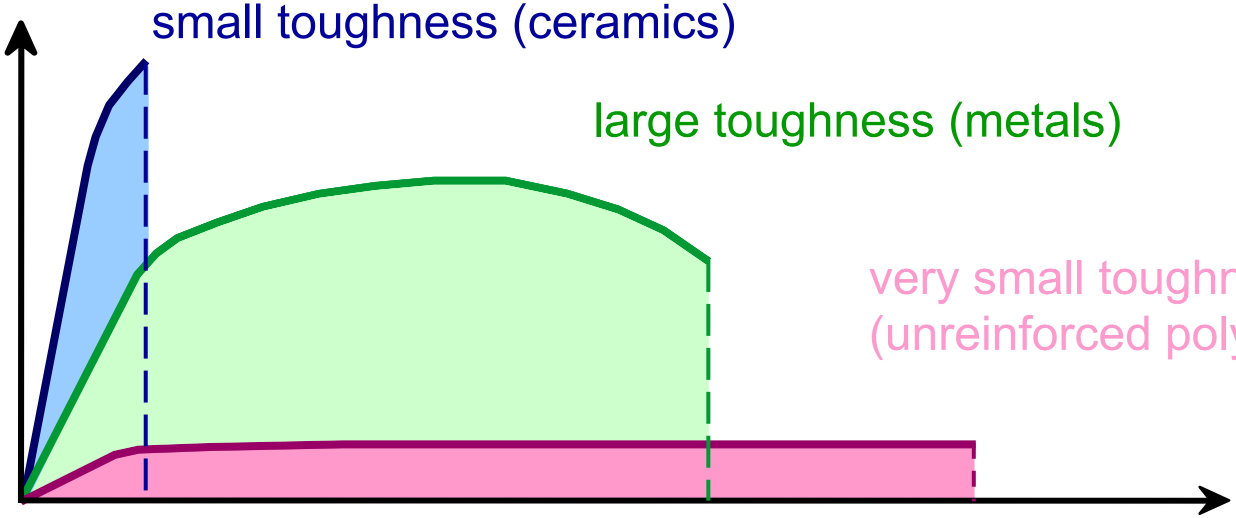
- Another ductility measure:

$$\%RA = \frac{A_o - A_f}{A_o} \times 100$$

% reduction in area

Toughness

- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve.



Adapted from Fig. 8.13, *Callister & Rethwisch 9e.*

Brittle fracture: elastic energy
Ductile fracture: elastic + plastic energy

Resilience, U_r

- Ability of a material to store energy
  - Energy stored best in elastic region

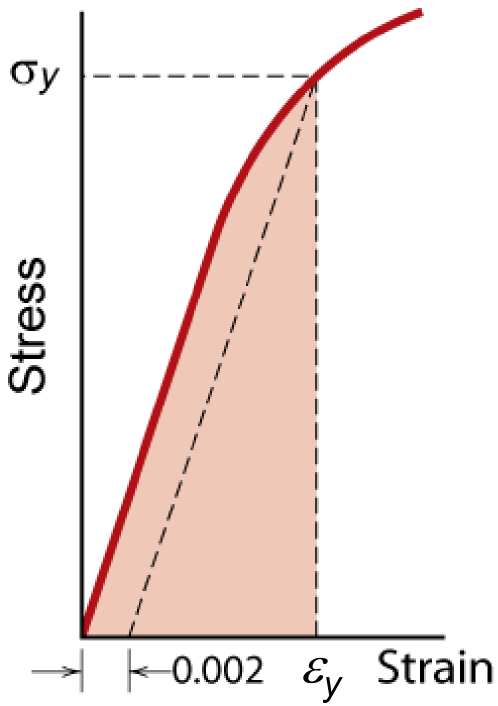


Fig. 8.15, *Callister & Rethwisch 9e.*

$$U_r = \int_0^y \sigma \, d\varepsilon$$

If we assume a linear stress-strain curve this simplifies to

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

True Stress & Strain

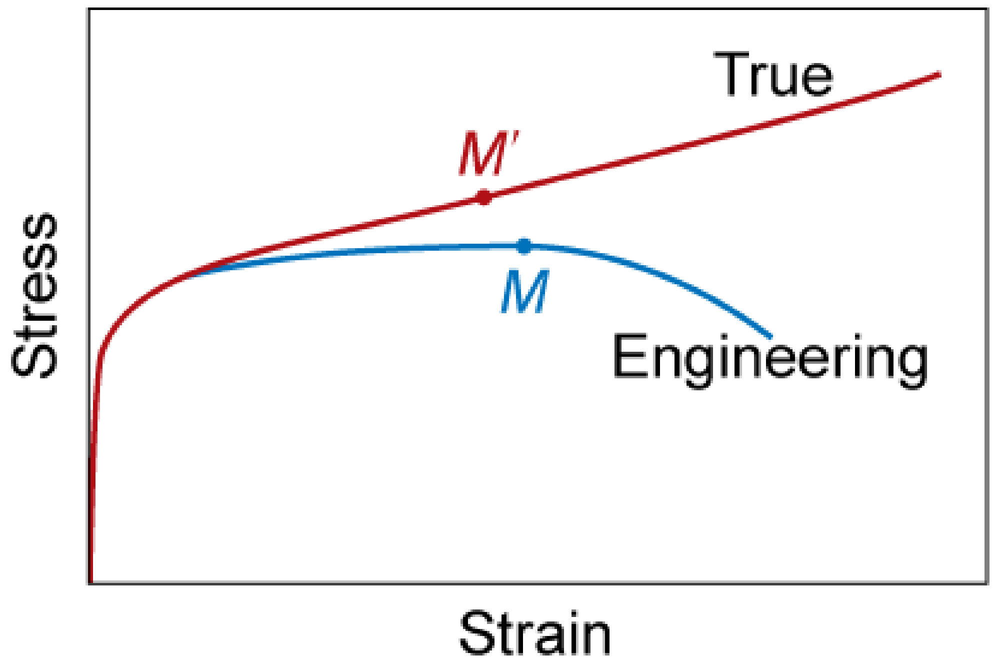
S.A. changes when sample stretched

True Stress (σ_T)

True stress is the stress determined by the instantaneous load acting on the instantaneous cross-sectional area

True Strain (ε_T)

The rate of instantaneous increase in the instantaneous gauge length.



Adapted from Fig. 8.16, *Callister & Rethwisch 9e.*

True Stress & Strain vs. Engineering Stress & Strain

Assuming material volume remains constant : $A_o\, l_o = A_i\, l_i$

$$\sigma_T = \frac{F}{A_i} = \frac{F}{A_o}\frac{A_o}{A_i} = \sigma\frac{l_i}{l_o} = \sigma\frac{l_o+\delta}{l_o} = \sigma(1+\varepsilon)$$

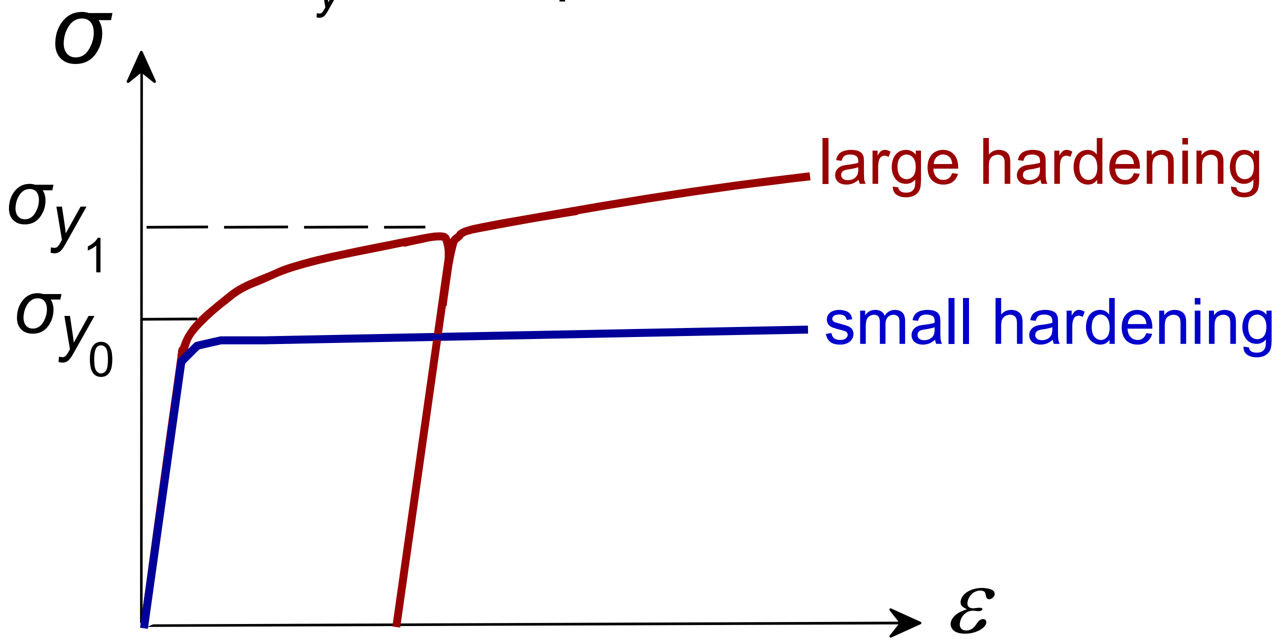
$$\varepsilon_T = \int_{l_o}^{l_i}\frac{dl}{l} = ln\left(\frac{l_i}{l_o}\right) = ln\left(\frac{l_o+\delta}{l_o}\right) = ln\,(1+\varepsilon)$$

True stress $\sigma_T = F/A_i$ $\sigma_T = \sigma(1+\epsilon)$

True strain $\epsilon_T = \ln(\ell_i/\ell_o)$ $\epsilon_T = \ln(1+\epsilon)$

Hardening

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

$$\sigma_T = K(\varepsilon_T)^n$$

"true" stress (F/A)

"true" strain: $\ln(\ell/\ell_o)$

hardening exponent:
n = 0.15 (some steels)
to n = 0.5 (some coppers)

Elastic Strain Recovery

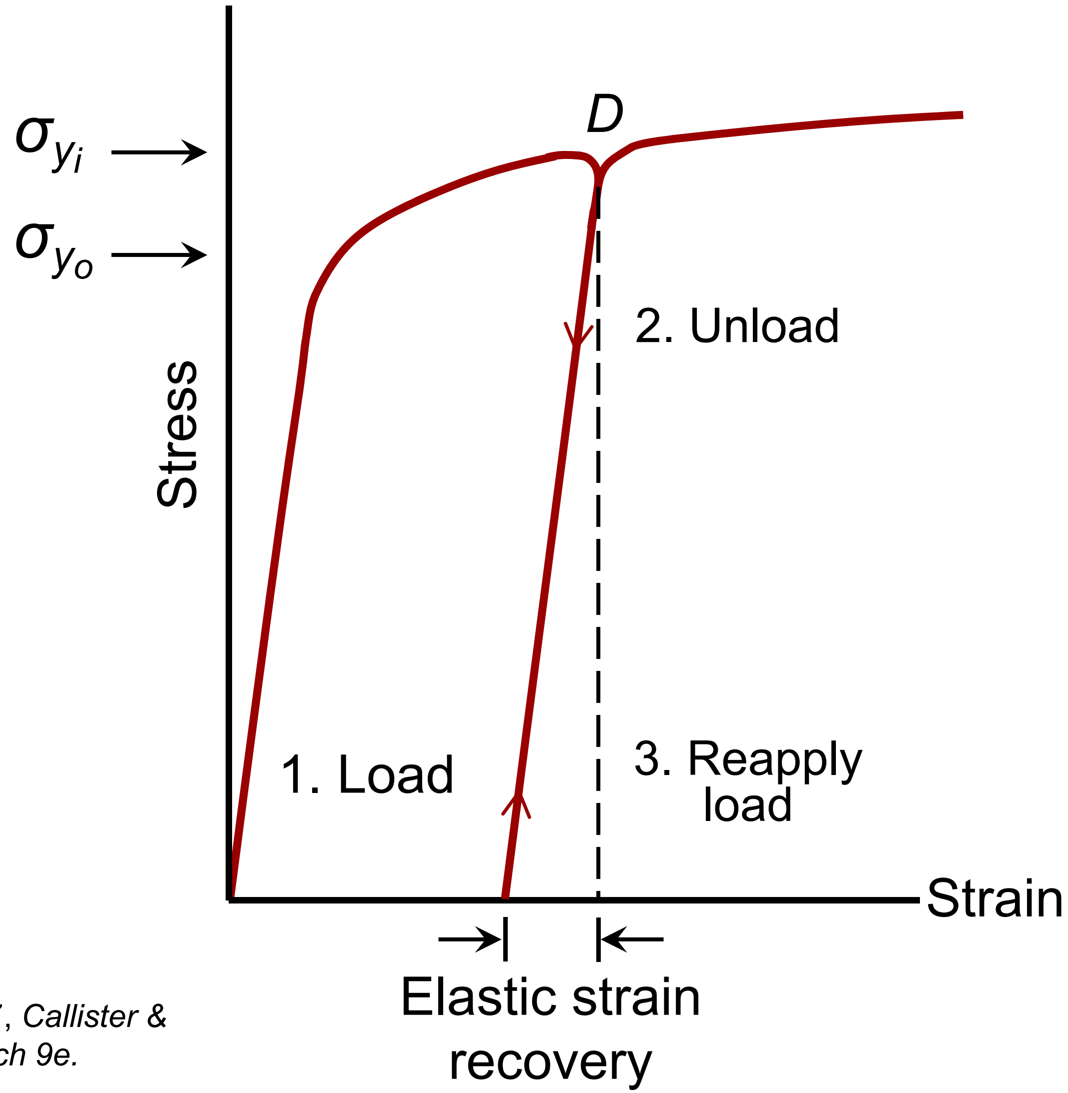
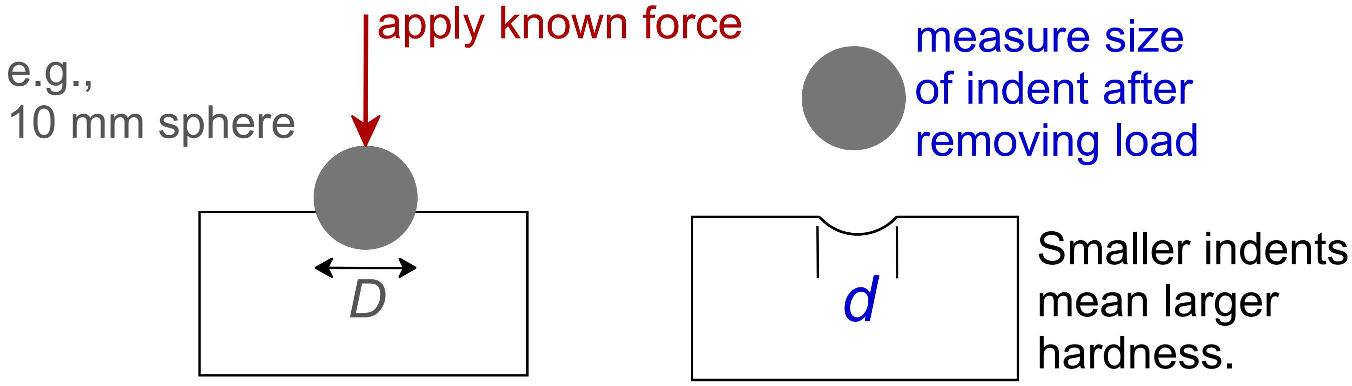
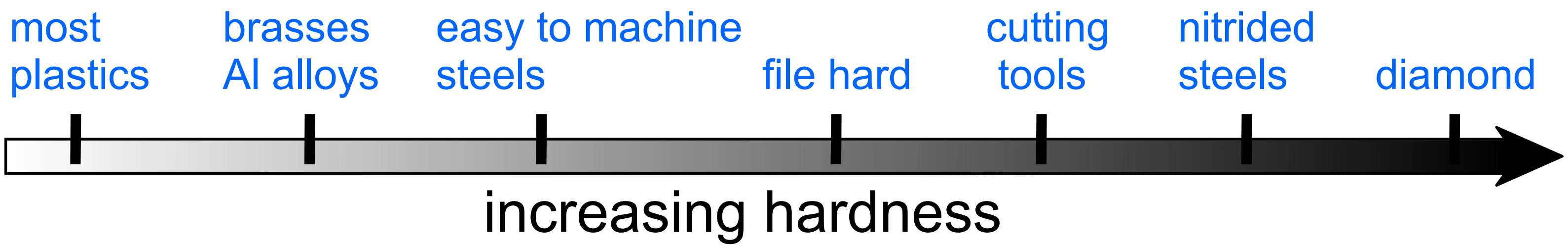


Fig. 8.17, *Callister & Rethwisch 9e.*

Hardness

- Resistance to permanently indenting the surface.
- Large hardness means:
  -- resistance to plastic deformation or cracking in compression.
  -- better wear properties.





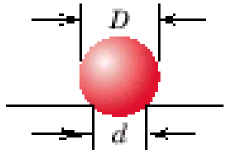
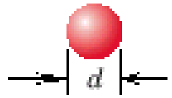
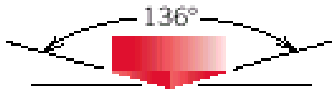
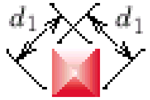
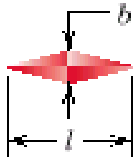
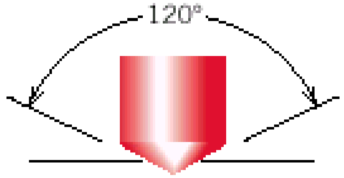
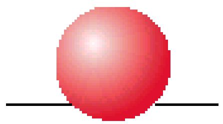
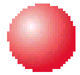
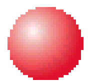
Hardness: Measurement

- Rockwell
  - No major sample damage
  - Each scale runs to 130 but only useful in range 20-100.
  - Minor load 10 kg
  - Major load 60 (A), 100 (B) & 150 (C) kg
    - A = diamond, B = 1/16 in. ball, C = diamond

- HB = Brinell Hardness
  - *TS* (MPa) = 3.45 x HB

Hardness: Measurement

Table 8.5 **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			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	 	 	60 kg, 100 kg, 150 kg: Rockwell; 15 kg, 30 kg, 45 kg: Superficial Rockwell	

[a] For the hardness formulas given, P (the applied load) is in kg, while D, d, d_1, and l are all in mm.

Source: Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior.* Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

Design or Safety Factors

- Design uncertainties mean we do not push the limit.
- Factor of safety, N

$$\sigma_{working} = \frac{\sigma_y}{N}$$

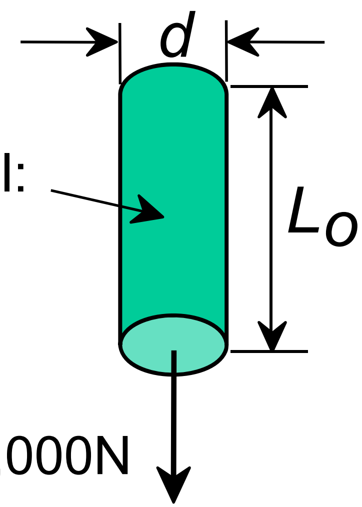
Often N is between 1.2 and 4

- Example: Calculate a diameter, d, to ensure that yield does not occur in the 1045 carbon steel rod below. Use a factor of safety of 5.

$$\sigma_{working} = \frac{\sigma_y}{N}$$

$$\frac{220{,}000\text{N}}{\pi\left(d^2/4\right)} \qquad N = 5$$

1045 plain carbon steel:
σ_y = 310 MPa
TS = 565 MPa



F = 220,000N

d = 0.067 m = 6.7 cm

Summary

- Stress and strain: These are size-independent measures of load and displacement, respectively.
- Elastic behavior: This reversible behavior often shows a linear relation between stress and strain. To minimize deformation, select a material with a large elastic modulus (E or G).
- Plastic behavior: This permanent deformation behavior occurs when the tensile (or compressive) uniaxial stress reaches σ_y.
- Toughness: The energy needed to break a unit volume of material.
- Ductility: The plastic strain at failure.