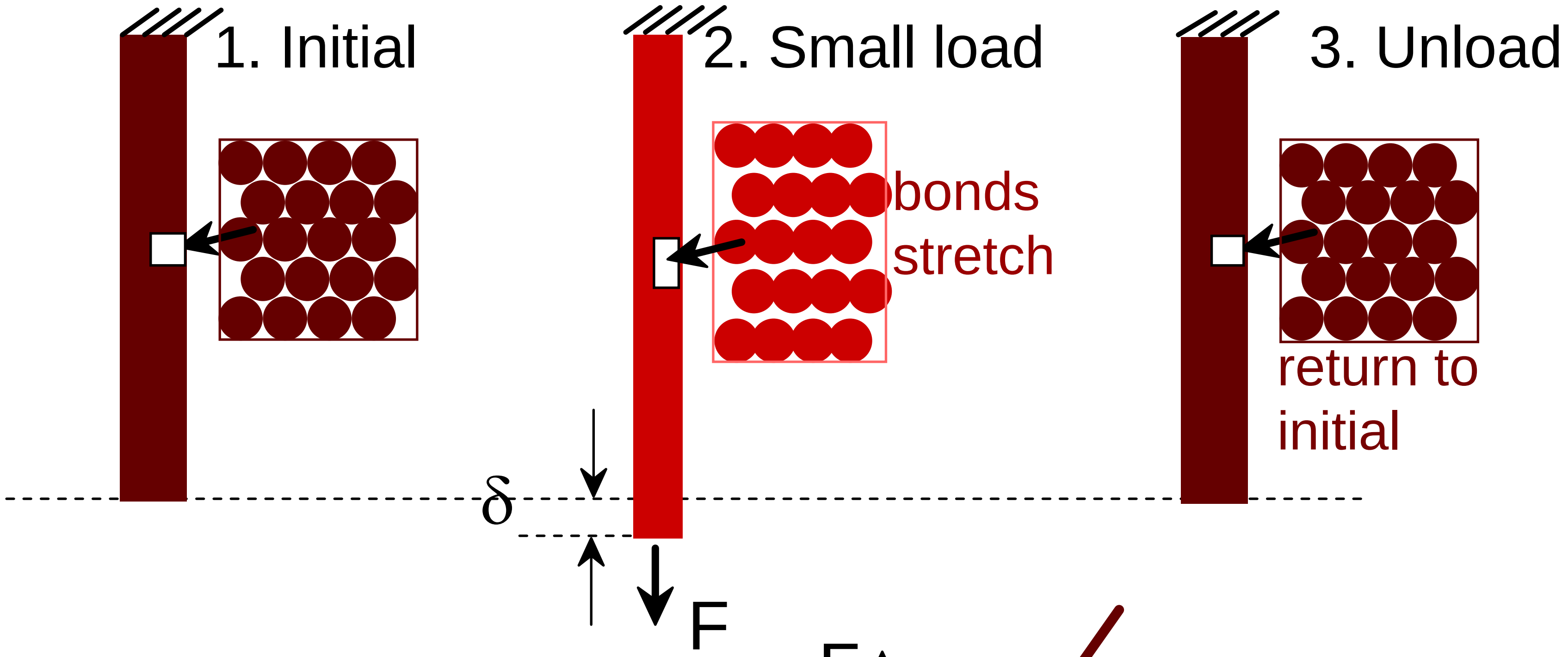
CHAPTER 6:
Mechanical properties

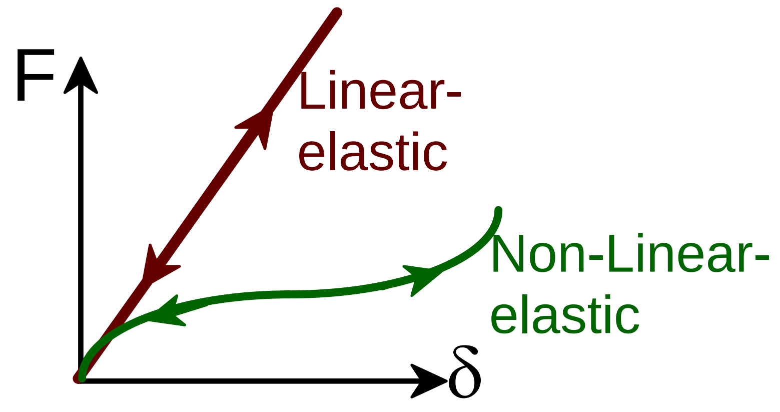
ISSUES TO ADDRESS...

- 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 do dislocations cause permanent deformation? What materials are most resistant to permanent deformation?
- Toughness and ductility: What are they and how do we measure them?

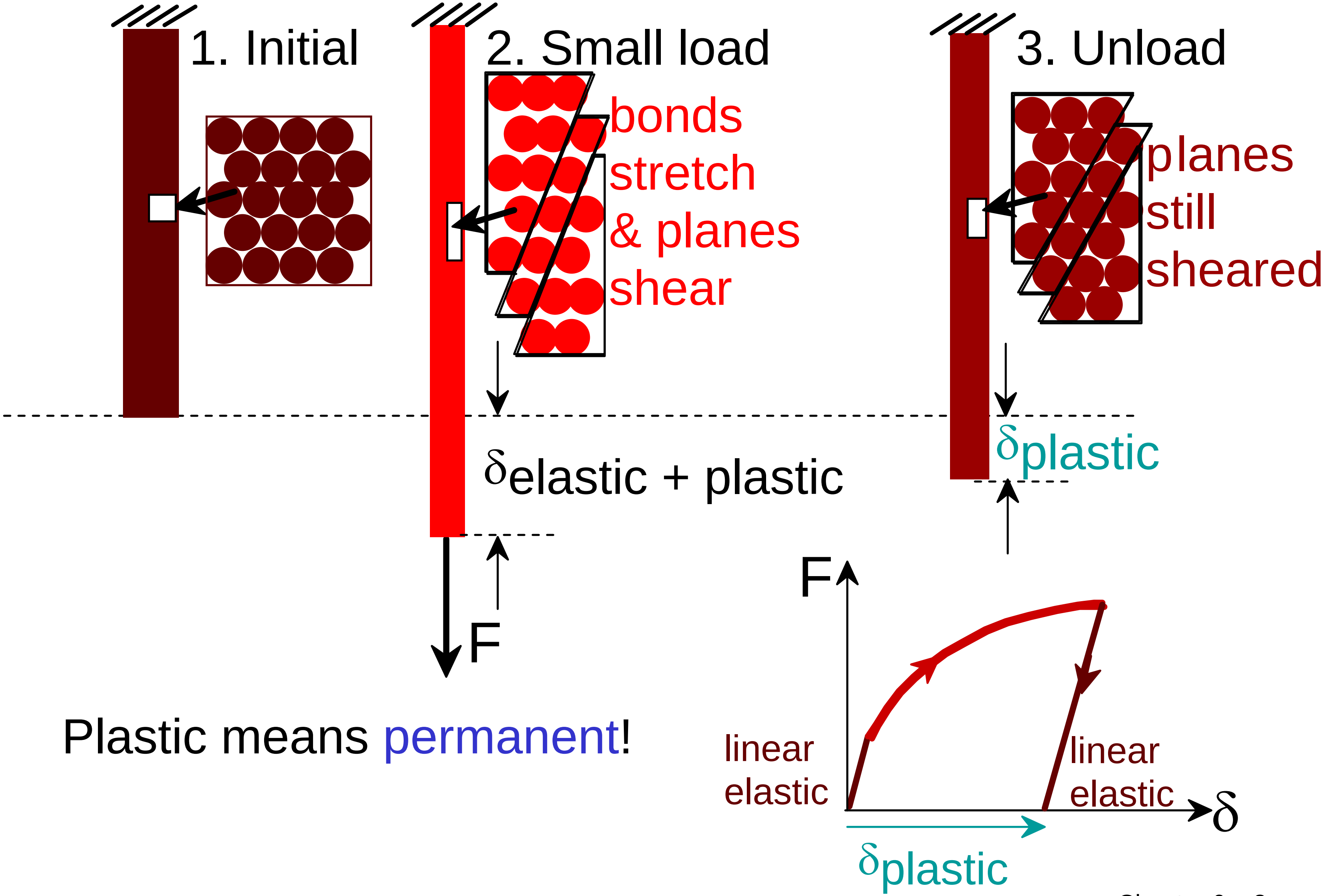
Elastic deformation



Elastic means reversible!



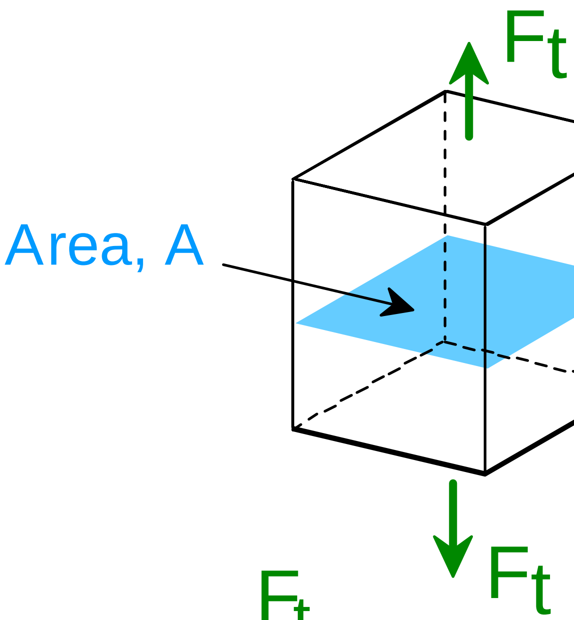
Plastic deformation (metals)



Plastic means permanent!

Engineering stress

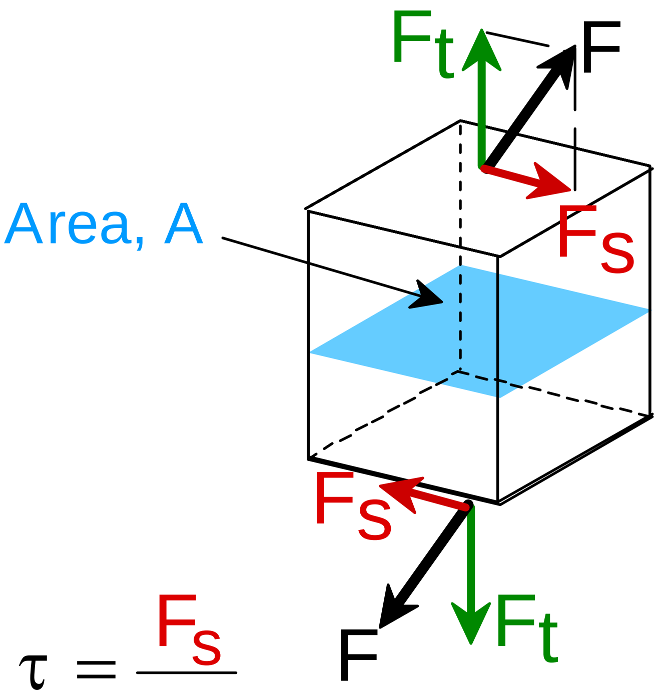
- Tensile stress, σ:



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

original area
before loading

- Shear stress, τ:

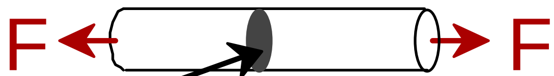


$$\tau = \frac{F_s}{A_o}$$

Stress has units:
N/m^2 or lb/in^2

Common states of stress

- Simple tension: cable

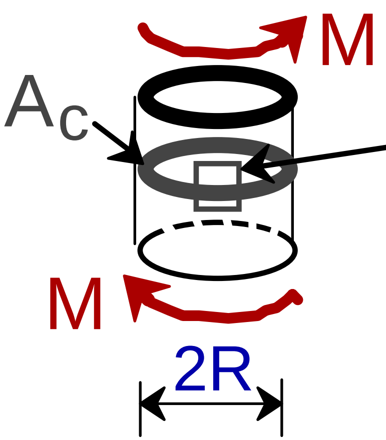


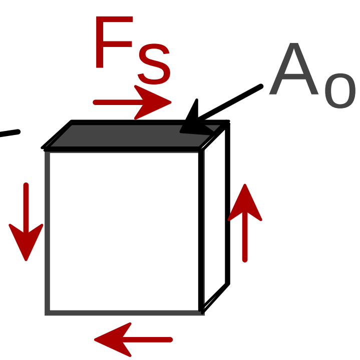
A_o = cross sectional Area (when unloaded)

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

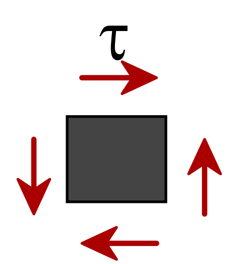
Ski lift (photo courtesy P.M. Anderson)

- Simple shear: drive shaft





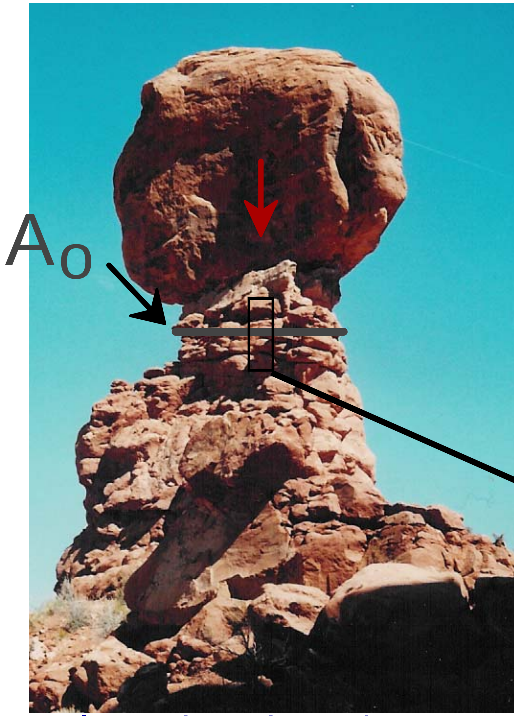
$$\tau = \frac{F_s}{A_o}$$



Note: $\tau = M/A_c R$ here.

Other common stress states (1)

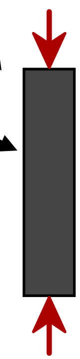
- Simple compression:



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

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

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



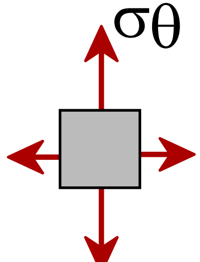
Note: compressive structure member ($\sigma < 0$ here).

Other common stress states (2)

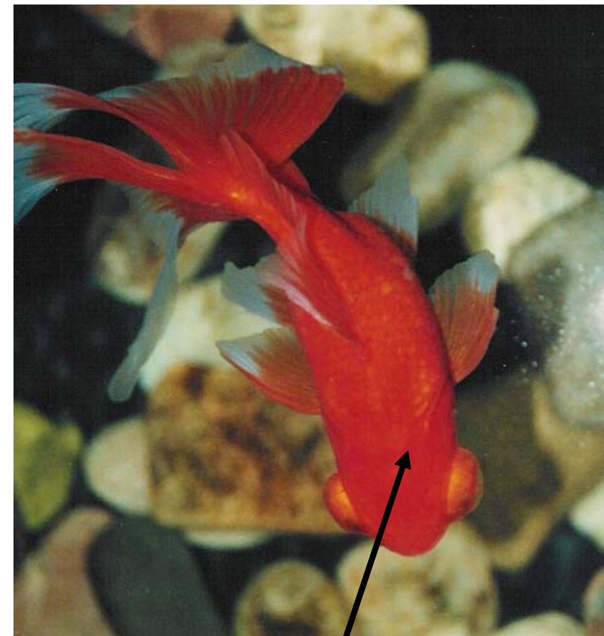
- Bi-axial tension:
- Hydrostatic compression:

Pressurized tank
(photo courtesy
P.M. Anderson)

$\sigma_\theta > 0$



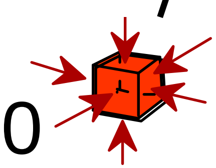
$\sigma_z > 0$



Fish under water

(photo courtesy
P.M. Anderson)

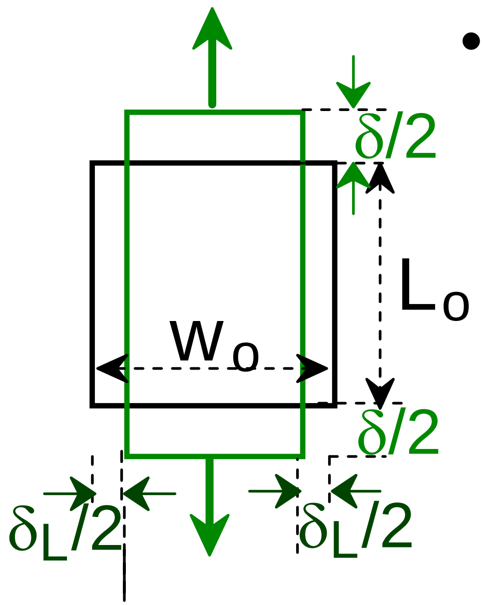
$\sigma_h < 0$



Engineering strain

- Tensile strain:

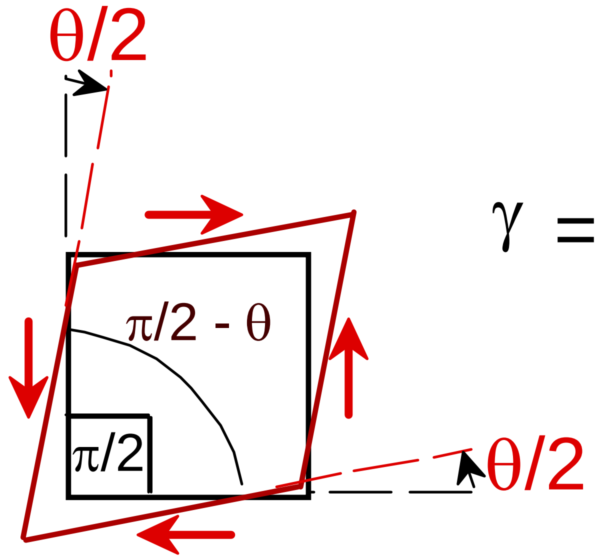
$$\varepsilon = \frac{\delta}{L_o}$$



- Lateral strain:

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

- Shear strain:

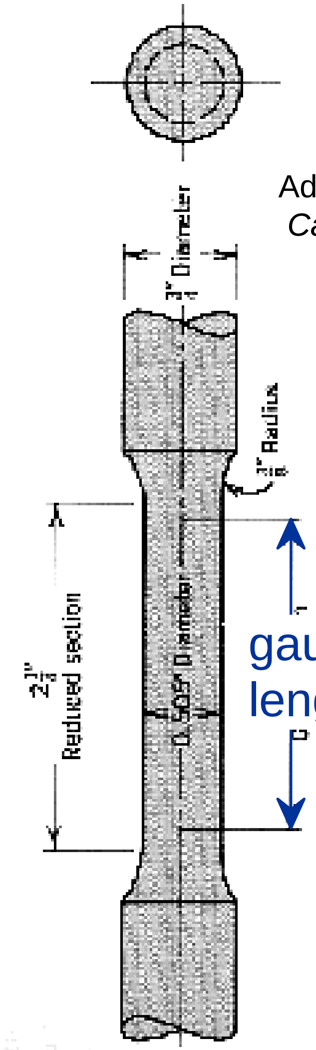


$$\gamma = \tan\,\theta$$

Strain is always dimensionless.

Stress-strain testing

- Typical tensile specimen

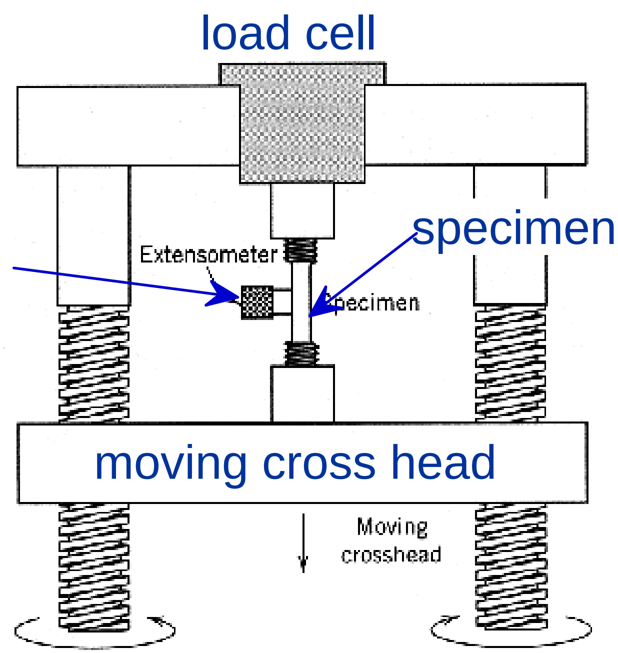


Adapted from Fig. 6.2, *Callister 6e.*

gauge length = (portion of sample with reduced cross section)

- Other types of tests:
  - --compression: brittle materials (e.g., concrete)
  - --torsion: cylindrical tubes, shafts.

- Typical tensile test machine



Adapted from Fig. 6.3, *Callister 6e.* (Fig. 6.3 is 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.)

Linear elastic properties

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

- Hooke's Law:

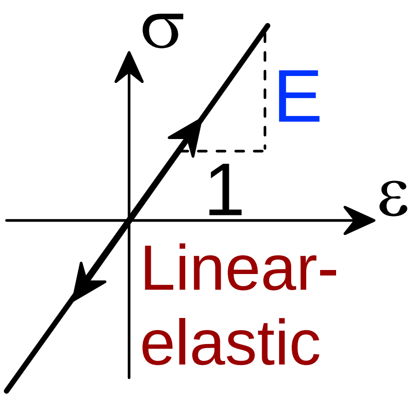
$$\sigma = E\,\varepsilon$$

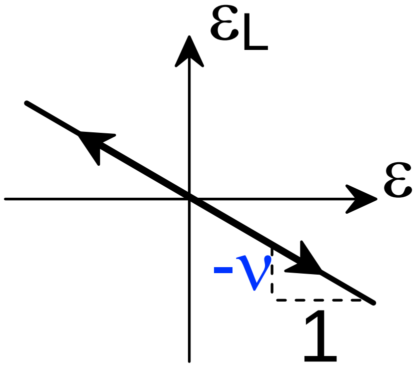
- Poisson's ratio, ν:

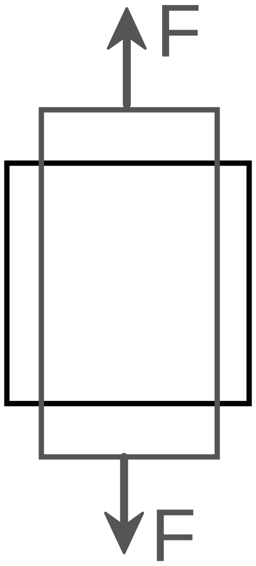
$$\nu = -\frac{\varepsilon_L}{\varepsilon}$$

metals: $\nu \sim 0.33$
ceramics: ~0.25
polymers: ~0.40

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





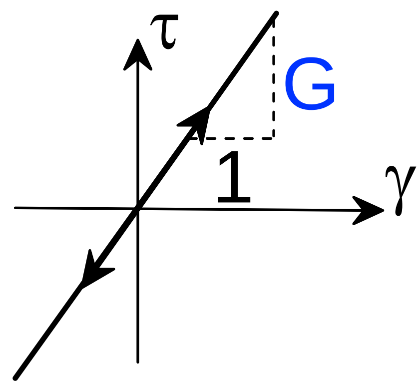


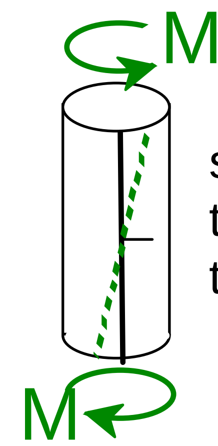
simple
tension
test

Other elastic properties

- Elastic Shear modulus, G:

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

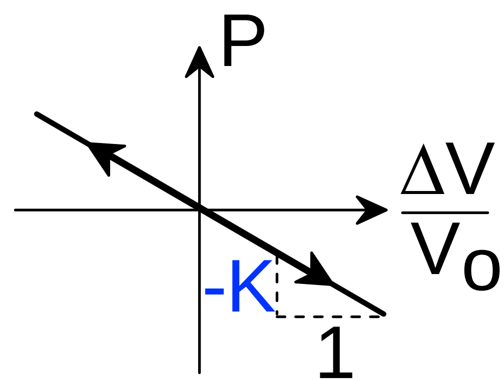


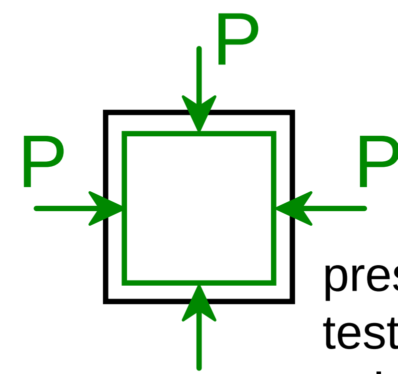


simple
torsion
test

- Elastic Bulk modulus, K:

$$P = -K\frac{\Delta V}{V_o}$$



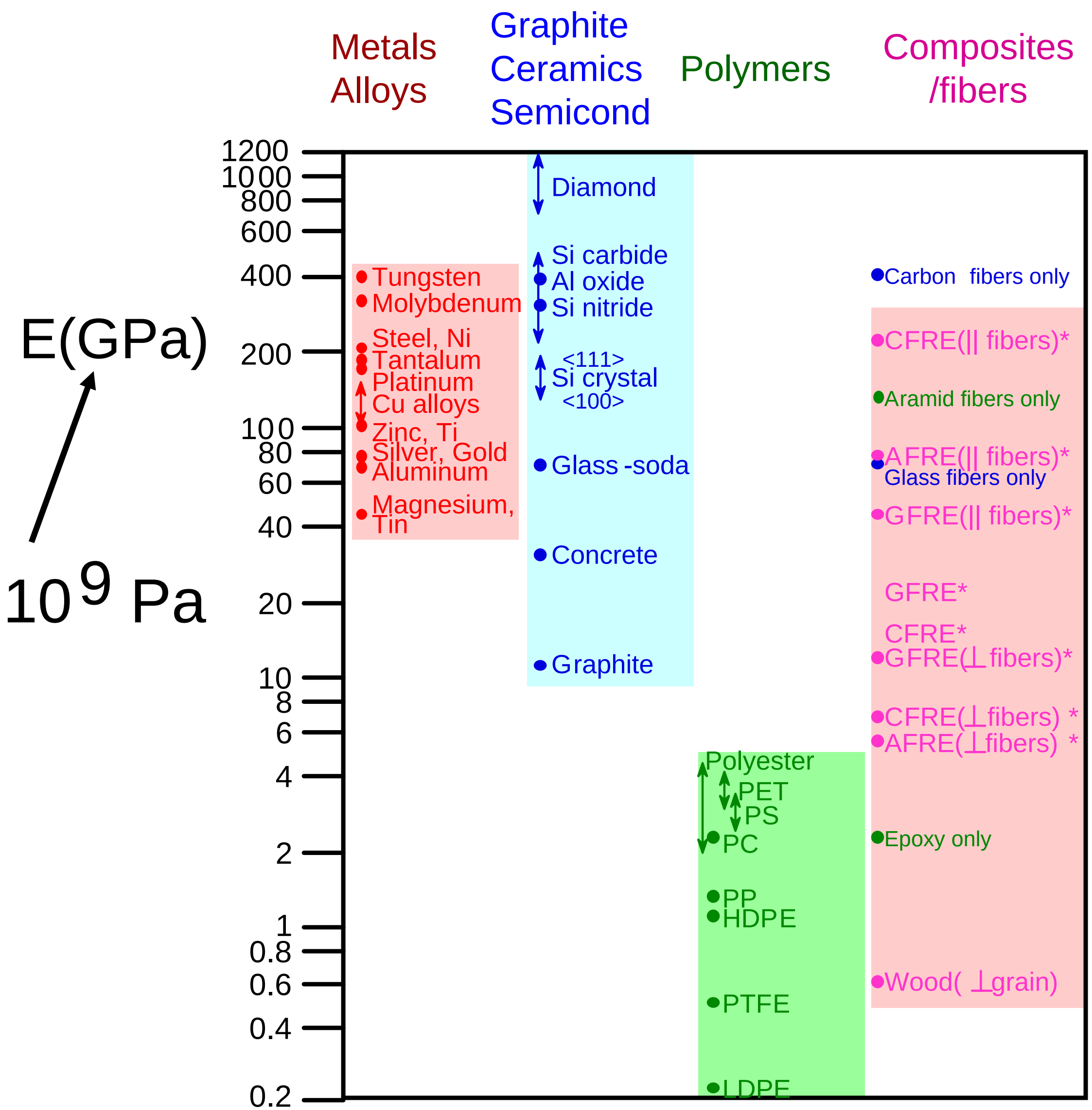


pressure test: Init. vol $=V_o$. Vol chg. $= \Delta V$

- Special relations for isotropic materials:

$$G = \frac{E}{2(1+\nu)} \qquad K = \frac{E}{3(1-2\nu)}$$

Young's moduli: comparison



$E_{ceramics}$
$> E_{metals}$
$>> E_{polymers}$

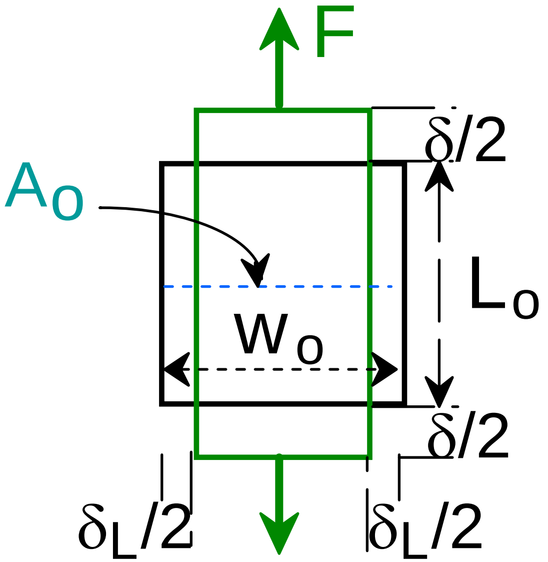
Based on data in Table B2, *Callister 6e*.

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

Useful linear elastic relations

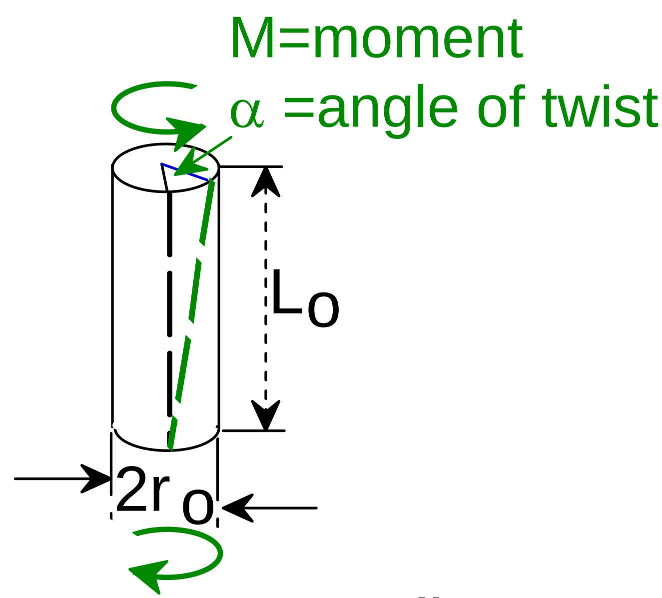
- Simple tension:

$$\delta = \frac{FL_o}{EA_o} \qquad \delta_L = -\nu \frac{Fw_o}{EA_o}$$



- Simple torsion:

$$\alpha = \frac{2ML_o}{\pi r_o^4 G}$$

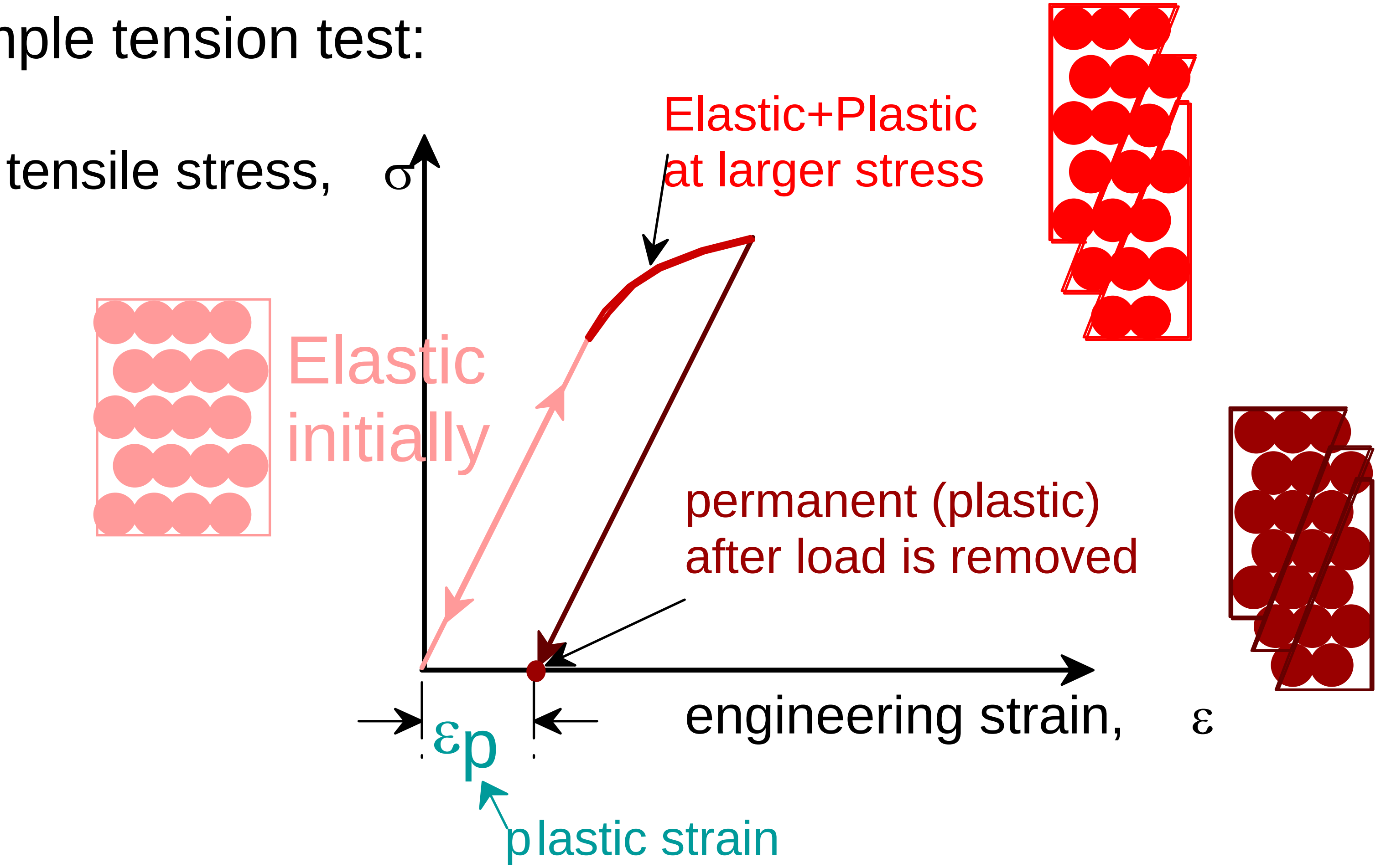


- Material, geometric, and loading parameters all contribute to deflection.
- Larger elastic moduli minimize elastic deflection.

Plastic (permanent) deformation

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

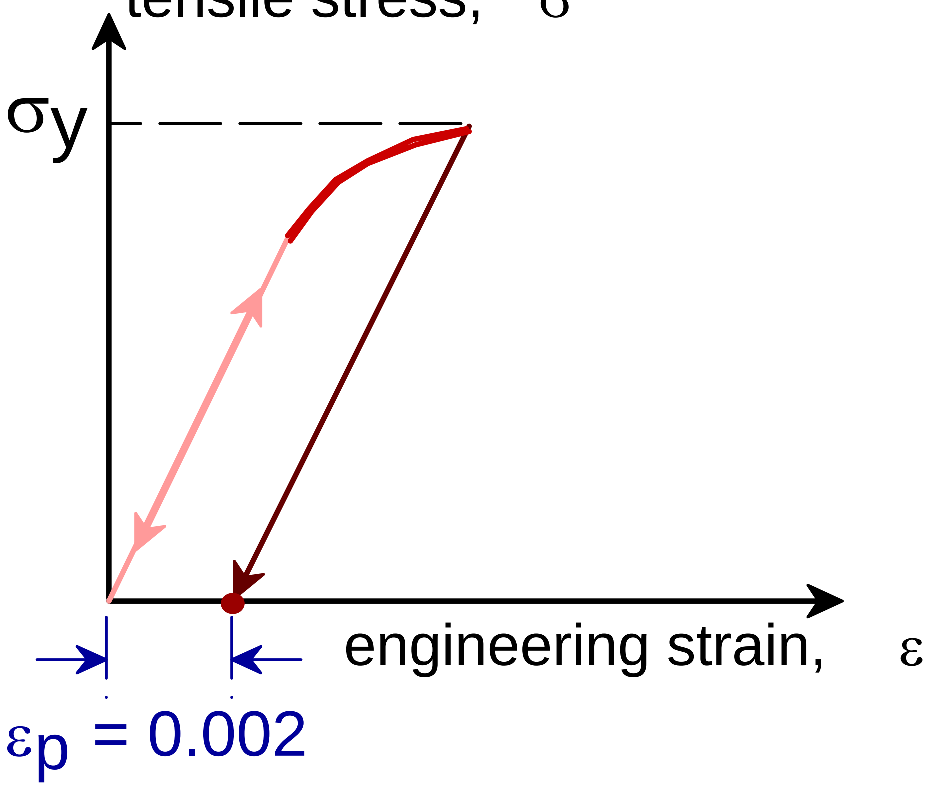
- Simple tension test:



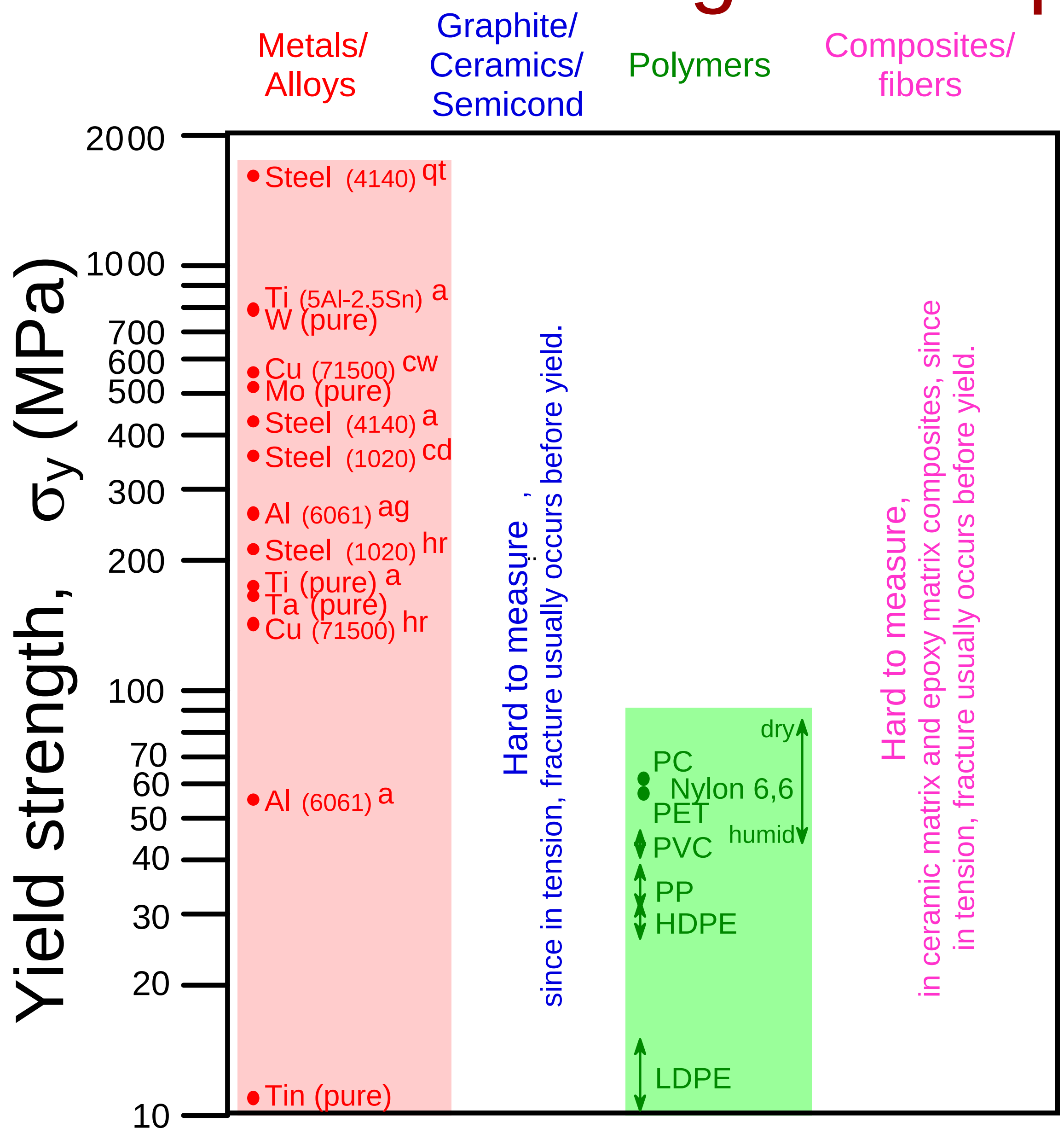
Yield strength, σ_y

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

when $\varepsilon_p = 0.002$



Yield strength: comparison



σ_y(ceramics)

>> σ_y(metals)

>> σ_y(polymers)

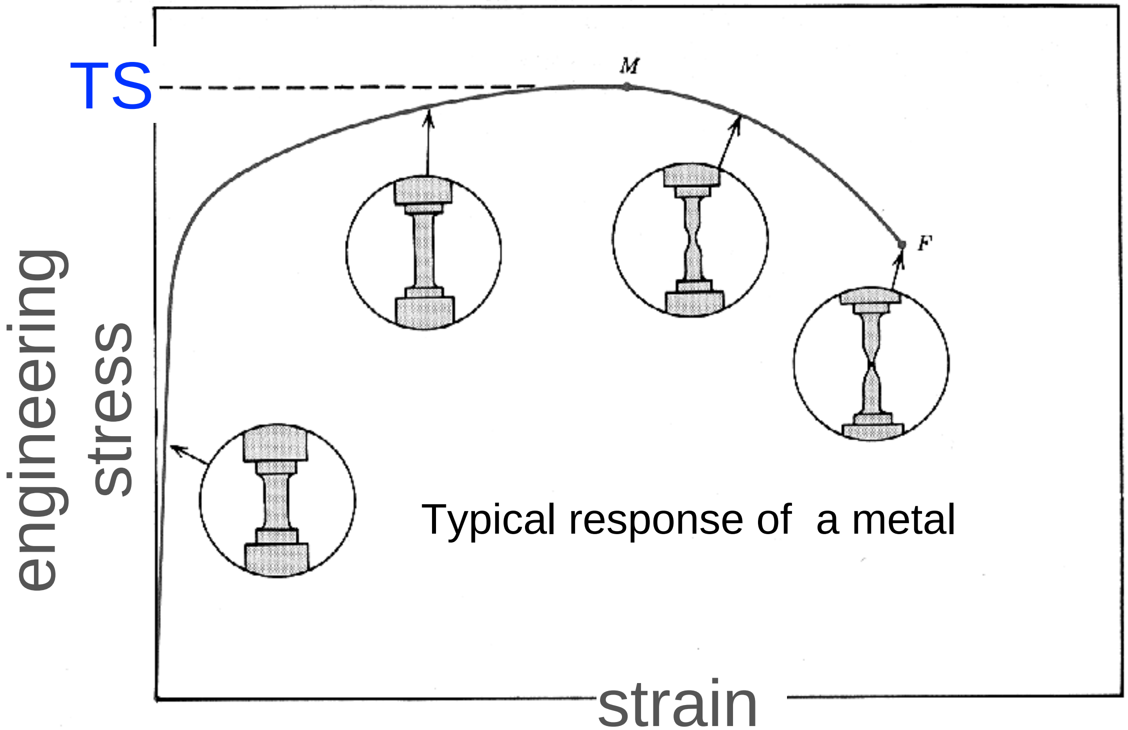
Room T values

Based on data in Table B4, *Callister 6e*.

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

Tensile strength, TS

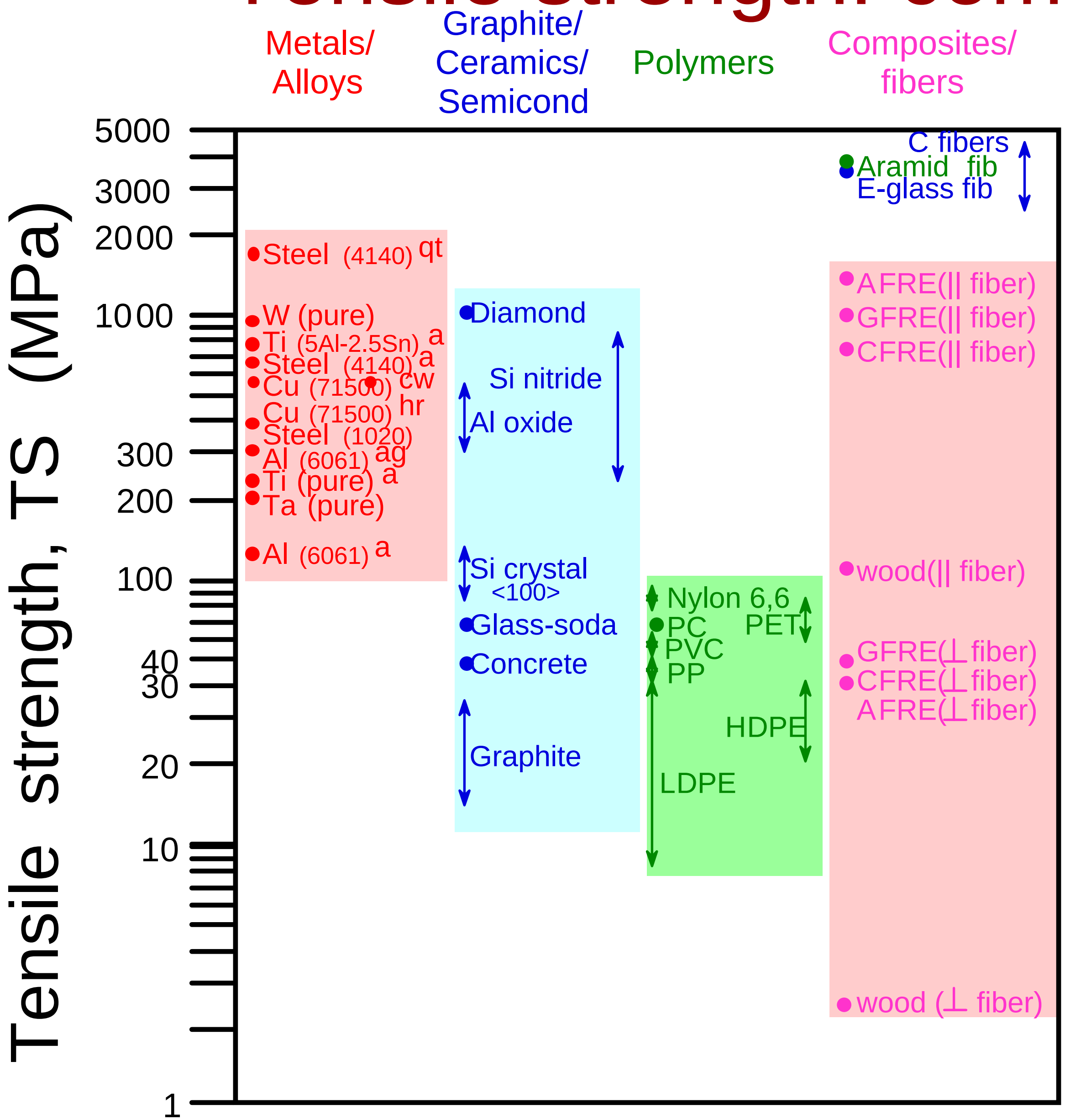
- Maximum possible engineering stress in tension.



Adapted from Fig. 6.11, *Callister 6e.*

- Metals: occurs when noticeable necking starts.
- Ceramics: occurs when crack propagation starts.
- Polymers: occurs when polymer backbones are aligned and about to break.

Tensile strength: comparison



TS(ceram) ~TS(met) ~ TS(comp) >> TS(poly)

Room T values

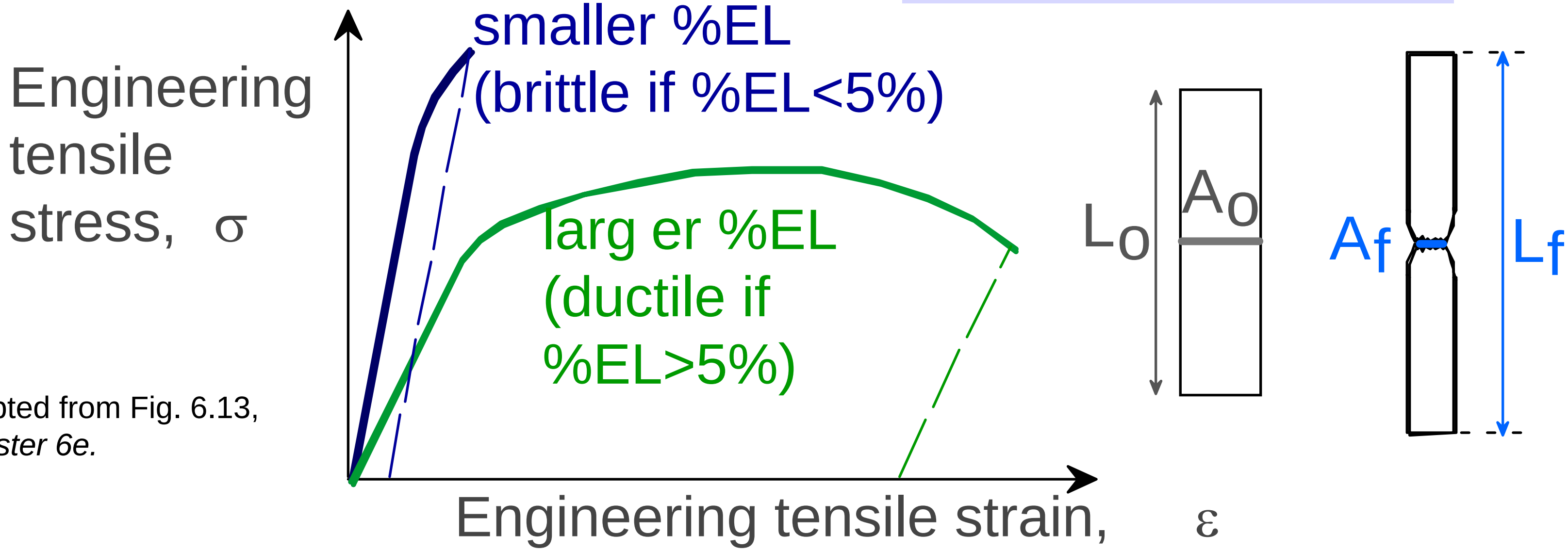
Based on data in Table B4, *Callister 6e*.

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, %EL

- Plastic tensile strain at failure: $$\%EL = \frac{L_f - L_o}{L_o} \times 100$$



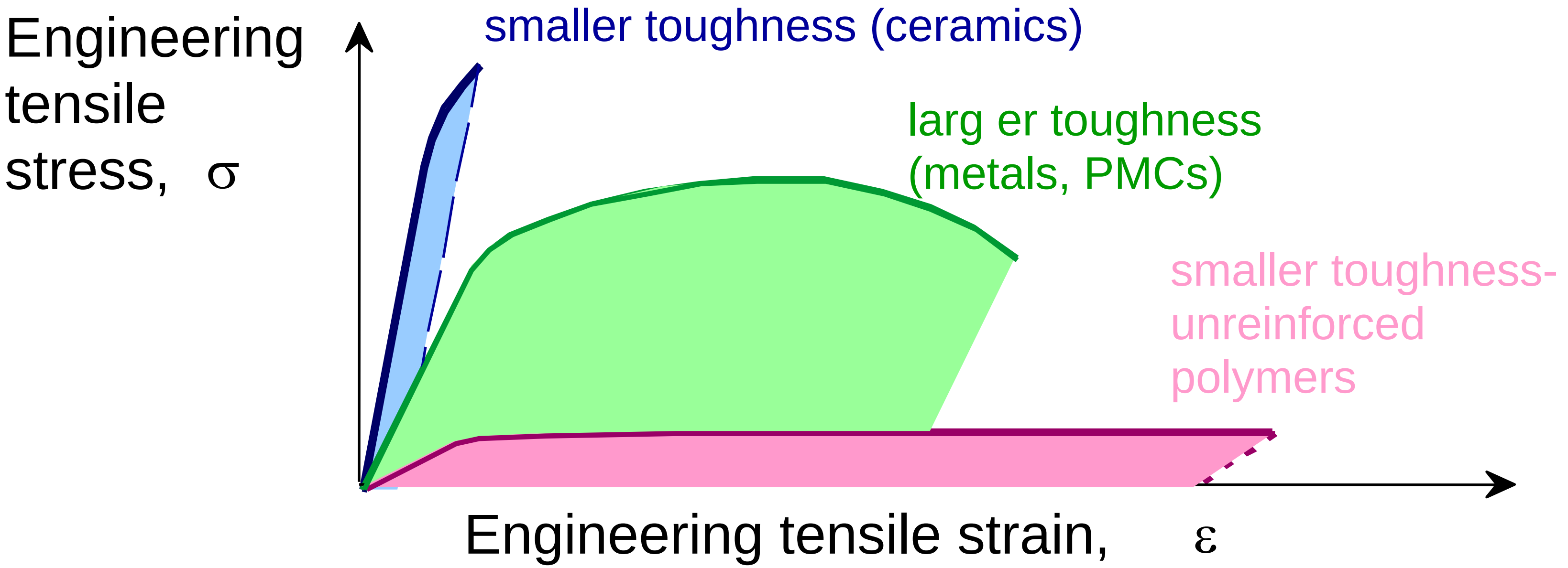
Adapted from Fig. 6.13, *Callister 6e.*

- Another ductility measure: $$\%AR = \frac{A_o - A_f}{A_o} \times 100$$

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

Toughness

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



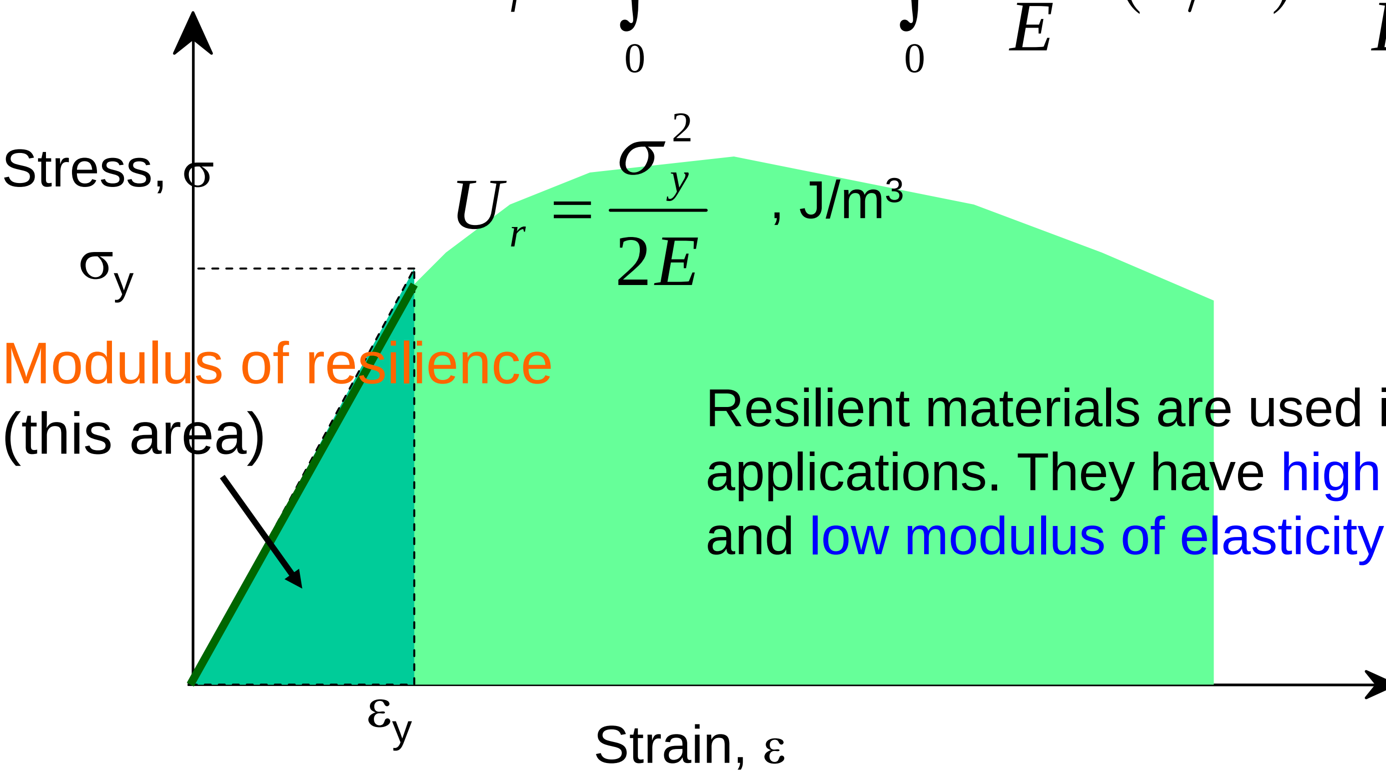
Resilience

Resilience is the capacity to absorb energy in the elastic region

Modulus of resilience is the total elastic strain energy per unit volume (Area under elastic portion of σ vs. ε)

$$U_r = \int_0^{\sigma_y} E\varepsilon d\varepsilon = \int_0^{\sigma_y} E\frac{\sigma}{E} d\left(\sigma/E\right) = \frac{1}{E}\int_0^{\sigma_y} \sigma d\sigma$$

$$U_r = \frac{\sigma_y^2}{2E}$$, J/m^3



Resilient materials are used in spring applications. They have high yield stress and low modulus of elasticity.

Elastic properties of spring mtls

Material	σ_y (ksi)	Prop limit (ksi)	E 10^3 ksi	Recov. strain %	Normalized Mod. of resil.
Ti-55Ni	30	27	10	1.00	1
17-7PH	200	180	29	0.62	2.2
MP55N-Co	225	203	33.6	0.6	2.4
5160	250	225	30	0.75	3.3
Ti-6Al-4V	120	108	16.5	0.65	1.4
Beta C Ann.	120	108	13.0	0.83	1.8
Beta C + CW	170	160	13.0	1.18	3.6
Beta C + CW+ Aged	210	185	15.5	1.22	4.6

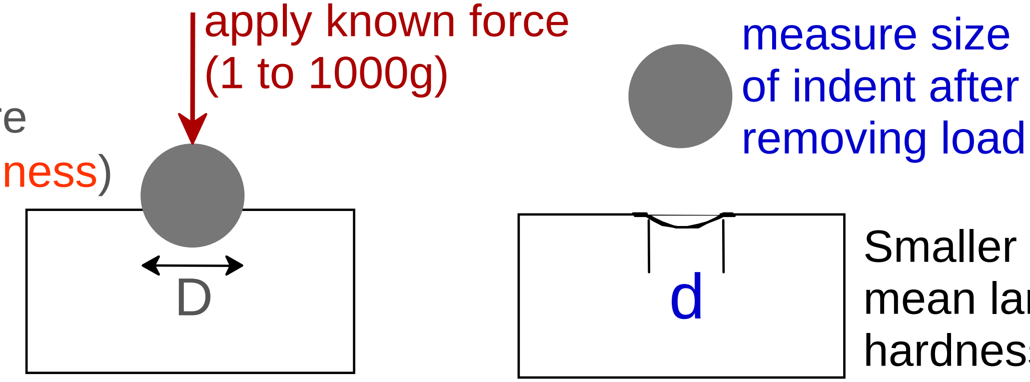
Hardness

- Resistance to permanently indenting the surface.
- Large hardness means:

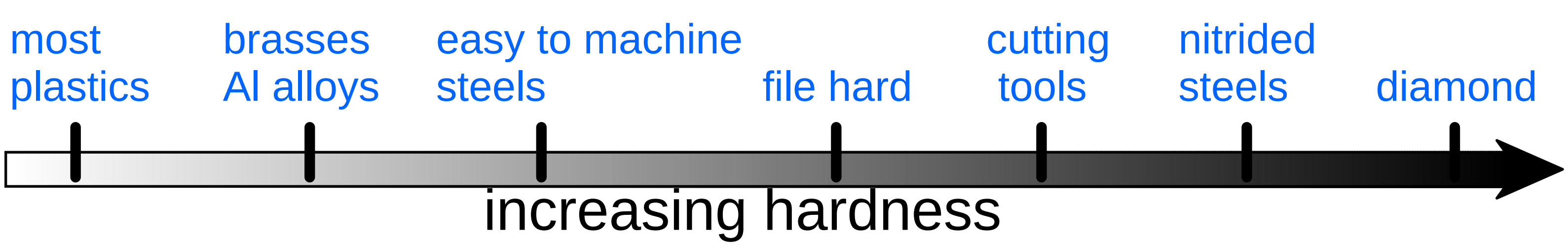
--resistance to local plastic deformation or cracking in compression.

--better wear properties.

e.g., 10mm sphere (Brinell Hardness)



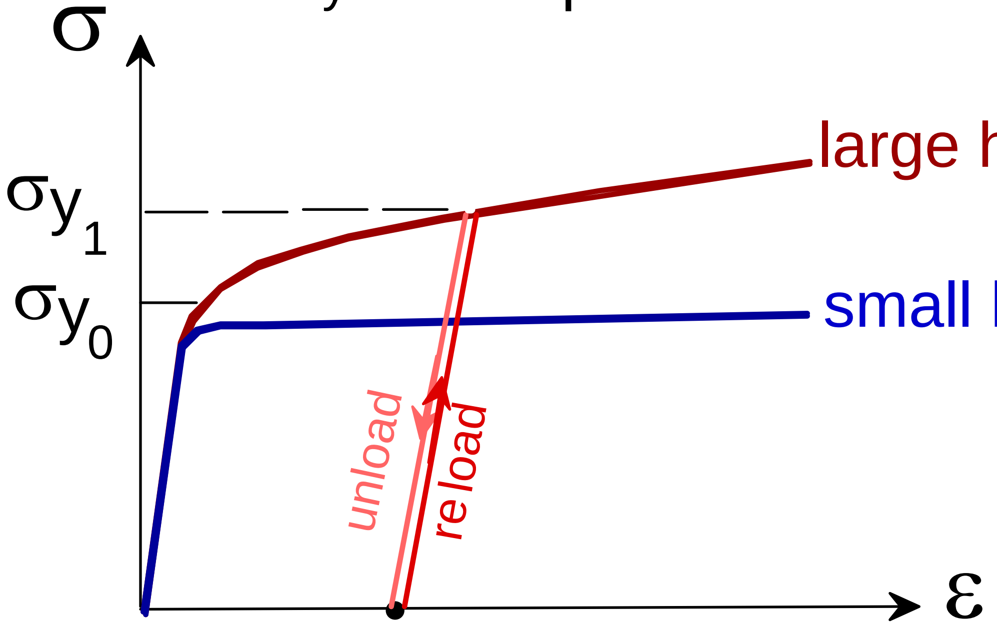
Smaller indents mean larger hardness.



Adapted from Fig. 6.18, *Callister 6e.* (Fig. 6.18 is adapted from G.F. Kinney, *Engineering Properties and Applications of Plastics*, p. 202, John Wiley and Sons, 1957.)

Strain hardening

- An increase in σ_y due to plastic deformation.



- Curve fit to the stress-strain response:

$$\sigma_T = C\left(\varepsilon_T\right)^n$$

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

“true” stress (F/A)

“true” strain: ln(L/L$_o$)

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

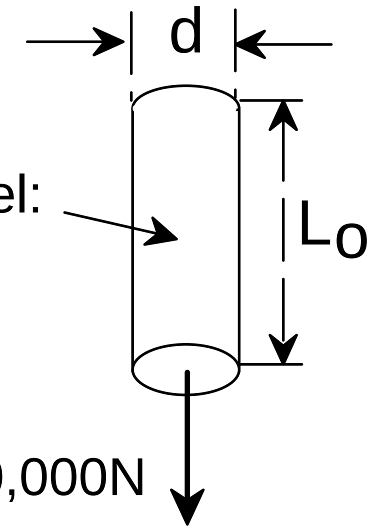
- Ex: Calculate a diameter, d, to ensure that yield does not occur in the 1045 carbon steel rod below when subjected to a load of 200, 000N. Use a factor of safety of 5.

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

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

5

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



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 σy.
- Toughness: The energy needed to break a unit volume of material.
- Resilience: Energy absorbed during elastic deformation
- Ductility: The plastic strain at failure.

ANNOUNCEMENTS

Reading: Chapter 6.1-12

Core Problems: Chapter 6, Problems 4, 8, 25, 29, 46

Self-help Problems: Review Example problems 6.2, 6.3, 6.4, 6.4, 6.5