ARCHITECTURAL STRUCTURES:
FORM, BEHAVIOR, AND DESIGN
ARCH 331
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SUMMER 2013

lecture
five

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mechanics of materials

Mechanics of Materials

- MECHANICS
- MATERIALS

Mechanics of Materials

- external loads and their effect on deformable bodies
- use it to answer question if structure meets requirements of
  - stability and equilibrium
  - strength and stiffness
- other principle building requirements
  - economy, functionality and aesthetics

Knowledge Required

- material properties
- member cross sections
- ability of a material to resist breaking
- structural elements that resist excessive
  - deflection
  - deformation

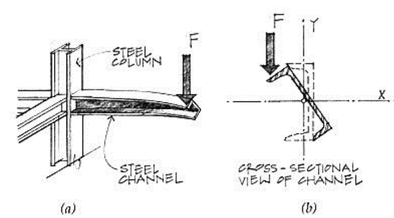
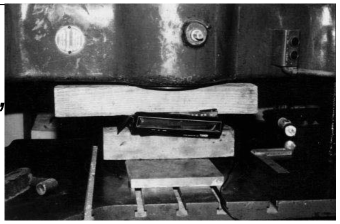


Figure 2.34 An example of torsion on a cantilever beam.

Problem Solving



1. STATICS:

   equilibrium of external forces, internal forces, stresses

2. GEOMETRY:

   cross section properties, deformations and conditions of geometric fit, strains

3. MATERIAL PROPERTIES:

   stress-strain relationship for each material obtained from testing

Stress

- *stress is a term for the intensity of a force, like a pressure*
- *internal or applied*
- *force per unit area*

$$stress = f = \frac{P}{A}$$

Design

- *materials have a critical stress value where they could break or yield*
  - *ultimate stress*
  - *yield stress*
  - *compressive stress*
  - *fatigue strength*
  - *(creep & temperature)*

acceptance vs. failure (applies to the first four items above)

Design (cont)

- *we'd like*

$$f_{actual} << F_{allowable}$$

- *stress distribution may vary: average*
- *uniform distribution exists IF the member is loaded axially (concentric)*

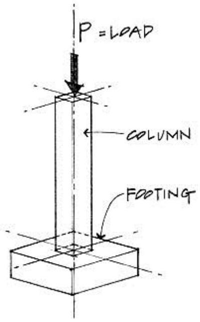
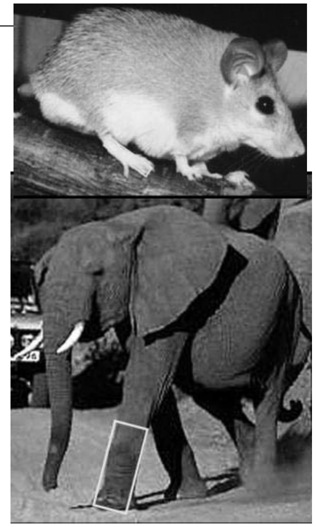


Figure 5.3 Centric loads.

Scale Effect

- model scale
  - material weights by volume, small section areas
- structural scale
  - much more material weight, bigger section areas
- scale for strength is not proportional: $\dfrac{\gamma L^3}{L^2} = \gamma L$



Normal Stress (direct)

- normal stress is normal to the cross section
  - stressed area is perpendicular to the load

$$f_{t\ or\ c} = \frac{P}{A}$$
$$(\sigma)$$

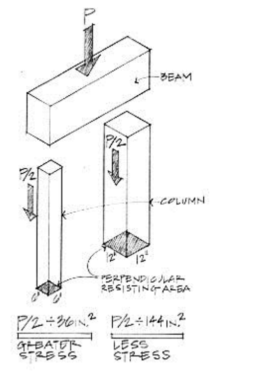


Figure 5.7 Two columns with the same load, different stress.

Shear Stress

- stress parallel to a surface

$$f_v = \frac{P}{A} = \frac{P}{td}$$
$$(\tau_{ave})$$

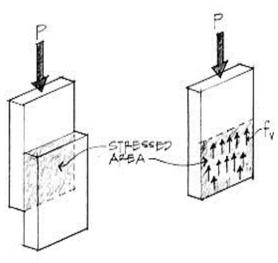


Figure 5.10 Shear stress between two glued blocks.

Bearing Stress

- stress on a surface by contact in compression

$$f_p = \frac{P}{A} = \frac{P}{td}$$
$$(\sigma)$$

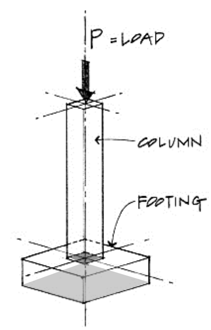


Figure 5.3 Centric loads.

Bending Stress

- *normal stress caused by bending*

$$f_b = \frac{Mc}{I} = \frac{M}{S}$$
$$(\sigma)$$

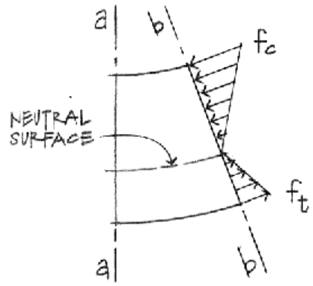
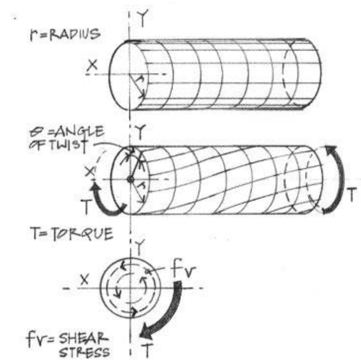


Figure 8.8 Bending stresses on section b-b.

Torsional Stress

- *shear stress caused by twisting*

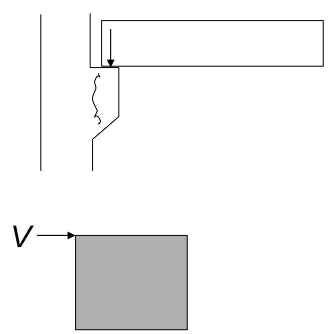
$$f_v = \frac{T\rho}{J}$$
$$(\tau)$$



Structures and Shear

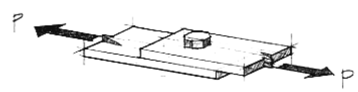
- *what structural elements see shear?*
  - *beams*
  - *bolts*
  - *splices*
  - *slabs*
  - *footings*
  - *walls*
    - *wind*
    - *seismic loads*

beams, bolts, splices: connections

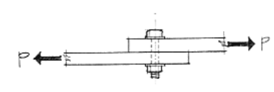


Bolts

- *connected members in tension cause shear stress*

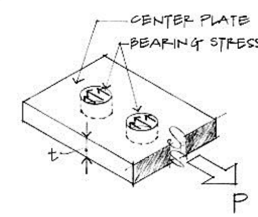


(a) Two steel plates bolted using one bolt.



(b) Elevation showing the bolt in

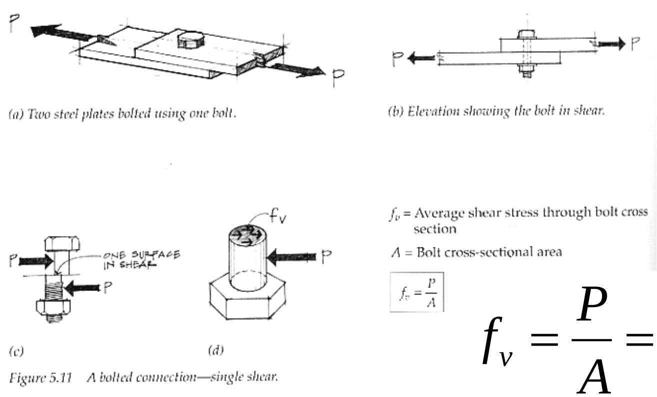
- *connected members in compression cause bearing stress*



Bearing stress on plate.

Single Shear

- seen when 2 members are connected



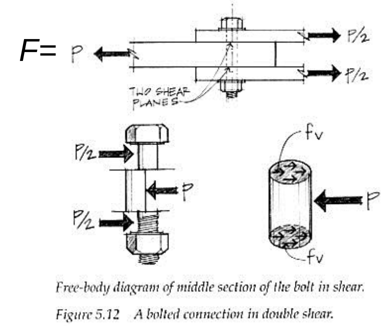
$$f_v = \frac{P}{A} = \frac{P}{\pi \frac{d^2}{4}}$$

Double Shear

- seen when 3 members are connected
- <u>two</u> areas

$f_v = \frac{P}{2A}$

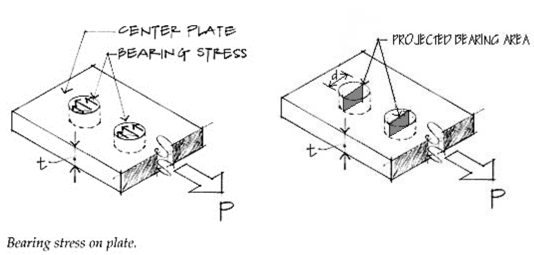
(two shear planes)



$$f_v = \frac{P}{2A} = \frac{P/2}{A} = \frac{P/2}{\pi \, d^2/4}$$

Bolt Bearing Stress

- compression & contact
- projected area

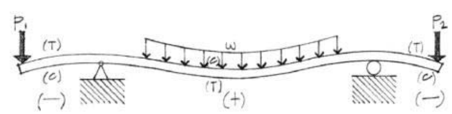


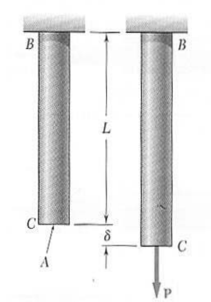
Bearing stress on plate.

$$f_p = \frac{P}{A_{projected}} = \frac{P}{td}$$

Strain

- materials deform
- axially loaded materials change length
- bending materials deflect



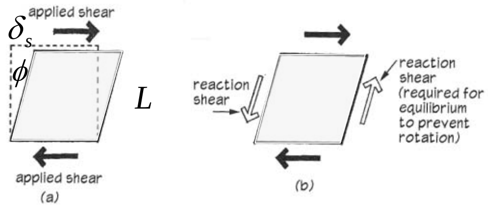


- STRAIN:
  - change in length over length + UNITLESS

$$strain = \varepsilon = \frac{\Delta L}{L}$$

Shearing Strain

- deformations with shear
- parallelogram
- change in angles
- stress: τ
- strain: γ
  - unitless (radians)

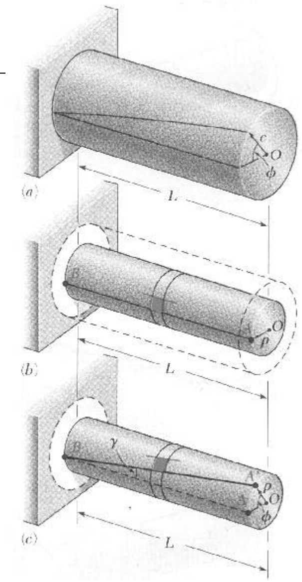


$$\gamma = \frac{\delta_s}{L} = \tan\phi \cong \phi$$

Shearing Strain

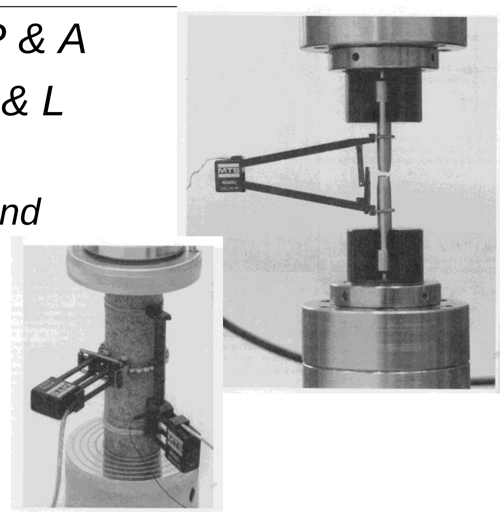
- deformations with torsion
- twist
- change in angle of line
- stress: τ
- strain: γ
  - unitless (radians)

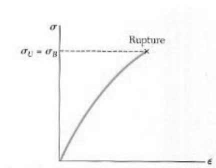
$$\gamma = \frac{\rho\phi}{L}$$



Load and Deformation

- for stress, need P & A
- for strain, need δ & L
  - how?
  - TEST with load and measure
  - plot P/A vs. ε





Material Behavior

- every material has its own response
  - 10,000 psi
  - L = 10 in
  - Douglas Fir vs. steel?

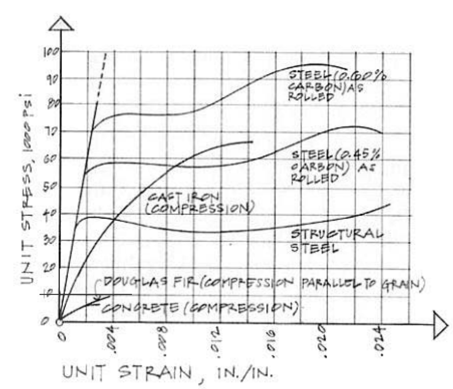


Figure 5.20 Stress-strain diagram for various materials.

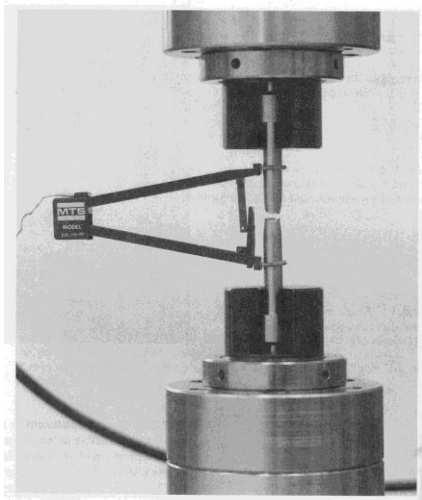
Behavior Types

- ductile - “necking”
- true stress

$$f = \frac{P}{A}$$

- engineering stress
  – (simplified)

$$f = \frac{P}{A_o}$$



Behavior Types

- brittle

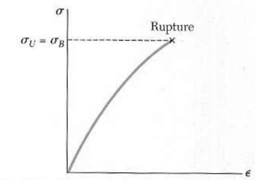


Fig. 2.11 Stress-strain diagram for a typical brittle material.

- semi-brittle

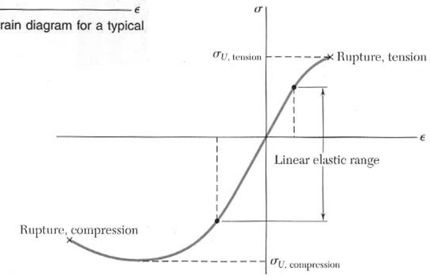


Fig. 2.14 Stress-strain diagram for concrete.

Stress to Strain

- important to us in f-ε diagrams:
  – straight section
  – LINEAR-ELASTIC
  – recovers shape (no permanent deformation)

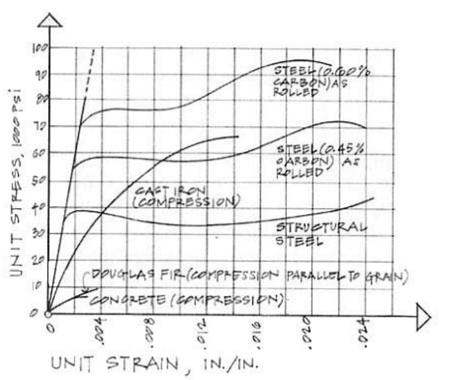
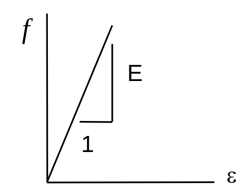


Figure 5.20 Stress-strain diagram for various materials.

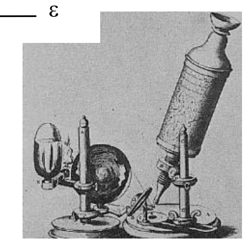
Hooke’s Law

- straight line has constant slope
- Hooke’s Law

$$f = E \cdot \varepsilon$$



- E
  – Modulus of elasticity
  – Young’s modulus
  – units just like stress



Stiffness

- *ability to resist strain*
- *steels*
  - *same E*
  - *different <u>yield points</u>*
  - *different <u>ultimate strength</u>*

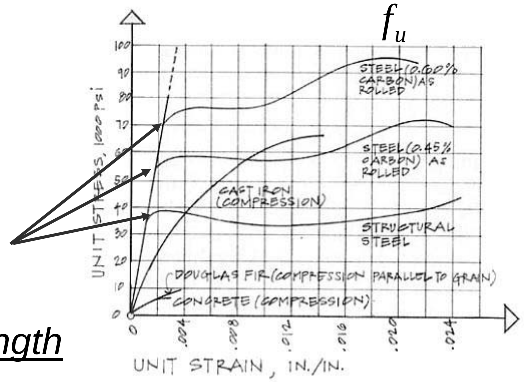
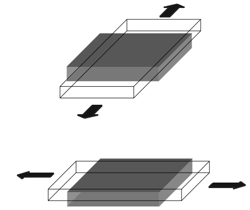


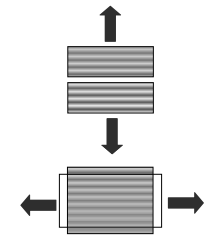
Figure 5.20 Stress-strain diagram for various materials.

Isotropy & Anisotropy

- *ISOTROPIC*
  - *materials with E same at any direction of loading*
  - *ex. steel*

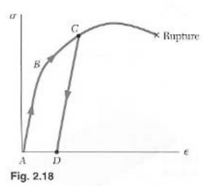


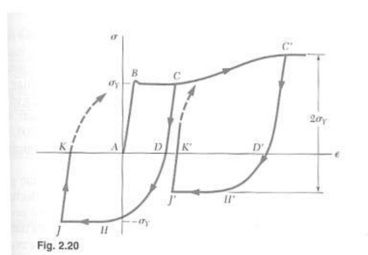
- *ANISOTROPIC*
  - *materials with different E at any direction of loading*
  - *ex. wood is <u>orthotropic</u>*



Elastic, Plastic, Fatigue

- *elastic springs back*
- *plastic has permanent deformation*
- *fatigue caused by reversed loading cycles*





Plastic Behavior

- *ductile*

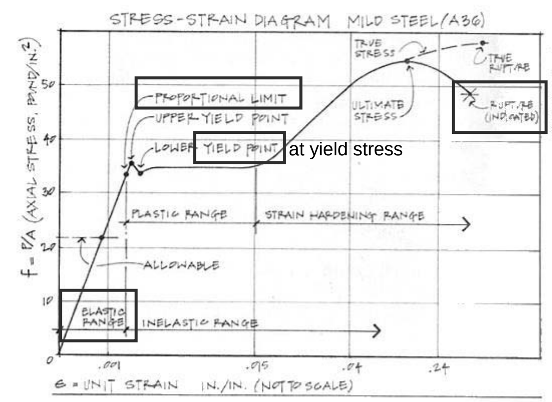
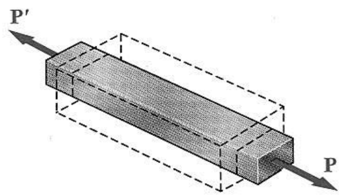


Figure 5.22 Stress-strain diagram for mild steel (A36) with key points highlighted.

Lateral Strain

- or "what happens to the cross section with axial stress"



$$\varepsilon_x = \frac{f_x}{E}$$

$$f_y = f_z = 0$$

- strain in lateral direction
  - negative
  - equal for isometric materials

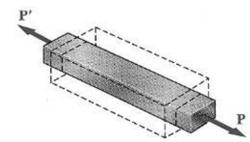
$$\varepsilon_y = \varepsilon_z$$

Poisson's Ratio

- constant relationship between longitudinal strain and lateral strain

$$\mu = -\frac{lateral\ strain}{axial\ strain} = -\frac{\varepsilon_y}{\varepsilon_x} = -\frac{\varepsilon_z}{\varepsilon_x}$$

$$\varepsilon_y = \varepsilon_z = -\frac{\mu f_x}{E}$$



- sign! $0 < \mu < 0.5$

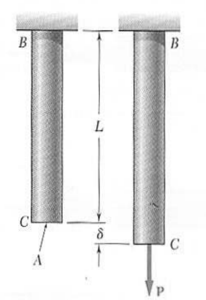
Calculating Strain

- from Hooke's law

$$f = E \cdot \varepsilon$$

- substitute

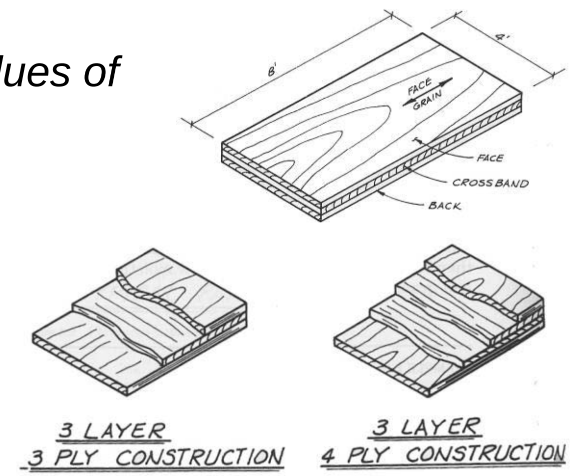
$$\frac{P}{A} = E \cdot \frac{\delta}{L}$$



- get $\Rightarrow$ $\delta = \frac{PL}{AE}$

Orthotropic Materials

- non-isometric
- directional values of E and μ
- ex:
  - plywood
  - laminates
  - polymer composites



Stress Concentrations

- why we use f_{ave}
- increase in stress at changes in geometry
  - sharp notches
  - holes
  - corners

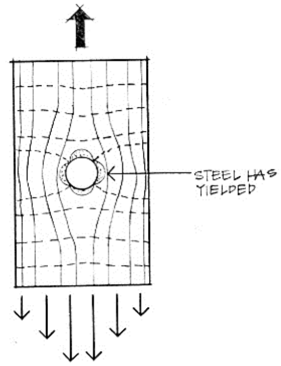
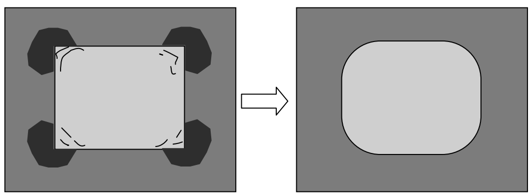
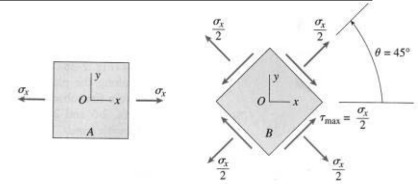


Figure 5.35 Stress trajectories around a hole.



Maximum Stresses

- if we need to know where max f and f_v happen:



$$\theta = 0° \rightarrow \cos\theta = 1 \qquad f_{max} = \frac{P}{A_o}$$

$$\theta = 45° \rightarrow \cos\theta = \sin\theta = \sqrt{0.5}$$

$$f_{v-max} = \frac{P}{2A_o} = \frac{f_{max}}{2}$$

Maximum Stresses

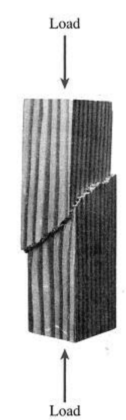
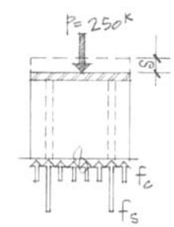


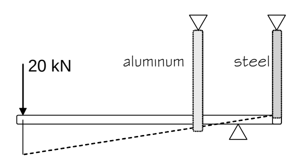
FIG. 2-37 Shear failure along a 45° plane of a wood block loaded in compression

FIG. 2-38 Slip bands (or Lüders' bands) in a polished steel specimen loaded in tension

Deformation Relationships

- physical movement
  - axially (same or zero)
  - rotations from axial changes

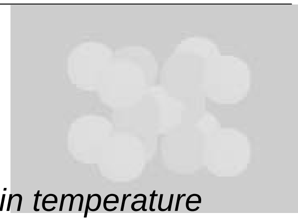


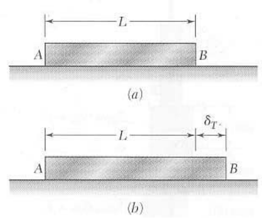


- $\delta = \dfrac{PL}{AE}$ relates δ to P

Deformations from Temperature

- atomic chemistry reacts to changes in energy
- solid materials
  - can contract with decrease in temperature
  - can expand with increase in temperature
- linear change can be measured per degree



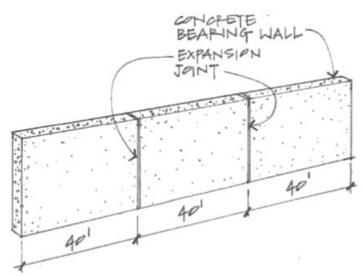


Thermal Deformation

- α - the rate of strain per degree
- UNITS : $/{}^{\circ}F$, $/{}^{\circ}C$
- length change: $\delta_T = \alpha(\Delta T)L$
- thermal strain: $\varepsilon_T = \alpha(\Delta T)$
  - <u>no stress</u> when movement allowed

Coefficients of Thermal Expansion

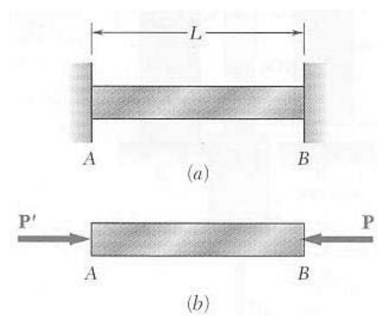
Material	Coefficients (α) [in./in./°F]
Wood	3.0×10^{-6}
Glass	4.4×10^{-6}
Concrete	5.5×10^{-6}
Cast Iron	5.9×10^{-6}
Steel	6.5×10^{-6}
Wrought Iron	6.7×10^{-6}
Copper	9.3×10^{-6}
Bronze	10.1×10^{-6}
Brass	10.4×10^{-6}
Aluminum	12.8×10^{-6}



Stresses and Thermal Strains

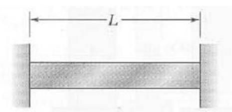
- if thermal movement is restrained <u>stresses</u> are induced

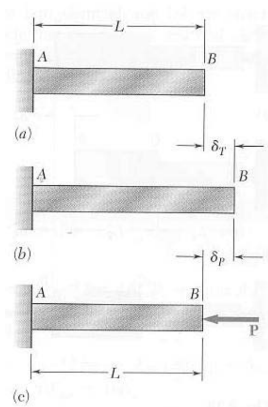
1. bar pushes on supports
2. support pushes back
3. reaction causes internal stress $f = \frac{P}{A} = \frac{\delta}{L}E$



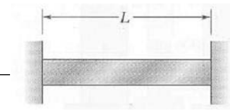
Superposition Method

- can remove a support to make it look determinant
- replace the support with a reaction
- enforce the geometry constraint





Superposition Method



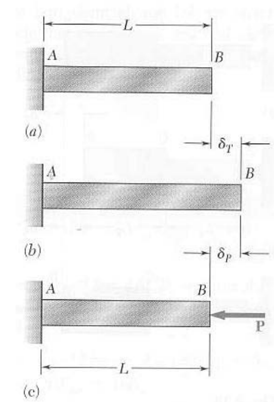
- total length change restrained to <u>zero</u>

constraint: $\delta_P + \delta_T = 0$

$$\delta_p = -\frac{PL}{AE} \qquad \delta_T = \alpha\left(\Delta T\right)L$$

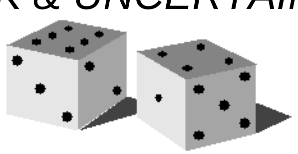
sub: $$-\frac{PL}{AE} + \alpha\left(\Delta T\right)L = 0$$

$$f = -\frac{P}{A} = -\alpha\left(\Delta T\right)E$$



Design of Members

- beyond allowable stress...
- materials aren't uniform 100% of the time
  - ultimate strength or capacity to failure may be different and some strengths hard to test for
- RISK & UNCERTAINTY



$$f_u = \frac{P_u}{A}$$

Factor of Safety

- accommodate uncertainty with a safety factor:

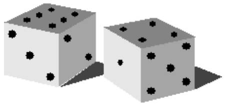
$$\text{allowable load} = \frac{\text{ultimate load}}{F.S}$$

- with linear relation between load and stress:

$$F.S = \frac{\text{ultimate load}}{\text{allowable load}} = \frac{\text{ultimate stress}}{\text{allowable stress}}$$

Load and Resistance Factor Design

- *loads on structures are*
  - *not constant*
  - *can be more influential on failure*
  - *happen more or less often*
  - *UNCERTAINTY*



$$R_u = \gamma_D R_D + \gamma_L R_L \le \phi R_n$$

ϕ - *resistance factor*

γ - *load factor for (D)ead & (L)ive load*