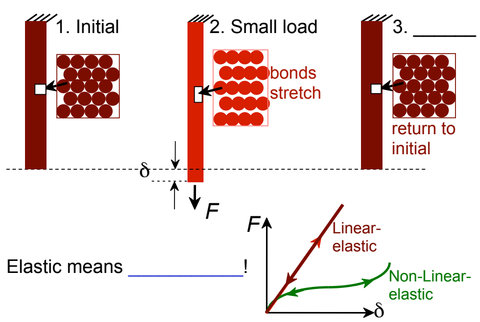
Chapter 6:
Mechanical Properties

ISSUES TO ADDRESS...

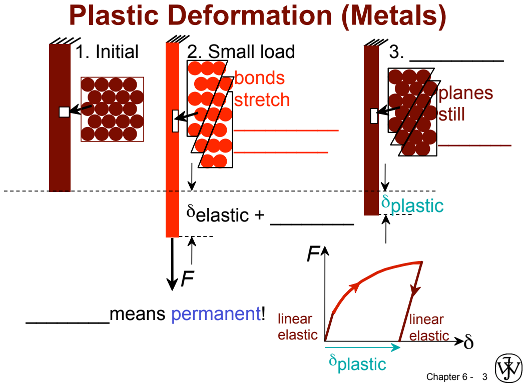
- Stress and strain: What are they and why are they used instead of _____ and deformation?
- Elastic behavior: When loads are ______, how much deformation occurs? What materials deform least?
- ________ behavior: At what point does permanent deformation occur? What materials are most resistant to permanent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

Elastic Deformation



Elastic means ____________!

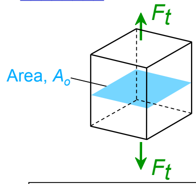
Plastic Deformation (Metals)



________means permanent!

Engineering Stress

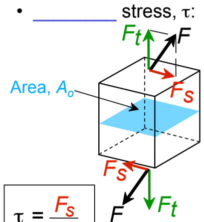
- ________ stress, σ:



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

________________ before loading

- ________ stress, τ:

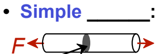


$$\tau = \frac{F_s}{A_o}$$

∴ Stress has units: N/m^2 or lb_f/in^2

Common States of ________

- **Simple ______: cable**

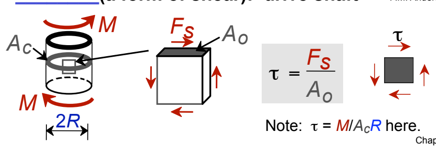


A_o = cross sectional area (when ____________)

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

Ski lift (photo courtesy P.M. Anderson)

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

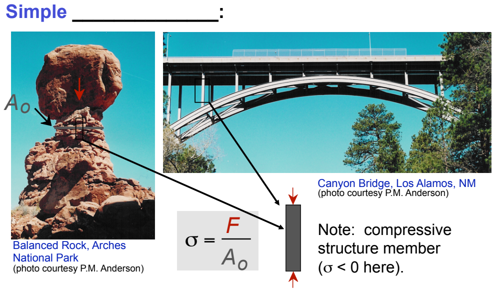


$$\tau = \frac{F_s}{A_o}$$

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

OTHER COMMON ________STATES (i)

- **Simple ______________:**



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

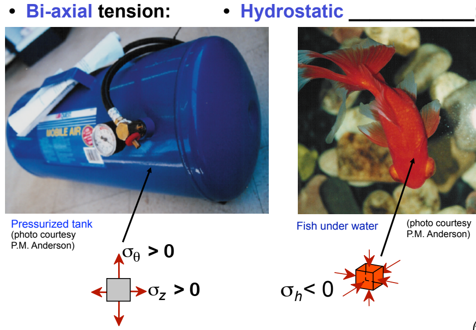
Canyon Bridge, Los Alamos, NM (photo courtesy P.M. Anderson)

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

Note: compressive structure member (σ < 0 here).

OTHER COMMON STRESS STATES (ii)

- **Bi-axial tension:**
- **Hydrostatic ___________:**



Chapter 6 - 7

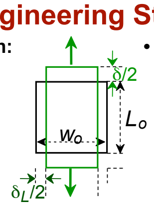
Engineering Strain

- ________ strain:

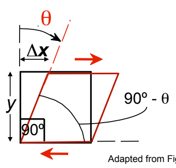
$$\varepsilon = \frac{\delta}{L_o}$$

- **Lateral strain:**

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



- _______ strain:



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

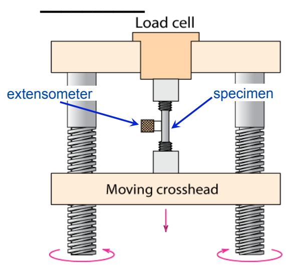
Strain is always ______________.

Adapted from Fig. 6.1(a) and (c), *Callister & Rethwisch 8e.*

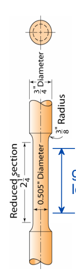
Chapter 6 - 8

Stress-Strain Testing

- **Typical tensile test ___________**



- **Typical ______ specimen**



Adapted from Fig. 6.2, *Callister & Rethwisch 8e.*

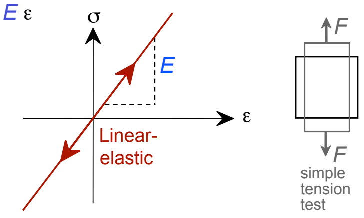
Adapted from Fig. 6.3, *Callister & Rethwisch 8e.* (Fig. 6.3 is taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)

Chapter 6 - 9

Linear Elastic Properties

- _______________, *E*:
  (also known as Young's modulus)
- ________ Law:

$\sigma = E\,\varepsilon$



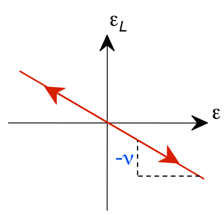
Chapter 6 - 10

Poisson's ratio, ν

- __________ ratio, ν:

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

_____: ν ~ 0.33
ceramics: ν ~ 0.25
polymers: ν ~ 0.40



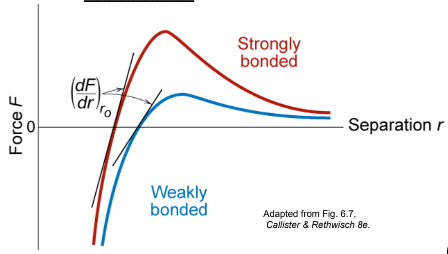
Units:
E: [GPa] or [psi]
ν: dimensionless

ν > 0.50 _______ increases
ν < 0.50 density decreases (voids form)

Chapter 6 - 11

Mechanical Properties

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



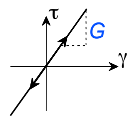
Adapted from Fig. 6.7, *Callister & Rethwisch 8e.*

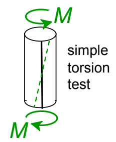
Chapter 6 - 12

Other Elastic Properties

- Elastic ________ ________, *G*:

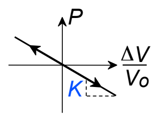
$\tau = G\gamma$

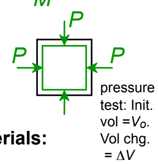




- Elastic ________ ________, *K*:

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

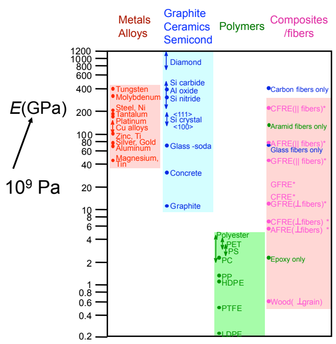




- Special relations for __________ materials:

$G = \dfrac{E}{2(1+\nu)}$ $\qquad K = \dfrac{E}{\_\_\_\_\_\_}$

Young's Moduli: Comparison

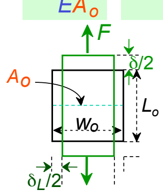


Based on data in Table B.2, *Callister & Rethwisch 8e.* Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

Useful Linear Elastic Relationships

- Simple ________:

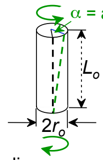
$\delta = \dfrac{FL_o}{EA_o} \qquad \delta_L = -\nu\dfrac{Fw_o}{EA_o}$



- Simple ________:

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

M = moment
α = angle of twist

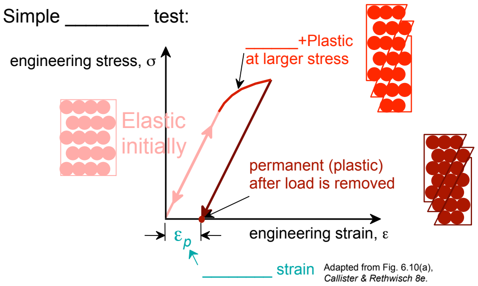


- Material, ____________, and loading parameters all contribute to deflection.
- Larger elastic moduli minimize _________ deflection.

Plastic (Permanent) Deformation

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

- Simple ________ test:



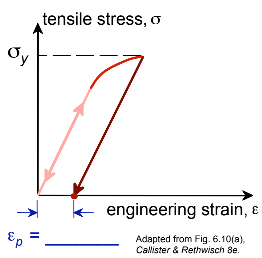
Adapted from Fig. 6.10(a), *Callister & Rethwisch 8e.*

Chapter 6 - 16

Yield Strength, σ_y

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

when ε_p = 0.002



ε_p = __________

σ_y = _______________

Note: for 2 inch sample

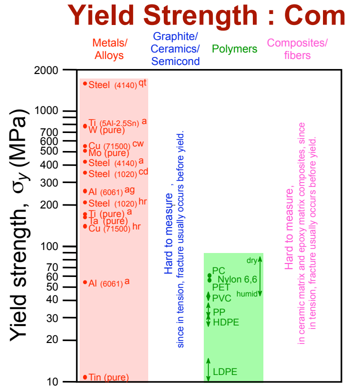
ε = ______ = $\Delta z/z$

$\therefore\ \Delta z$ = ________

Adapted from Fig. 6.10(a), *Callister & Rethwisch 8e.*

Chapter 6 - 17

Yield Strength : Comparison



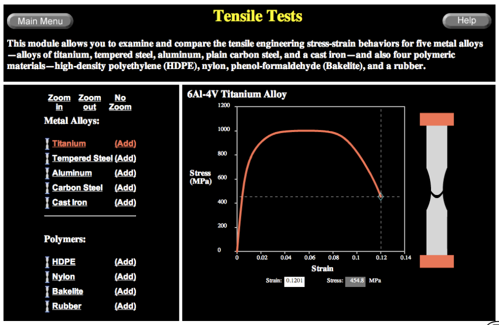
Room temperature values

Based on data in Table B.4, *Callister & Rethwisch 8e.*

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

Chapter 6 - 18

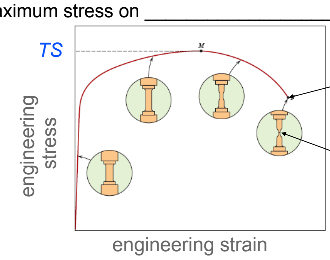
VMSE: Virtual Tensile Testing



Chapter 6 - 19

Tensile Strength, TS

• Maximum stress on ______________________________.



Adapted from Fig. 6.11, *Callister & Rethwisch 8e.*

F = fracture or

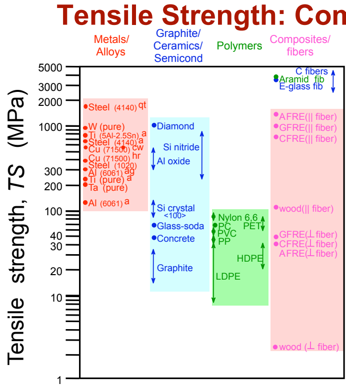
______ strength

Neck – acts as stress concentrator

• ________: occurs when noticeable necking starts.
• ________: occurs when ____________________ chains are aligned and about to break.

Chapter 6 - 20

Tensile Strength: Comparison



Room temperature values

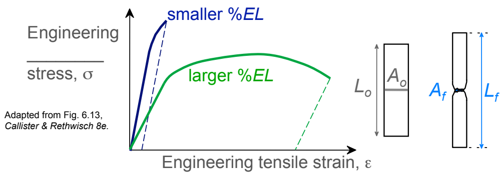
Based on data in Table B.4, *Callister & Rethwisch 8e.*

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.

Chapter 6 - 21

Ductility

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



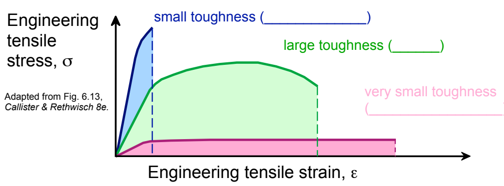
Adapted from Fig. 6.13, *Callister & Rethwisch 8e.*

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

Chapter 6 - 22

Toughness

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



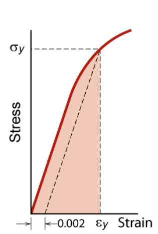
Adapted from Fig. 6.13, *Callister & Rethwisch 8e.*

Brittle fracture: elastic energy
Ductile fracture: elastic + _______ energy

Chapter 6 - 23

Resilience, U_r

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



Adapted from Fig. 6.15, *Callister & Rethwisch 8e.*

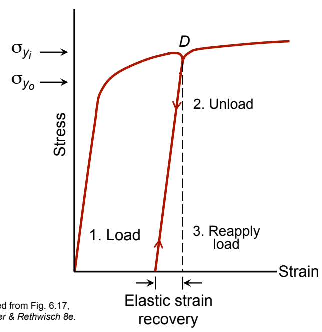
$$U_r = \int_0^{\varepsilon_y} \sigma d\varepsilon$$

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

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

Chapter 6 - 24

Elastic Strain Recovery

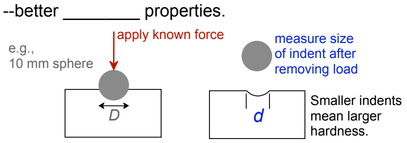


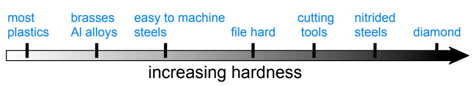
Adapted from Fig. 6.17, *Callister & Rethwisch 8e.*

Chapter 6 - 25

Hardness

- Resistance to permanently ___________ the surface.
- Large __________ means:
  - --resistance to plastic ___________ or cracking in compression.
  - --better _______ properties.





Chapter 6 - 26

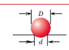
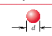
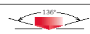
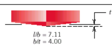
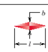
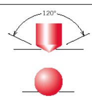
Hardness: Measurement

- Rockwell
  - No major sample _________
  - Each scale runs to 130 but only useful in range ________.
  - Minor load 10 kg
  - Major load 60 (A), 100 (B) & 150 (C) kg
    - A = diamond, B = 1/16 in. ball, C = diamond
- HB = _________ Hardness
  - *TS* (psia) = 500 x HB
  - *TS* (MPa) = 3.45 x HB

Chapter 6 - 27

Hardness: Measurement

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			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.

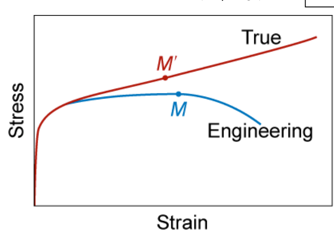
Source: Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

Chapter 6 - 28

True Stress & Strain

Note: S.A. changes when _________ stretched

- True _______ ____________ $\sigma_T = \sigma(1+\varepsilon)$
- True Strain $\varepsilon_T = \ln(\ell_i/\ell_o)$ $\varepsilon_T = \ln(1+\varepsilon)$

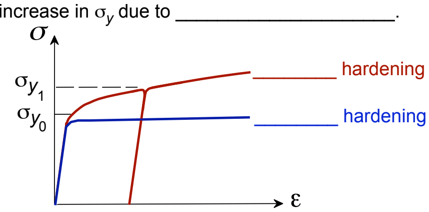


Adapted from Fig. 6.16, *Callister & Rethwisch 8e.*

Chapter 6 - 29

Hardening

- An increase in σ_y due to ___________________.



- Curve fit to the stress-strain ____________:

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

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

"true" stress (F/A)

"true" strain: $\ln(L/L_o)$

Chapter 6 - 30

Variability in Material Properties

- Elastic ________ is material property
- Critical properties depend largely on sample flaws (defects, etc.). Large sample to sample variability.
- ___________
  - Mean $\quad \bar{x} = \dfrac{\sum^{n} x_n}{n}$
  - _________________ $\quad s = \left[\dfrac{\sum^{n} \left(x_i - \bar{x} \right)^2}{n-1} \right]^{\frac{1}{2}}$

where n is the number of data points

Design or Safety Factors

- Design ______________ mean we do not push the limit.
- Factor of ___________, N

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

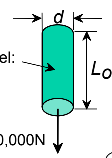
Often N is between 1.2 and 4

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

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

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

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



F = 220,000N

d = _________________

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.