Week 8, 19 & 21 March

Mechanics in Energy Resources Engineering - Chapter 5 Stresses in Beams (Basic topics)

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Shear Forces and Bending Moments
Review (Chapter 4)

- Introduction
- Types of Beams, Loads, and Reactions
- Shear Forces and Bending Moments
- Relationships Between Loads, Shear Forces and Bending Moments
- Shear-Force and Bending-Moment Diagrams

Preview (Chapter 5)

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- Introduction
- Pure Bending and Nonuniform Bending
- Curvature of Beam
- Longitudinal Strains in Beams
- Normal Stress in Beams
- Design of Beams for Bending Stresses
- Nonprismatic Beams
- Shear Stresses in Beams of Rectangular Cross Section
- Shear Stresses in Beams of Circular Cross Section
- Shear Stresses in the Webs of Beams with Flanges

Shear-Force and Bending-Moment Diagrams

Concentrated Load

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- Shear Force Diagram,

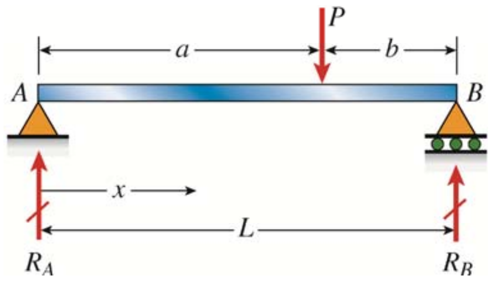
$$V = \frac{Pb}{L} \qquad (0 < x < a)$$

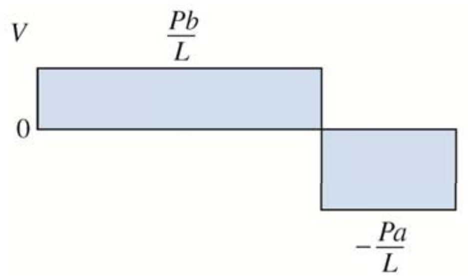
$$V = -\frac{Pa}{L} \qquad (0 < x < a)$$

- Bending Moment Diagram

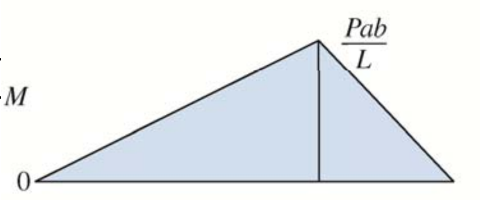
$$M = \frac{Pbx}{L} \qquad (a < x < L)$$

$$M = \frac{Pa}{L}(L - x) \qquad (a < x < L$$





Slope dV/dx =0
→ q=0
Area for x < a
→ increase in M
Area for a<x<b
→ decrease in M



Slope dM/dx = V

Shear-Force and Bending-Moment Diagrams
Uniform Load

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- From Moment Equilibrium,

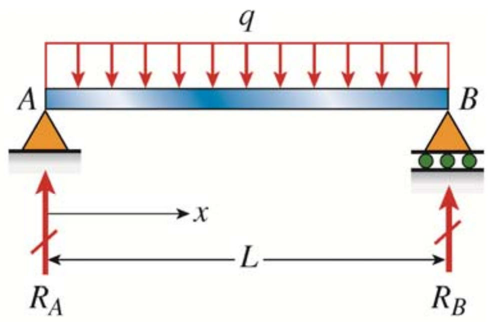
$$R_A = R_B = \frac{qL}{2}$$

- From Free Body Diagram,

$$V = R_A - qx = \frac{qL}{2} - qx$$

$$M = R_A x - qx\left(\frac{x}{2}\right) = \frac{qLx}{2} - \frac{qx^2}{2}$$

- Slope of V?
- Slope of M?



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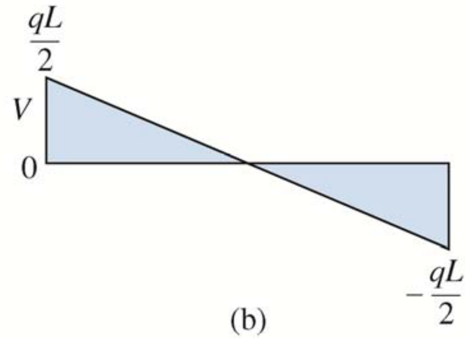

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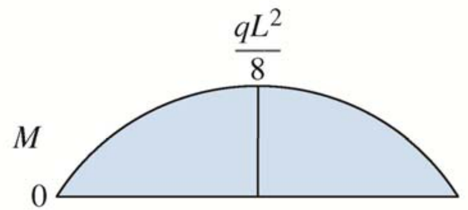

(c)

Shear-Force and Bending-Moment Diagrams
Several Concentrated Loads

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- From Moment Equilibrium,

$$R_A + R_B = P_1 + P_2 + P_3$$

- From Free Body Diagram,

$$V = R_A \quad M = R_A x \qquad (0 < x < a_1)$$

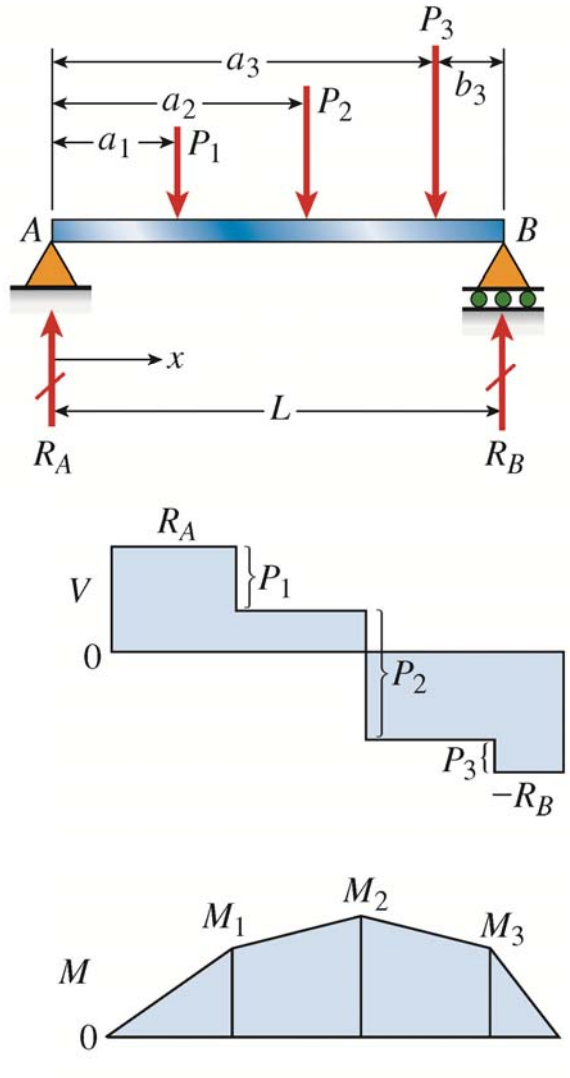
$$V = R_A - P_1 \quad M = R_A x - P_1(x - a_1) \qquad (a_1 < x < a_2)$$

$$V = -R_B + P_3$$

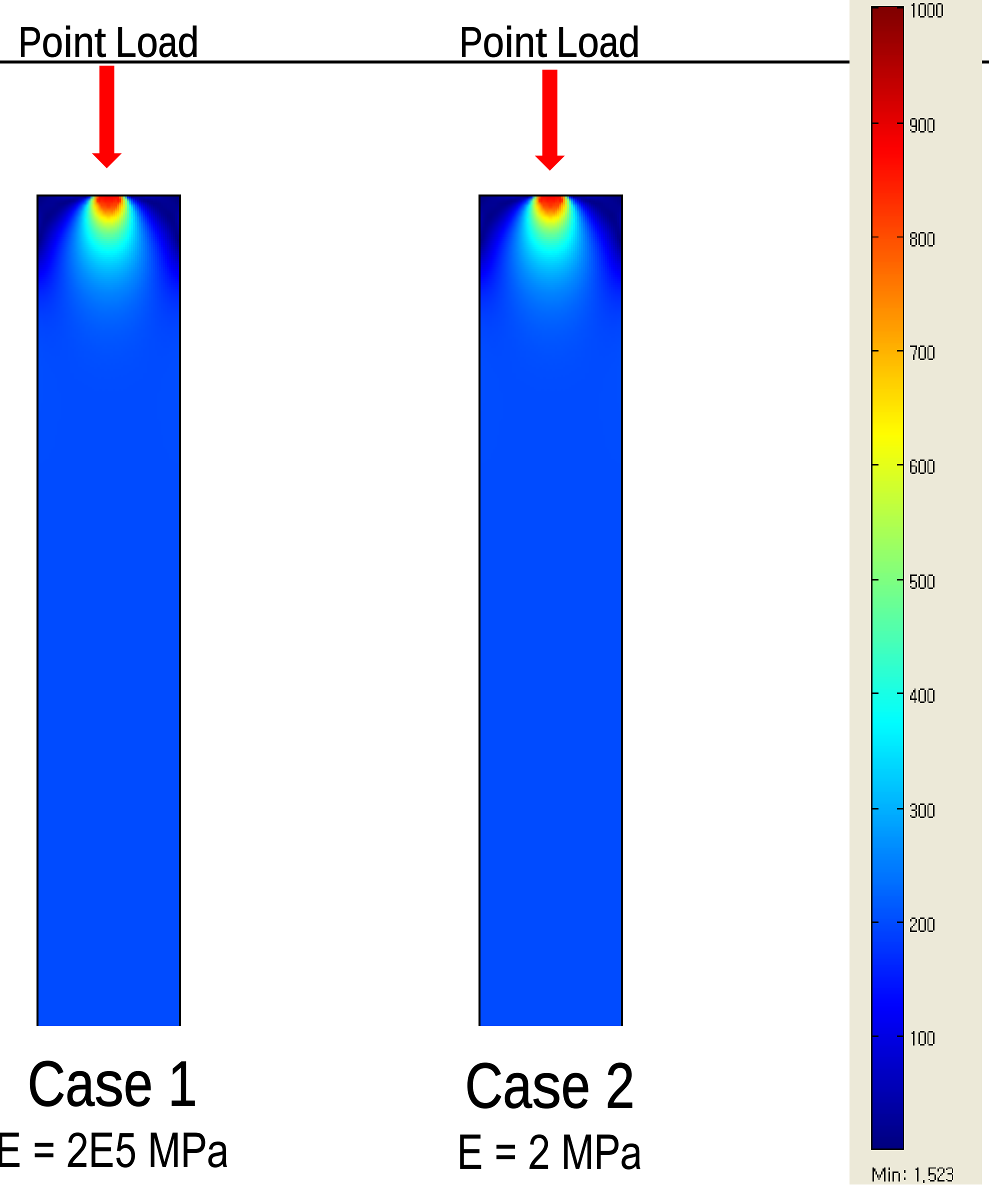
$$M = R_B(L - x) - P_3(L - b_3 - x) \qquad (a_2 < x < a_3)$$

$$V = -R_B$$

$$M = R_B(L - x) \qquad (a_3 < x < L)$$



Saint-Venant Principle
Effect of material property?



Case 1
E = 2E5 MPa

Case 2
E = 2 MPa

Outline

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- Introduction
- Pure Bending and Nonuniform Bending
- Curvature of Beam
- Longitudinal Strains in Beams
- Normal Stress in Beams
- Design of Beams for Bending Stresses
- Nonprismatic Beams
- Shear Stresses in Beams of Rectangular Cross Section
- Shear Stresses in Beams of Circular Cross Section
- Shear Stresses in the Webs of Beams with Flanges

Introduction

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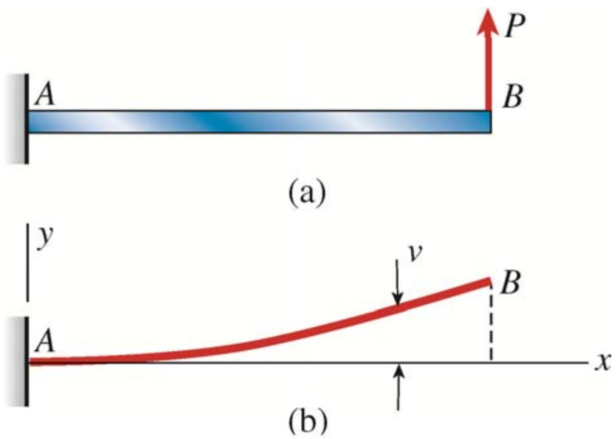
- Chapter 4 → Shear forces (V) & Bending Moments (M).
- How about stresses and strains associated with V & M?
- Assumption:
  - Beams are symmetric about the xy plane.
  - y-axis is an axis of symmetry of the cross section
  - All loads act in this same plane, known as the plane of bending



Pure Bending and Nonuniform Bending

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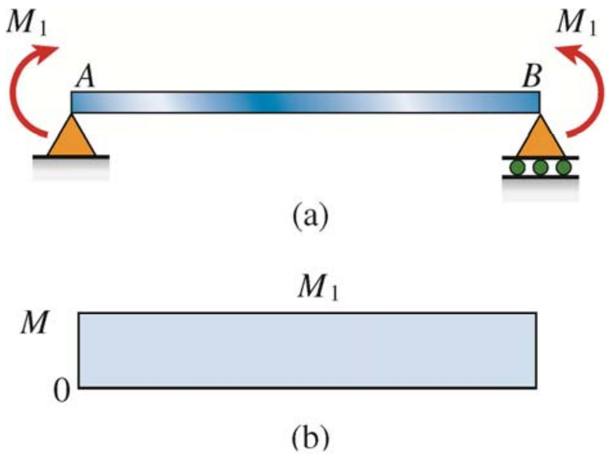
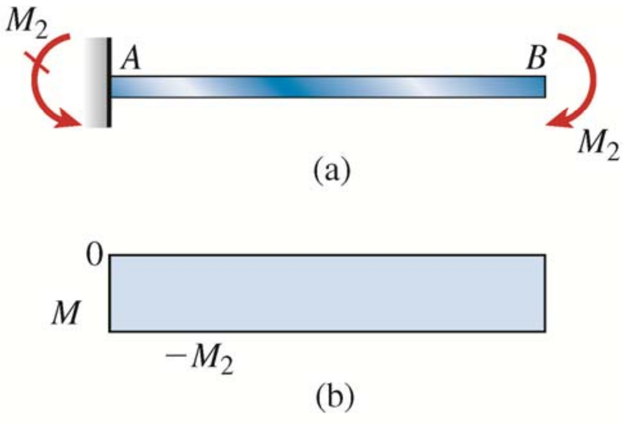
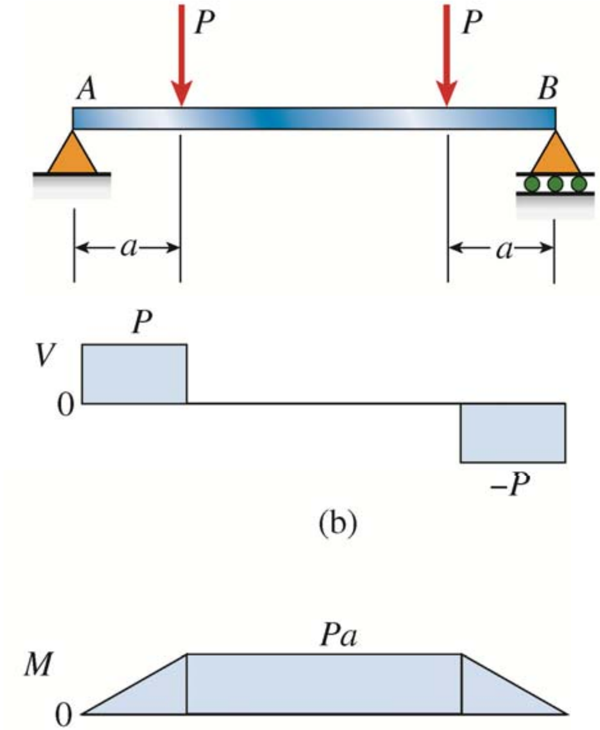
- Pure Bending:
  - Flexure of a beam under a constant bending moment.
  - Occurs only in regions with zero shear force
- Nonuniform bending
  - Flexure in the presence of shear forces
  - Bending moment changes
- Simple beam AB loaded by two couples M_1
  - Constant bending moment & shear force 0



Pure Bending and Nonuniform Bending
Other examples





nonuniform bending

Pure bending

nonuniform bending

Curvature of a Beam
definition

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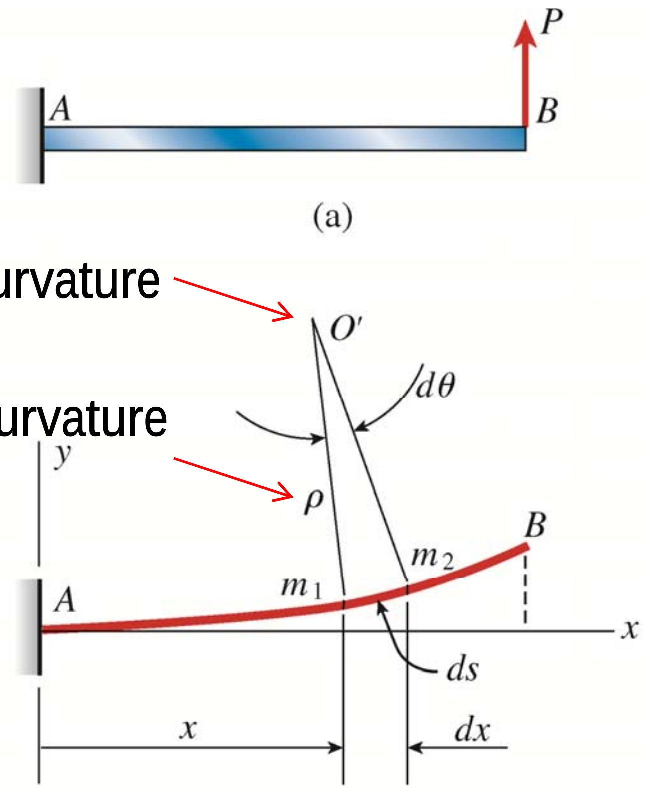
- Strains and stresses due to lateral load are directly related to the curvature of deflection curve.
  - Two points m_1 & m_2 on the deflection curve
  - Center of curvature
  - Radius of curvature
- Curvature (κ, 곡률, 曲率): reciprocal of the radius of curvature
  - Measure of how sharply a beam is bent

$$\kappa = \frac{1}{\rho}$$



Curvature of a Beam

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- From the geometry of triangle $O'm_1m_2$,

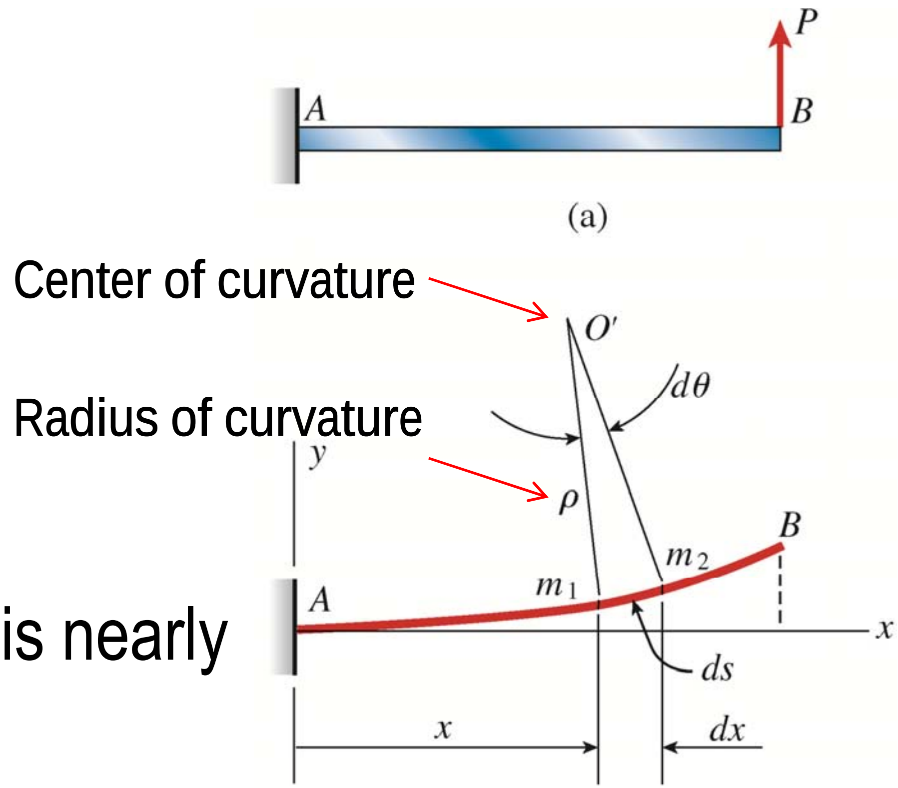
$$\rho d\theta = ds$$

- By rearranging,

$$\boxed{\kappa = \frac{1}{\rho} = \frac{d\theta}{ds}}$$

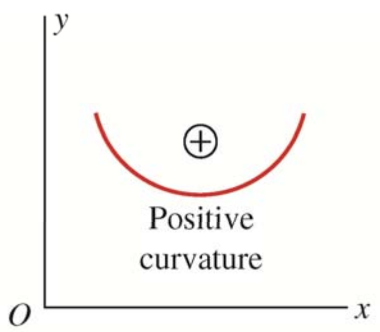
- Under the assumption of small deflections → deflection curve is nearly flat

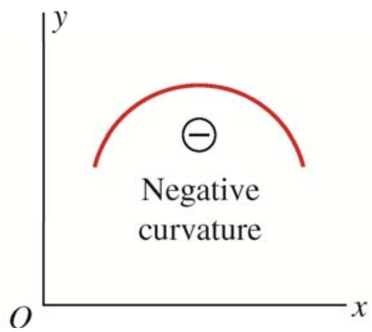
$$\boxed{\kappa = \frac{1}{\rho} = \frac{d\theta}{dx}}$$



Curvature of a Beam
sign convention

- Sign convention of curvature
  - (+) : beam is bent concave upward (위로 오목)
  - (-): beam is bent concave downward (아래로 오목)





Longitudinal Strains in Beams

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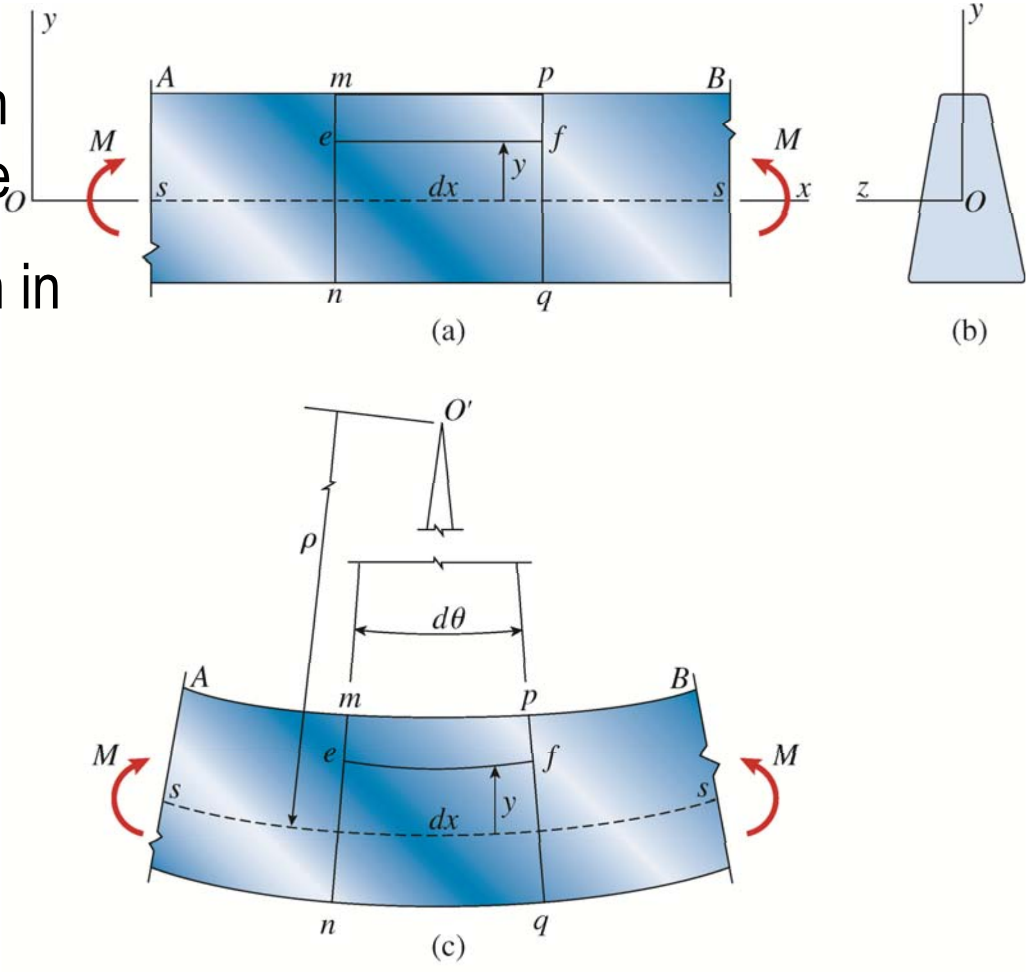
- Basic assumption:
  - Cross section of a beam in pure bending remain plane
  - (There can be deformation in the plane itself)
- Upper part: shorten→ compression
- Lower part: elongate→ tension



Longitudinal Strains in Beams

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– Neutral surface: no longitudinal strain

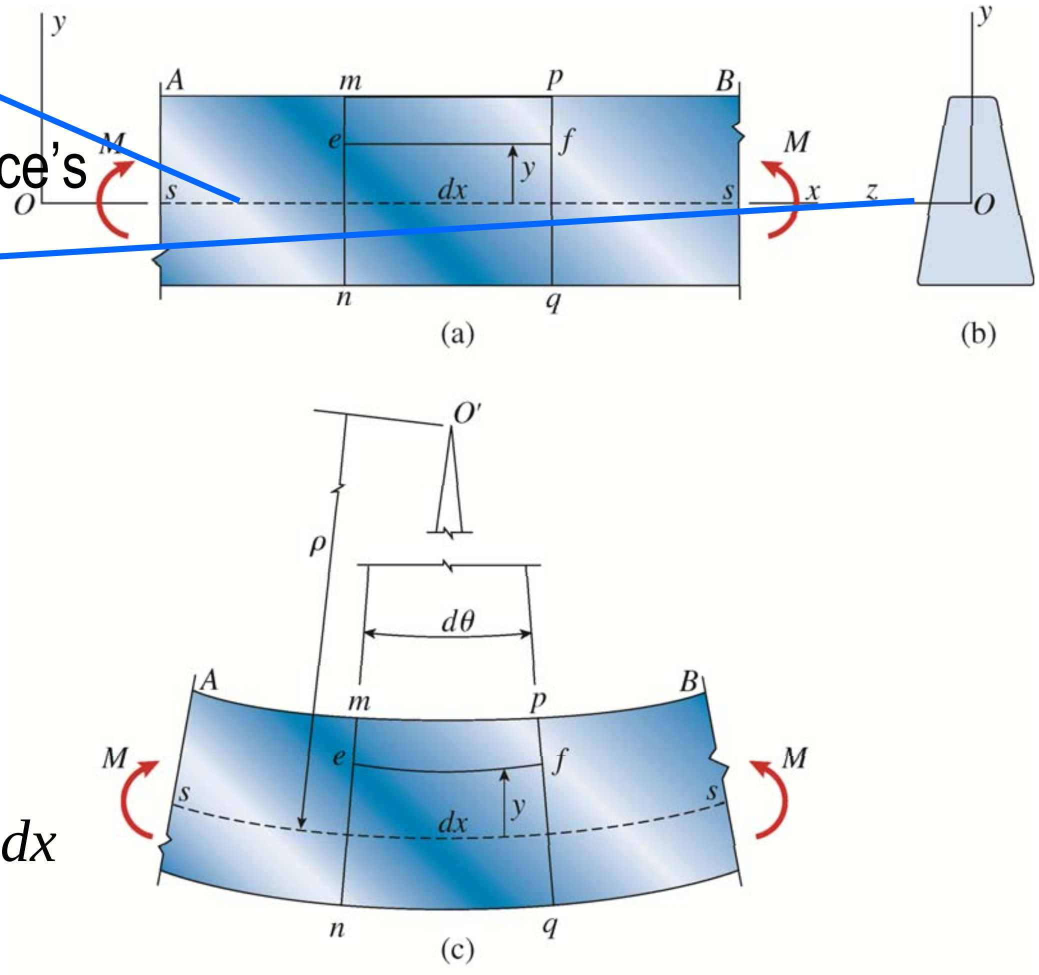
– Neutral axis: neutral surface's intersection with cross-sectional plane

– At neutral surface:

$$dx = \rho d\theta$$

– Length L1 of line *ef* after bending

$$L_1 = (\rho - y)d\theta = dx - \frac{y}{\rho}dx$$



Longitudinal Strains in Beams

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- Longitudinal strain

$$\varepsilon_x = -\frac{y}{\rho} = -\kappa y$$

  - Strain-curvature relation
  - Longitudinal strain is proportional to the curvature & distance y from the neutral surface (regardless of the material)
  - Longitudinal stress expected
  - Transverse strains due to Poisson's ratio → does not induce transverse stress, why?

Normal Stress in Beams

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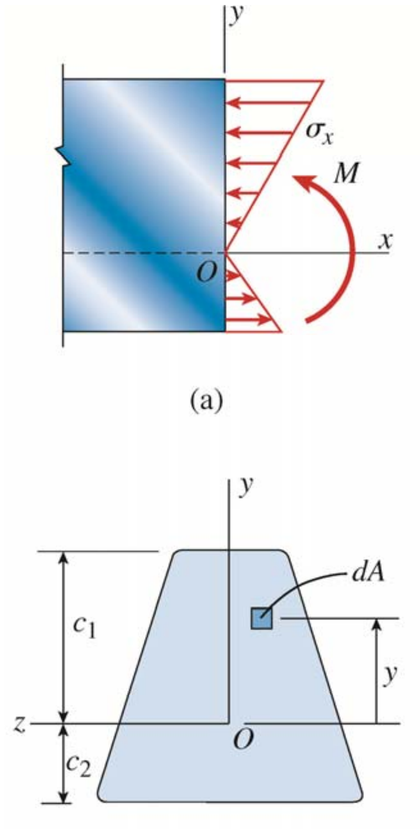
- From Hooke's Law,

$$\sigma_x = E\varepsilon_x = -\frac{Ey}{\rho} = -E\kappa y$$

  - Stresses are compression above the neutral surface with positive curvature
  - Still not practical. Why?
  - Determine y & relationship between κ (curvature) and M (Bending Moment)



Normal Stress in Beams

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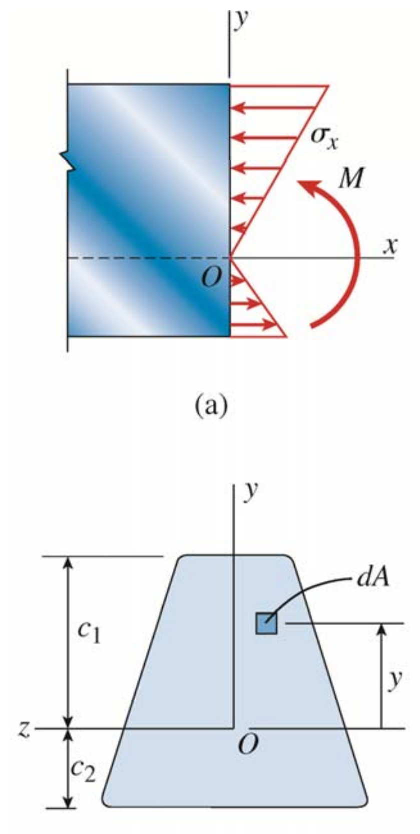
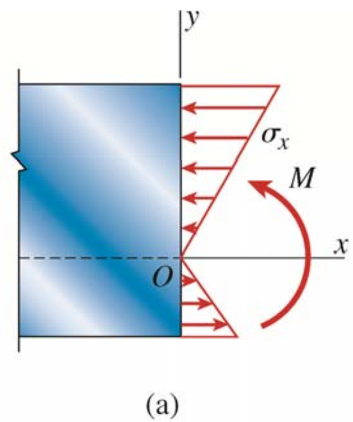
- Resultant of the normal stresses
  - Resultant force in x direction is zero
  - The resultant moment is equal to the bending moment M



Normal Stress in Beams
Location of Neutral Axis

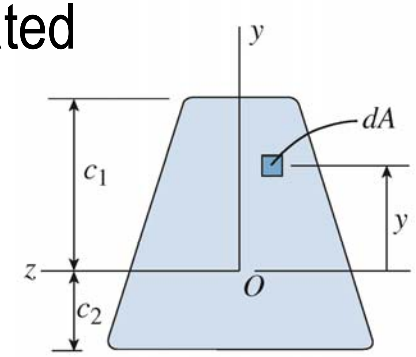
- Because there is no resultant force acting on the cross section



$$\int_A \sigma_x dA = -\int_A E\kappa y dA = 0$$

$$\int_A y dA = 0$$

  – First moment of the area of the cross section evaluated with respect to z-axis is zero. → z-axis must pass through the centroid.



  – Y axis is also axis of symmetry

- The origin O of coordinates is located at the centroid of the cross sectional area

Normal Stress in Beams
Moment-Curvature Relationship

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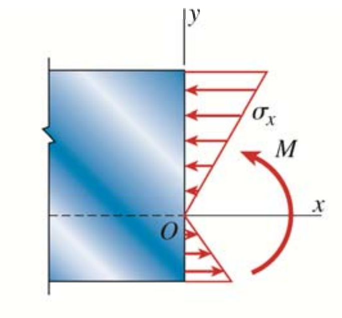
- Elemental moment

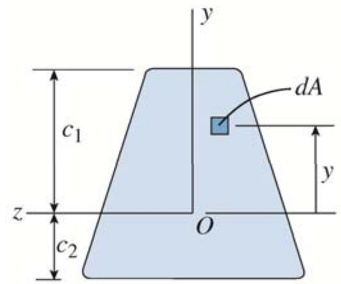
$$dM = -\sigma_x y dA$$

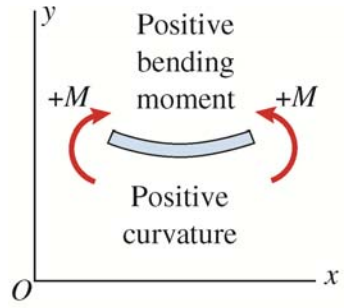
$$M = \int_A \kappa E y^2 dA = \kappa E \int_A y^2 dA$$

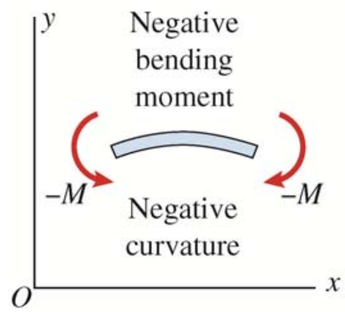
$$M = \kappa EI \qquad I = \int_A y^2 dA$$



(a)







- Moment-Curvature Equation

$$\kappa = \frac{1}{\rho} = \frac{M}{EI}$$

Flexural rigidity: a measure of the resistance of a beam to bending

Normal Stress in Beams
Flexure Formula (굽힘 공식)

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- Finally, bending stress due to bending moment is:

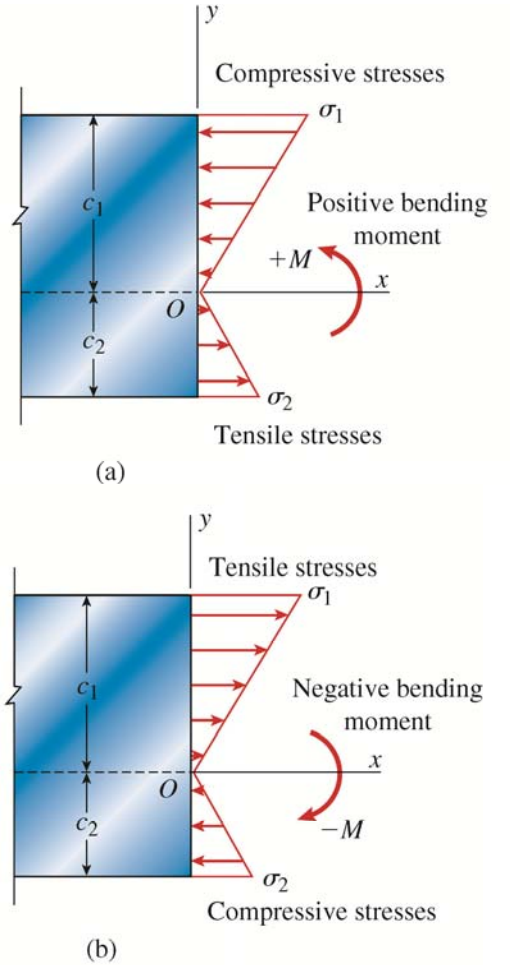
$$\sigma_x = -\frac{My}{I}$$

Bending stress

- Maximum tensile and compressive bending stresses occur at points located farthest from the neutral axis.

$$\sigma_1 = -\frac{Mc_1}{I} = -\frac{M}{S_1} \qquad \sigma_2 = \frac{Mc_2}{I} = \frac{M}{S_2}$$

$$S_1 = \frac{I}{c_1} \qquad S_2 = \frac{I}{c_2}$$



Normal Stress in Beams
Flexure Formula (굽힘 공식)

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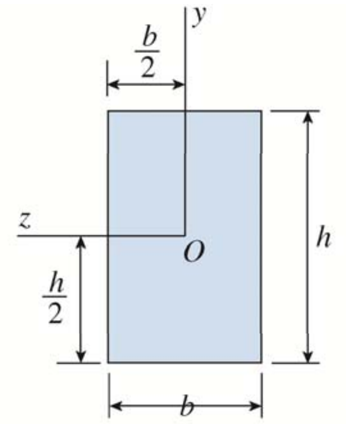
- Section modulus: combines properties into a single quantity.
- Doubly symmetric shapes: when $c_1 = c_2 = c$
- Maximum tensile and maximum compressive stresses are equal numerically

$$\sigma_1 = -\sigma_2 = -\frac{Mc}{I} = -\frac{M}{S}$$

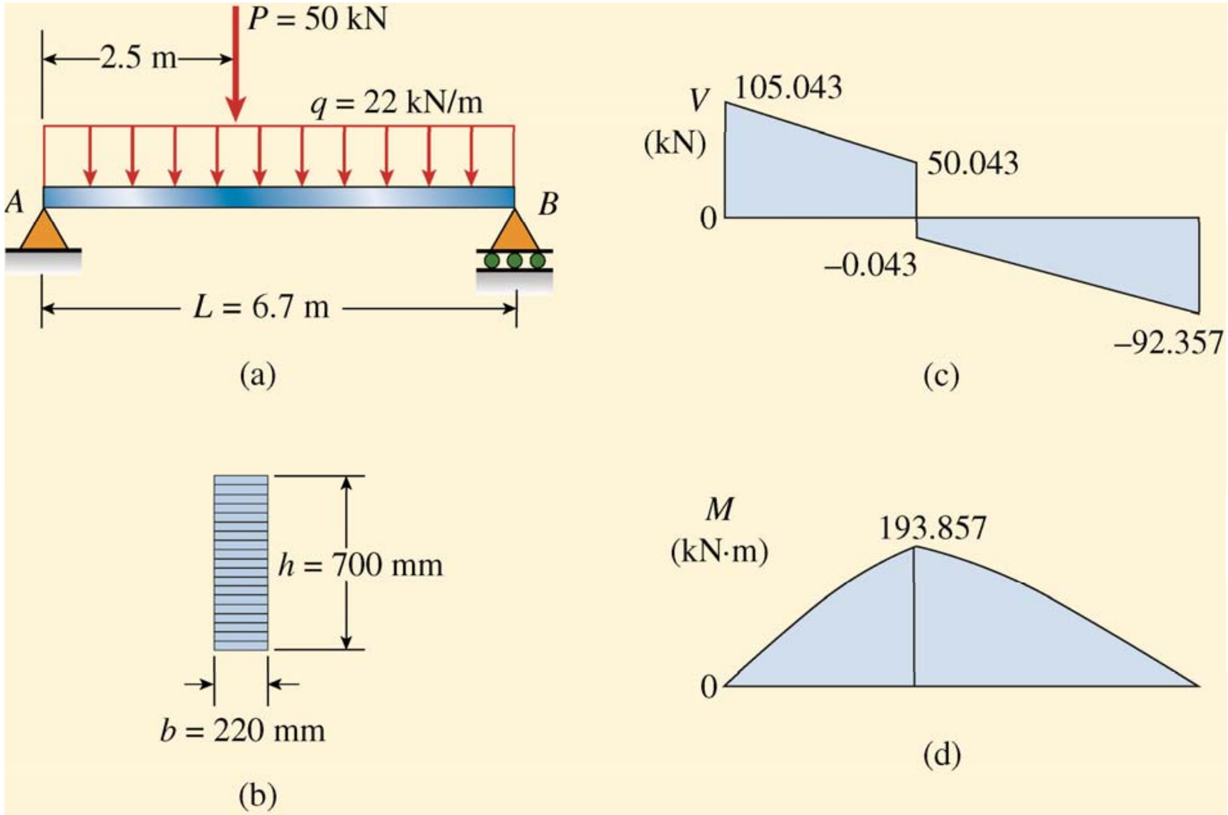
  – A beam of rectangular cross section

$$I = \frac{bh^3}{12} \qquad S = \frac{bh^2}{6}$$



Example 5-3

- Maximum tensile and compressive stress in the beam due to bending?



Design of Beams for Bending Stress

- Factors when designing a beam
  - Type of structure (airplane, automobile, bridge, building…)
  - Materials to be used
  - The loads to be supported
  - Environmental conditions
  - Cost
- Standpoint of strength
  - Shape and size of beam: actual stress < allowable stress

Design of Beams for Bending Stress

- Least cross sectional area ← minimize weight & cost
- Required section modulus ← mechanical stability

$$S = \frac{M_{\max}}{\sigma_{allow}}$$

  – Section modulus must be at least as large as above
  – When allowable stress are different for tension & compression → two section moduli needed

- We need to satisfy both 'least cross sectional area' & required section modulus

Design of Beams for Bending Stress
Relative Efficiency of Various Beam Shapes

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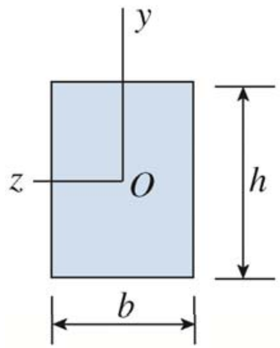
- Efficiency of a beam in bending depends primarily on the "shape of the cross section"
  - Material needs to be located as far as practical from the neutral axis → larger section modulus
- Section modulus of a rectangle of width b and height h;

$$S = \frac{I}{c} = \frac{bh^2}{6} = \frac{Ah}{6} = 0.167Ah$$



(a)

Design of Beams for Bending Stress
Relative Efficiency of Various Beam Shapes

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- Section moduli of a square cross section (with side *h*) & solid circular cross section of a diameter *d* with the same area ; $h = (d/2)\sqrt{\pi}$

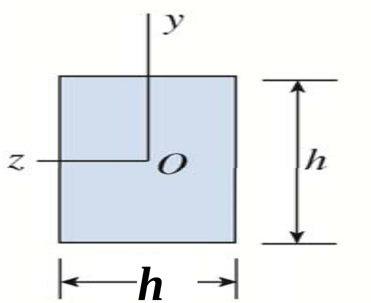
$$S_{square} = \frac{h^3}{6} = \frac{\pi\sqrt{\pi}d^3}{48} = 0.1160d^3$$

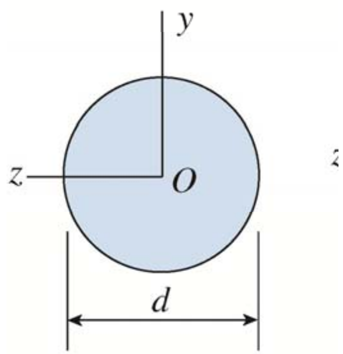
$$S_{circle} = \frac{\pi d^3}{32} = 0.0982d^3$$

$$\longrightarrow \quad \frac{S_{square}}{S_{circle}} = 1.18$$

■ more efficient than ● (with the same area). Why?

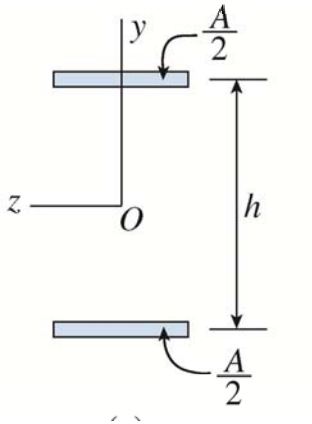
- Circle has a relatively larger amount of material located near the neutral axis → does not contribute as much to the strength of the beam





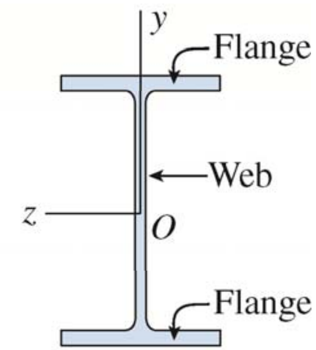
Design of Beams for Bending Stress
Relative Efficiency of Various Beam Shapes

- Ideal cross sectional shape;
  - A/2 at a distance *h*/2, and another A/2 at –*h*/2



$$I = 2\left(\frac{A}{2}\right)\left(\frac{h}{2}\right)^2 = \frac{Ah^2}{4} \qquad S = \frac{I}{h/2} = 0.5Ah$$

- Standard wide-flange beams;



$$S \approx 0.35Ah$$

  - Less than ideal but larger than S of rectangular cross section of the same area and height
  - The web cannot be too thin (← susceptible to localized buckling or overstresses in shear)

Design of Beams for Bending Stress

Relative Efficiency of Various Beam Shapes

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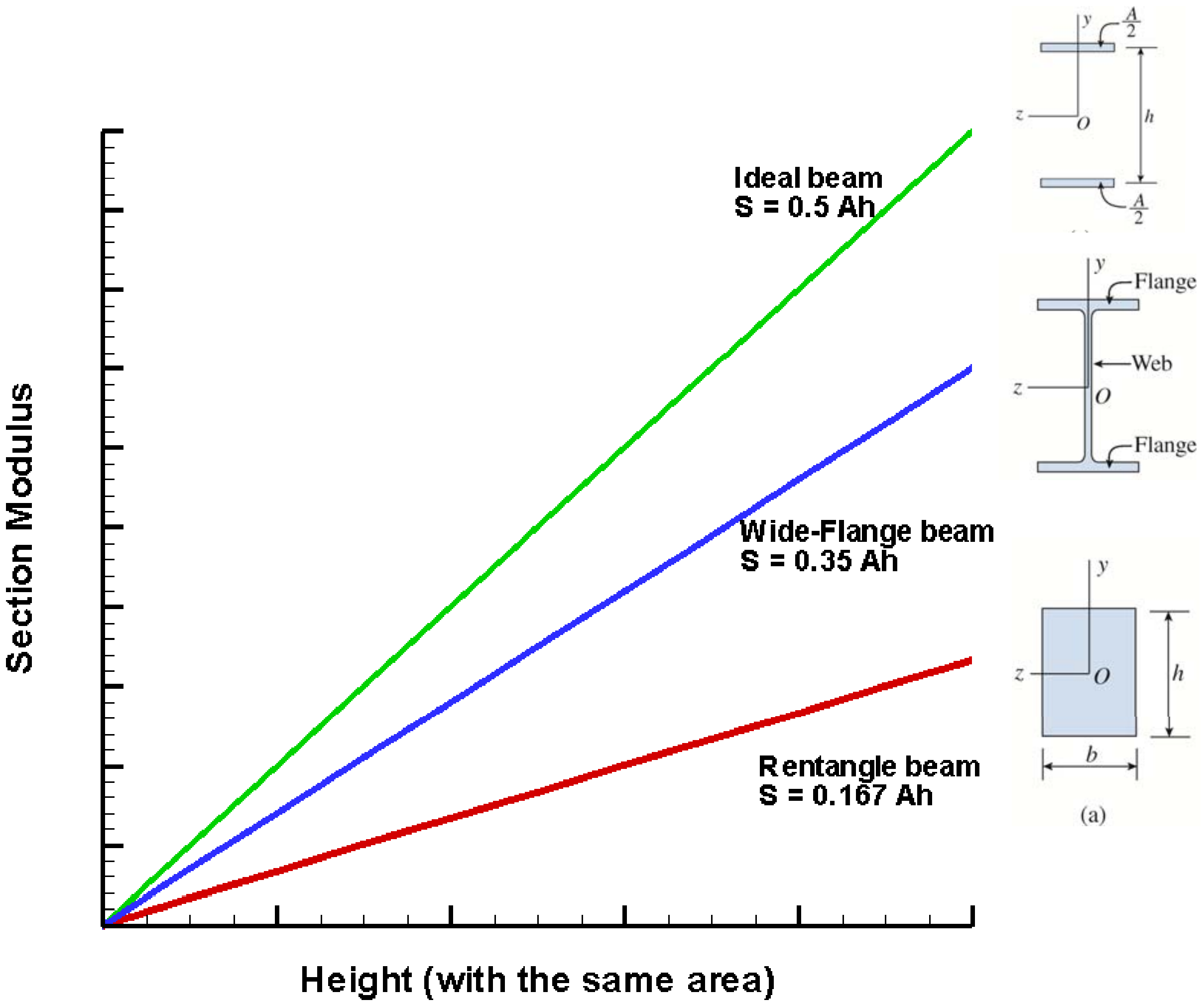

Design of Beams for Bending Stress
Example 5-6

- Minimum required diameter d_1 of the wood post if the allowable bending stress is 15 MPa?
- Minimum required outer diameter d_2 of the aluminum tube if the inner diameter is $3/4d_2$ & allowable bending stress in the aluminum is 50 MPa?

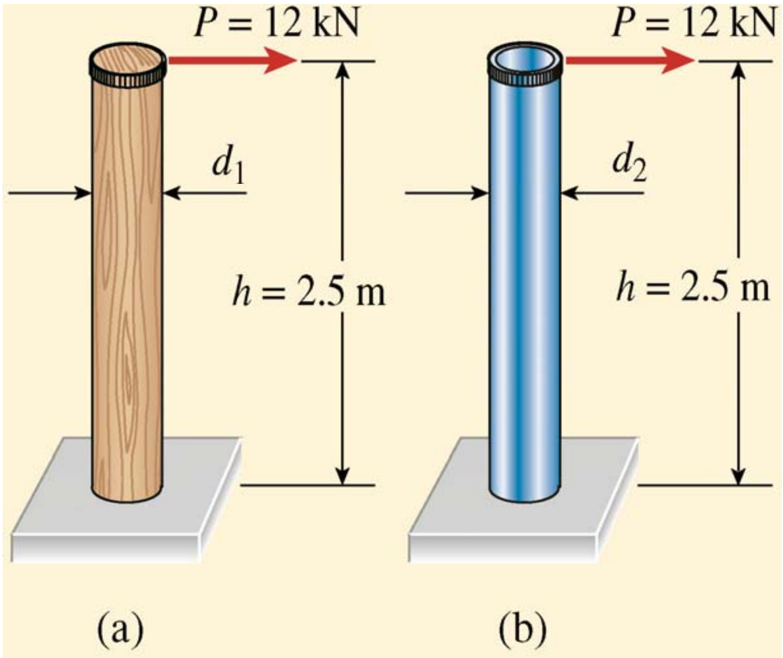

FIG. 5-20 Example 5-6. (a) Solid wood post, and (b) aluminum tube

Design of Beams for Bending Stress
Example 5-8

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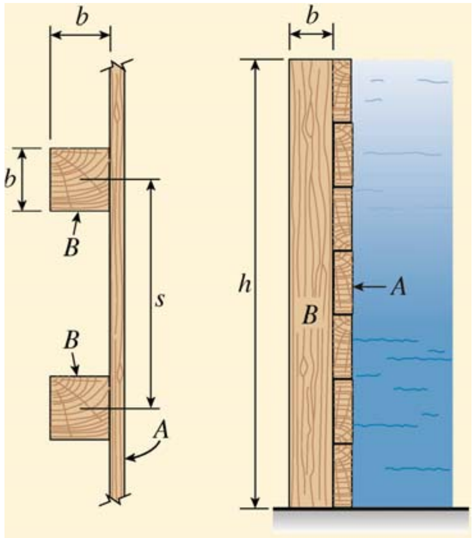
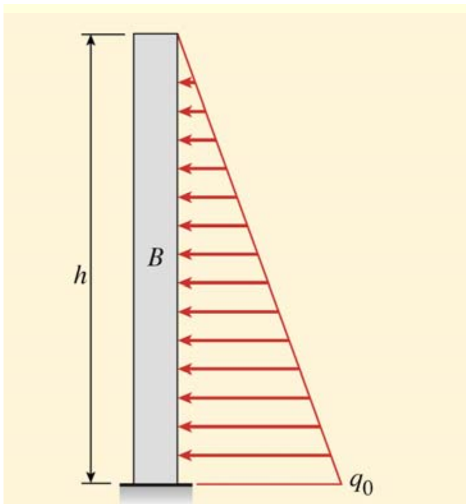
- A temporary dam with horizontal planks (널빠지) A supported by wood posts B (sunk into the ground, and act as cantilever). Height = 2 m, spacing = 0.8 m. σ_{allow} = 8.0 MPa
- Determine the minimum required dimension b of the post with square cross section.



(a) Top view (b) Side view



Nonprismatic beams

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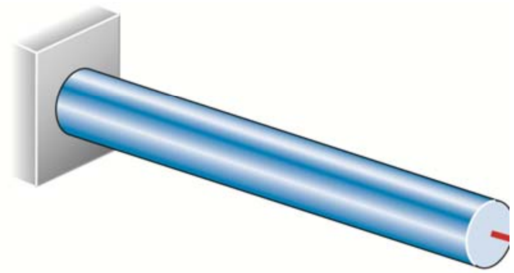
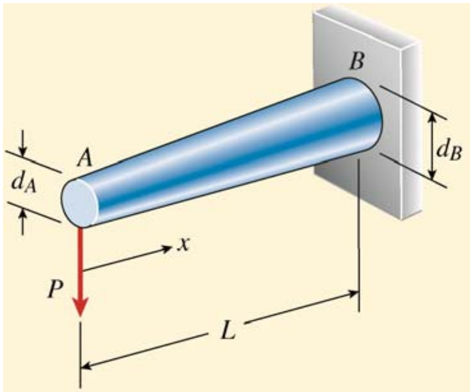
- Flexure formula still applies to nonprismatic beams when the changes are gradual

$$\sigma_x = -\frac{My}{I}$$



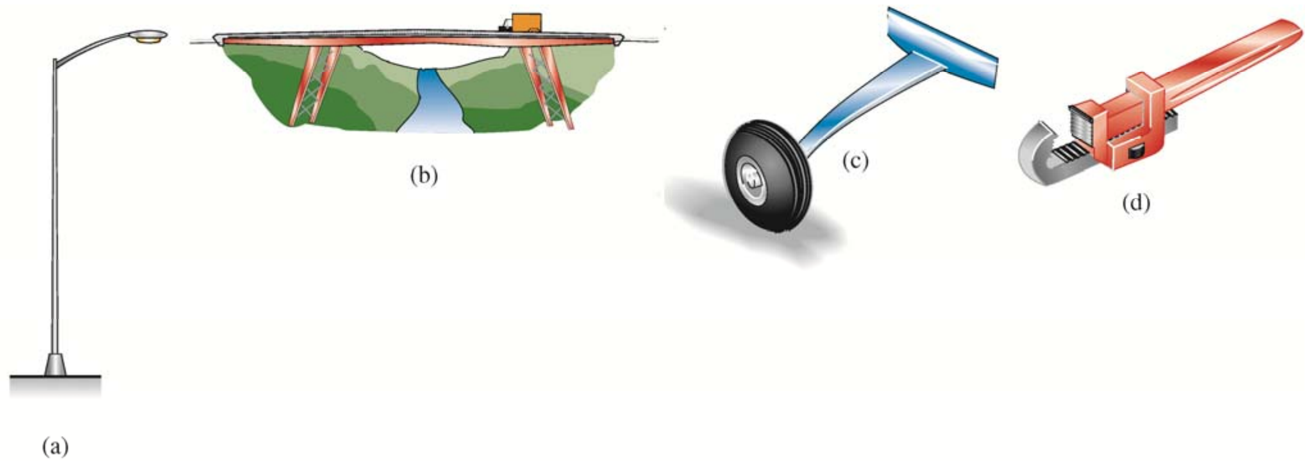
- Prismatic beam:
  - same cross section throughout their lengths
  - Maximum stress at the maximum bending moment



- Non prismatic beam:
  - cross section changes.
  - Maximum stress may NOT be at the maximum bending moment

Nonprismatic beams
examples

- Fully stressed beam
  - A beam with maximum allowable bending stress at every section
  - Minimize the amount of material → lightest possible beam



Nonprismatic beams
Example 5-9

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- $d_B = 2 \times d_A$
- Determine the maximum bending stress and compare this with the bending stress at the fixed end.

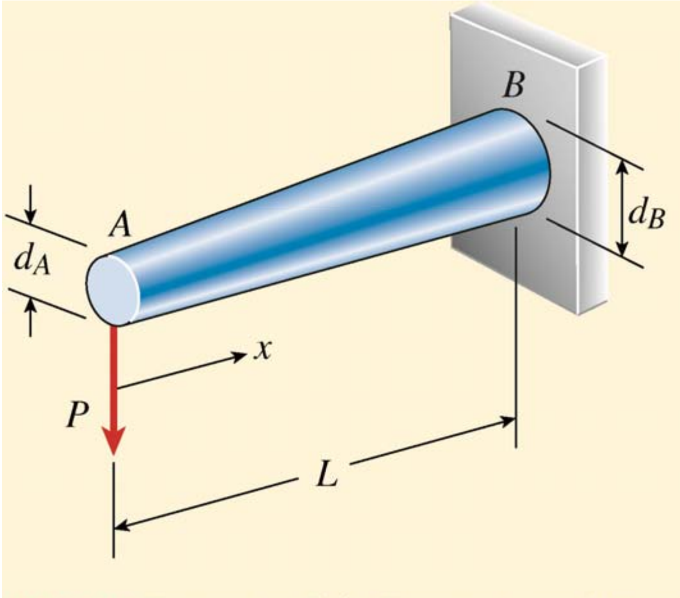
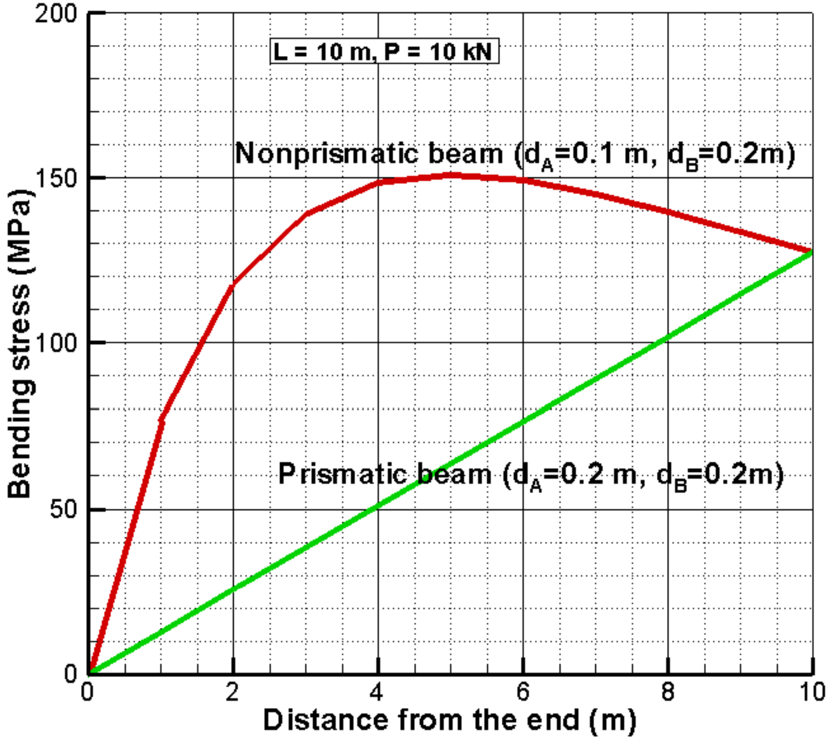


FIG. 5-24 Example 5-9. Tapered cantilever beam of circular cross section



2nd exam

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- 28 April   08:30 – 11:00
  - If you can solve the home assignment with confidence, you will do a good job.
  - More than 50% from the home assignments.
  - ~90% from the examples and the problems from the textbook.
  - Level of difficulty will be similar to that of the 1st exam.
  - Scope: Ch. 4, 5 & 12
  - Try to interpret the problem in terms of physical behaviour. You will be required to explain your answer physically.
  - Partial point will be minimized this time (at most 30%)

Problem solving and Q & A Session

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- Problem solving: 26 April 09:30 – 10:45

- Q & A session: 26 April 16:00 – 18:00 (?)
- Location: Seok Jeong Seminar Room (38-118)
- Teaching Assistant will be available for discussion.

Shear stresses in beams of rectangular cross section

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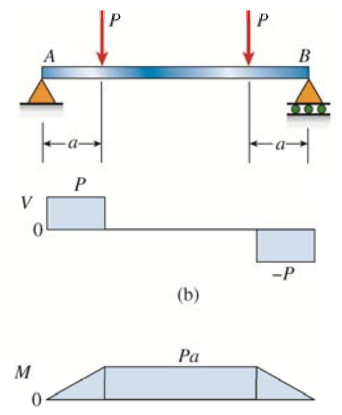
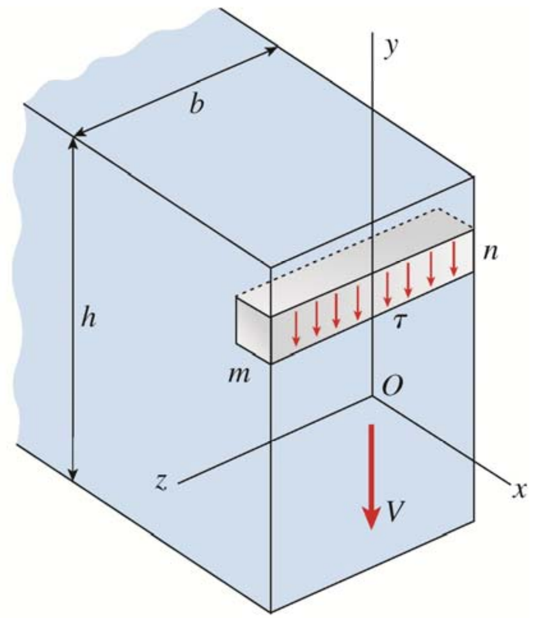


- Pure bending:
  - bending moment & normal stress
- Nonuniform bending:
  - bending moment, normal and shear stresses
- shear stresses due to shear force, V
  - Shear stress τ is parallel to the vertical side
  - Shear stress τ is uniform across the width of the beam (even if they may vary over the height)



Shear Stress and Strain

Equality of shear stress on perpendicular planes

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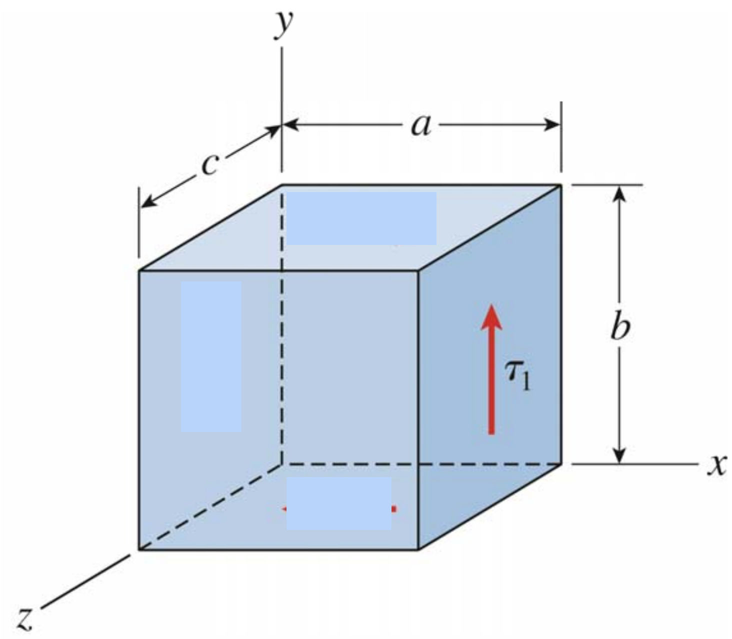


FIG. 1-27 Small element of material subjected to shear stresses

Assume a small element abc

1) Shear stress, τ_1 on area bc → force τ_1 x bc

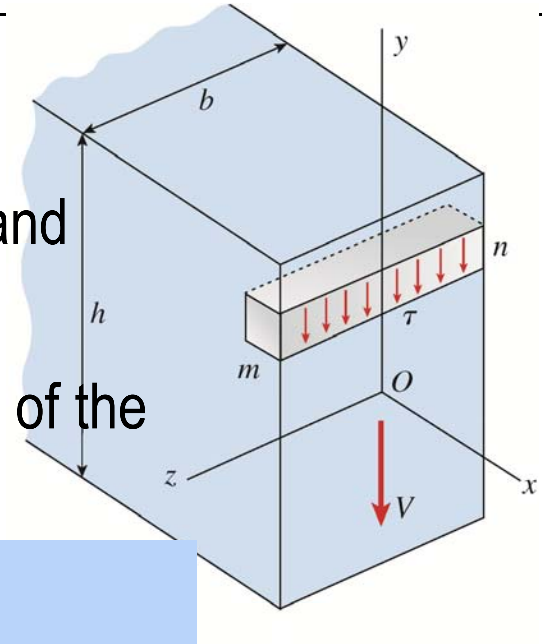
2) From 'Force Equilibrium'→ same shear stress in opposite side in opposite direction.
   Force τ_1 x bc on left and right-hand sides form a couple (우력)

3) From 'Moment equilibrium' → Force τ_2 x ac on top → τ_1 x abc = τ_2 x abc → $\tau_1 = \tau_2$

Shear stresses in beams of rectangular cross section

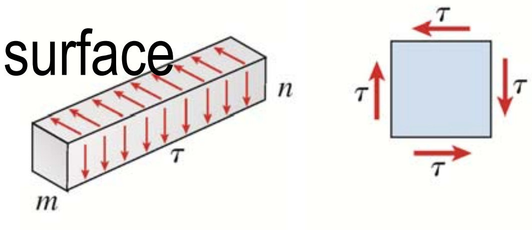
- Small element mn (two clues)
  1. Shear stress acting on the front face vertical and uniform
  2. Shear stress acting between horizontal layers of the beam (same magnitude)

From ‘equality of shear stresses on perpendicular planes,
Vertical shear stress = horizontal shear stress



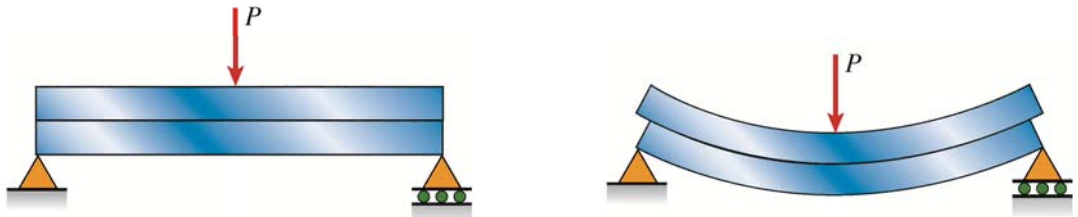
(a)

  - No horizontal shear stress at the bottom & the surface
    → τ = 0 at y = +h/2 & -h/2 (surface & bottom)



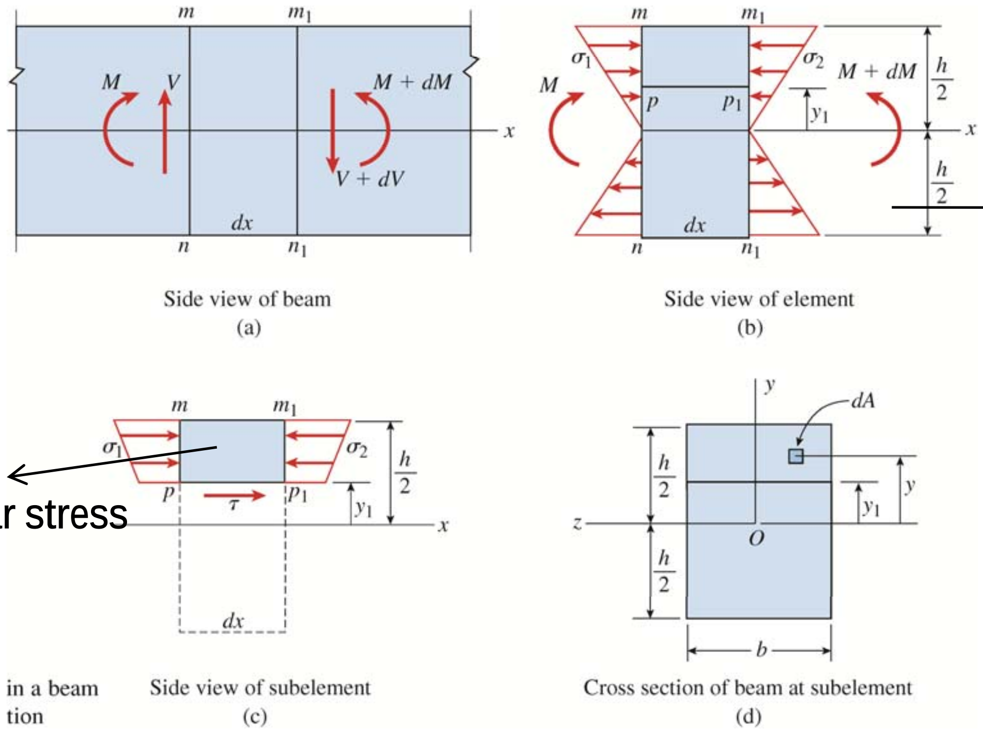
(b) (c)

FIG. 5-26 Shear stresses in a beam of rectangular cross section



Shear stresses in beams of rectangular cross section
Derivation of shear formula

- Easier to evaluate horizontal shear stress
  - We then equate horizontal shear stress with vertical one



Vertical Shear stress not shown

Vertical Shear stress not shown

Shear stresses in beams of rectangular cross section

Derivation of shear formula

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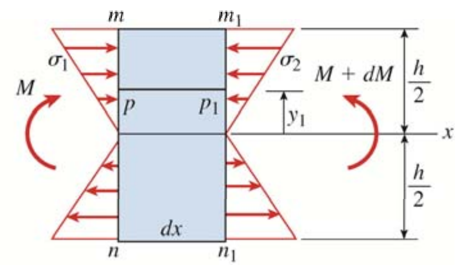
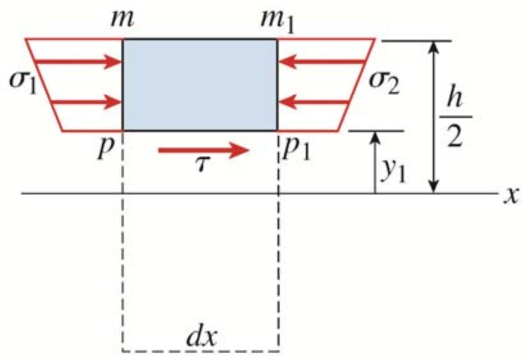
- Normal stresses at cross section mn & m_1n_1

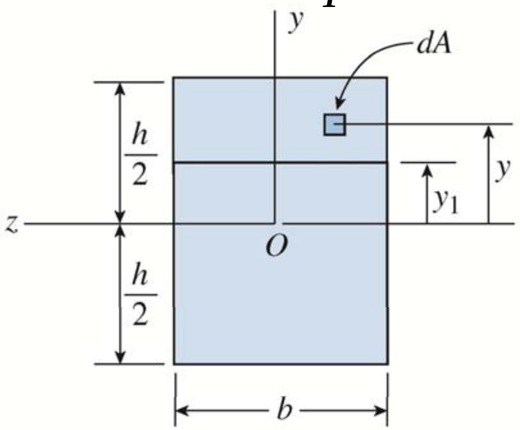


$$\sigma_1 = -\frac{My}{I} \qquad \sigma_2 = -\frac{(M + dM)y}{I}$$

- Normal stress at element of area dA (using absolute values)
  - Left-hand face mp $\quad \sigma_1 dA = \frac{My}{I} dA$
  - Right-hand face m1p1 $\quad \sigma_2 dA = \frac{(M + dM)y}{I} dA$



Side view of subelement



Cross section of beam at subelement

Shear stresses in beams of rectangular cross section

Derivation of shear formula

- Total horizontal forces acting on both faces

$$F_1 = \int \sigma_1 dA = \int \frac{My}{I} dA$$

$$F_2 = \int \sigma_2 dA = \int \frac{(M + dM)y}{I} dA$$

Integration performed from y_1 to h/2

- From equilibrium;

$$F_3 = F_2 - F_1 = \tau b dx$$

$$F_3 = \int \frac{(M + dM)y}{I} dA - \int \frac{My}{I} dA = \int \frac{(dM)y}{I} dA$$

- Shear stress;

$$\tau = \frac{dM}{dx}\left(\frac{1}{Ib}\right)\int y dA = \frac{V}{Ib}\int y dA = \frac{VQ}{Ib}$$

V

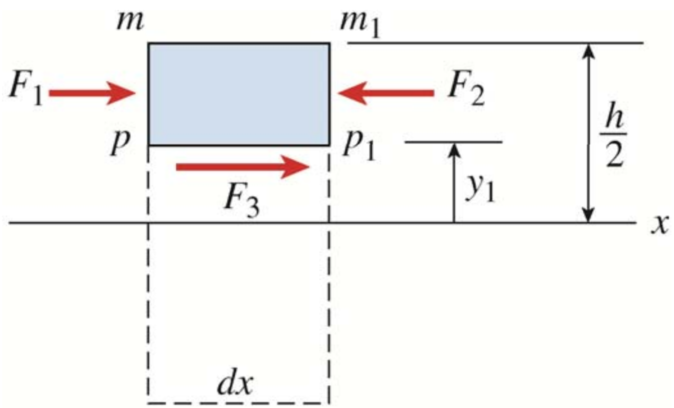


FIG. 5-29 Partial free-body diagram of subelement showing all horizontal forces (compare with Fig. 5-28c)

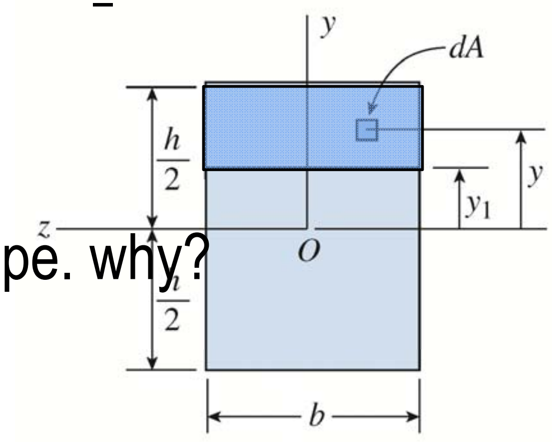
Shear stresses in beams of rectangular cross section
Derivation of shear formula

- Shear Formula

$$\tau = \frac{VQ}{Ib} \longleftarrow Q = \int_{y_1}^{h/2} y\,dA$$

First moment of the cross sectional area above the level at which the shear stress is being evaluated

- Shear stress at any point in the cross section of a rectangular beam
- V, I, b are constants while Q varies with distance y_1 from the neutral axis
- We don't bother with sign conventions
- Not applicable to triangular or semicircular shape. why?
- Applies only to prismatic beams



Cross section of beam at subelement

Flexure Formula vs. Shear Formula

- Flexure Formula

$$\sigma_x = -\frac{My}{I}$$

Distance from the neutral axis

Constant at a given location

- Shear Formula

$$\tau = \frac{VQ}{Ib}$$

First moment above the level

Shear stresses in beams of rectangular cross section

Distribution in a rectangular beam

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- Distribution of shear stress in a rectangular beam
  - First moment Q

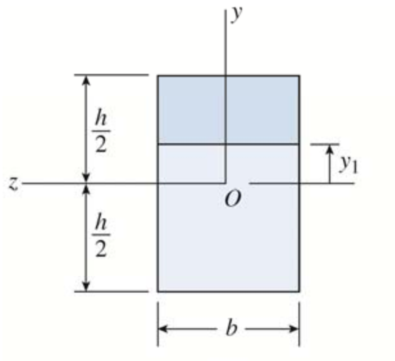
$$Q = \int y\,dA = \int_{y_1}^{h/2} y b\,dy = \frac{b}{2}\left(\frac{h^2}{4} - y_1^2\right)$$

  - Shear stress

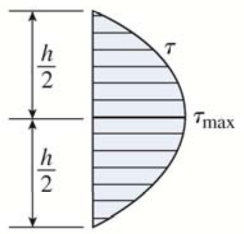
$$\tau = \frac{V}{2I}\left(\frac{h^2}{4} - y_1^2\right)$$

  - Maximum shear stress (at y_1=0)

$$\tau_{\max} = \frac{Vh^2}{8I} = \frac{3V}{2A}$$

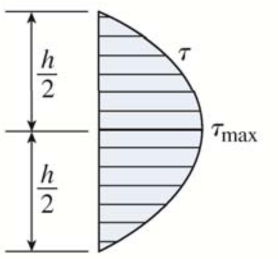


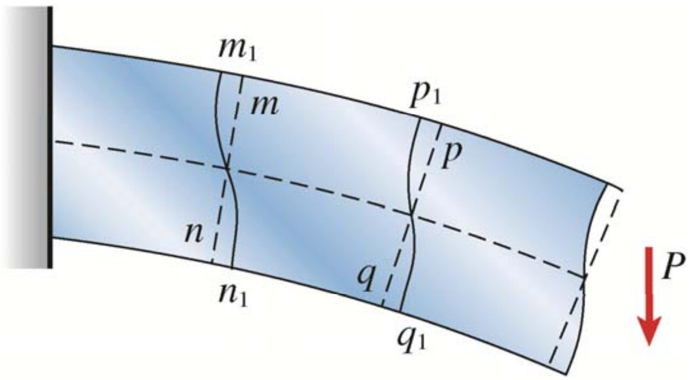
(a)



Shear stresses in beams of rectangular cross section
Effect of shear strains

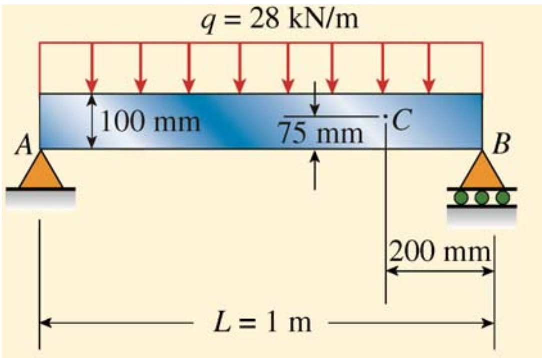
- Shear stress varies parabolically over the height of a rectangular beam → shear strain also varies parabolically
- Cross sections becomes warped
- distribution of normal stress in nonuniform bending is about the same as in pure bending
  - If V is constant along the axis of the beam, warping is the same at every cross section

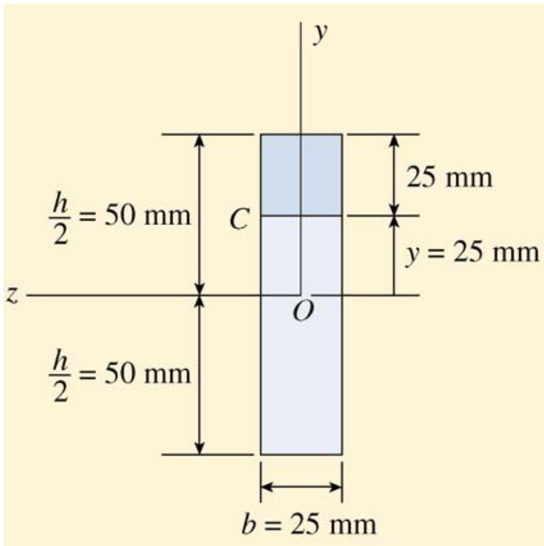


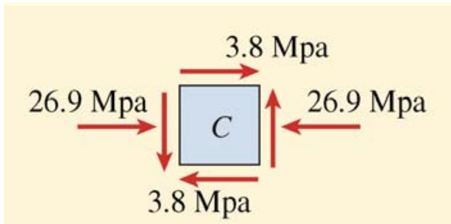


Shear stresses in beams of rectangular cross section
Example 5-11

- Determine the normal and shear stress at point C. Show these stresses on a sketch of a stress element at point C.







τ in beams of circular cross section

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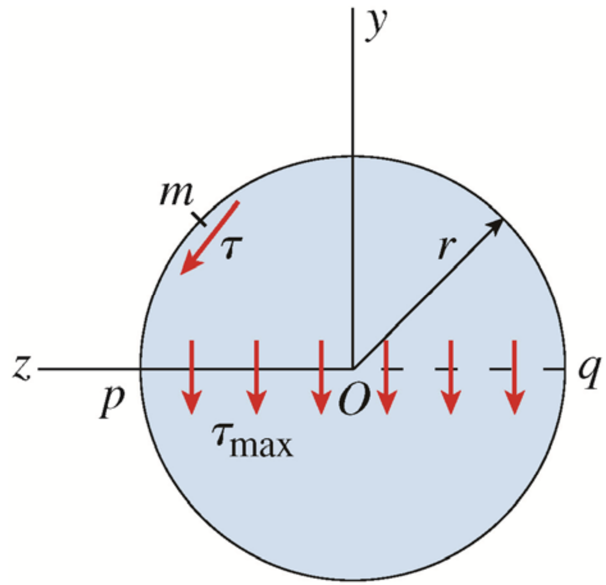
- When a beam has a circular cross section?
  - Shear stresses do not necessarily act parallel to y axis
  - Shear stress at point m act tangent to the boundary
- We can use shear formula only at the neutral axis

$$I = \frac{\pi r^4}{4} \qquad Q = A\bar{y} = \left(\frac{\pi r^2}{2}\right)\left(\frac{4r}{3\pi}\right) = \frac{2r^3}{3} \qquad b = 2r$$

$$\boxed{\tau_{\max} = \frac{VQ}{Ib} = \frac{4V}{3A}}$$



Shear Stresses in the Webs of Beams with Flanges

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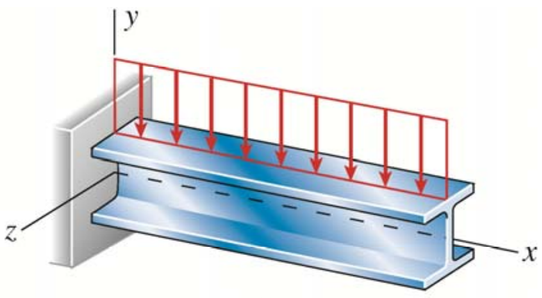
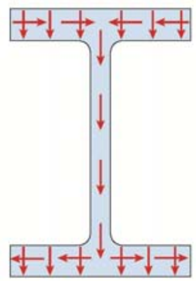
- The distribution of shear stresses in a wide-flange beam is more complicated than in a rectangular beam.
  - In the flange;
    - Both vertical and horizontal shear stresses
  - In the web
    - Shear stress only in vertical direction

Scope of this course



(a)



(b)

Shear Stresses in the Webs of Beams with Flanges

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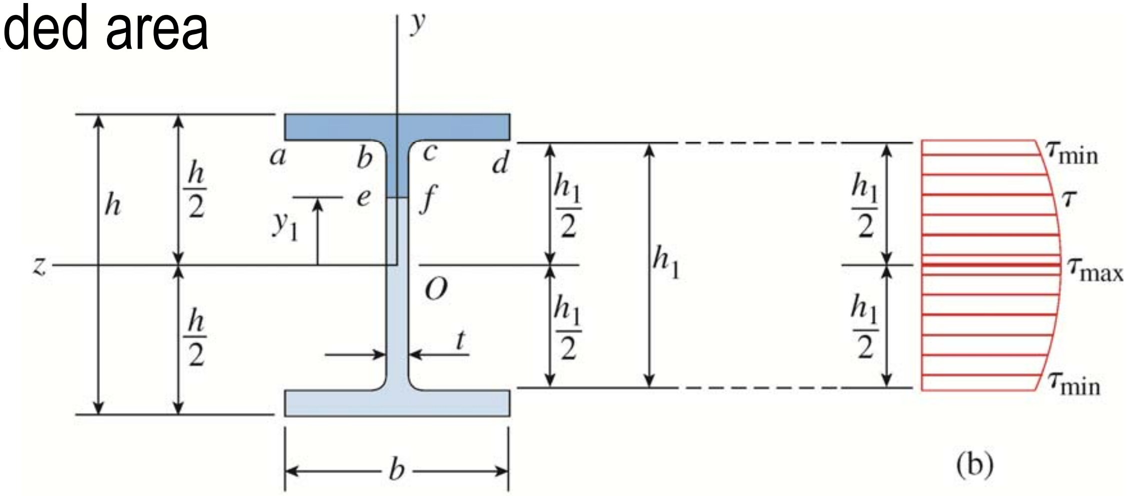
- Shear stresses at line *ef* in the web
  - Act parallel to the y-axis
  - Uniformly distributed across the thickness of the web

$$\tau = \frac{VQ}{Ib}$$

  - b: thickness of the web
  - Q: first moment of shaded area



Shear Stresses in the Webs of Beams with Flanges

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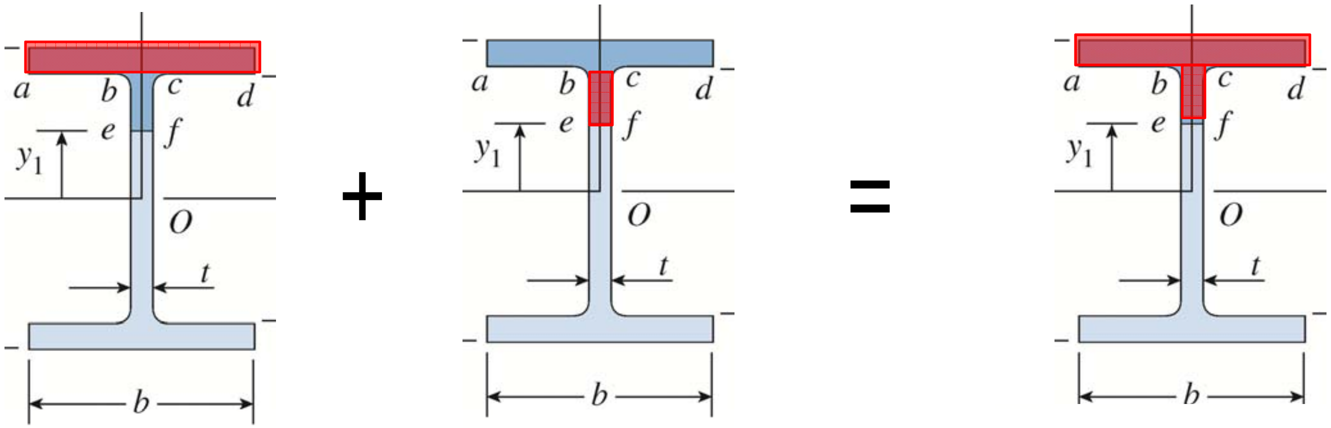
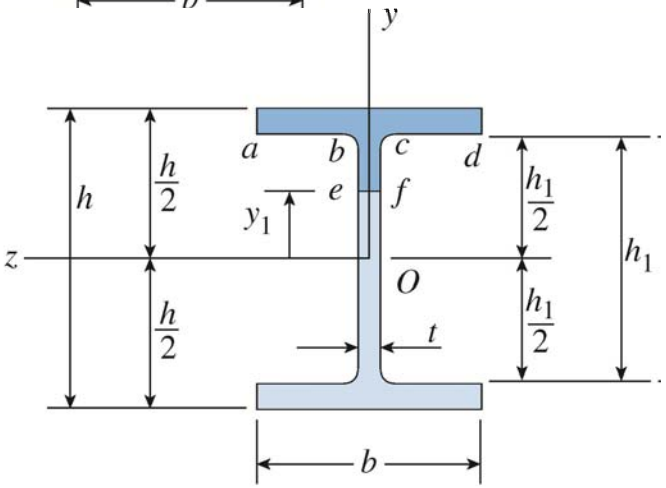
- First moment of the shaded area:



$$A_1 = b\left(h/2 - h_1/2\right) \qquad A_2 = t\left(h_1/2 - y_1\right)$$

$$Q = A_1\left(\frac{h_1}{2} + \frac{h/2 - h_1/2}{2}\right) + A_2\left(y_1 + \frac{h_1/2 - y_1}{2}\right)$$

$$Q = \frac{b}{8}\left(h^2 - h_1^2\right) + \frac{t}{8}\left(h_1^2 - 4y_1^2\right)$$



Shear Stresses in the Webs of Beams with Flanges

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- Shear stress in the web of the beam at distance y1 from the neutral axis is;

$$\tau = \frac{VQ}{It} = \frac{V}{8It}\left[b\left(h^2 - h_1^2\right) + t\left(h_1^2 - 4y_1^2\right)\right]$$

  - In which I is defined as;

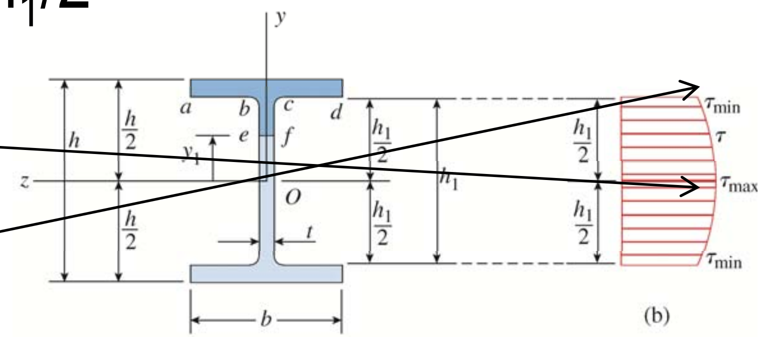
$$I = \frac{bh^3}{12} - \frac{(b-t)h_1^3}{12} = \frac{1}{12}\left(bh^3 - bh_1^3 + th_1^3\right)$$

  - Valid only in the web (not in the flange)

- Maximum at y_1=0, minimum at y_1=+-h_1/2

$$\tau_{\max} = \frac{V}{8It}\left(bh^2 - bh_1^2 + th_1^2\right)$$

$$\tau_{\min} = \frac{V}{8It}\left(bh^2 - bh_1^2\right)$$



Shear Stresses in the Webs of Beams with Flanges

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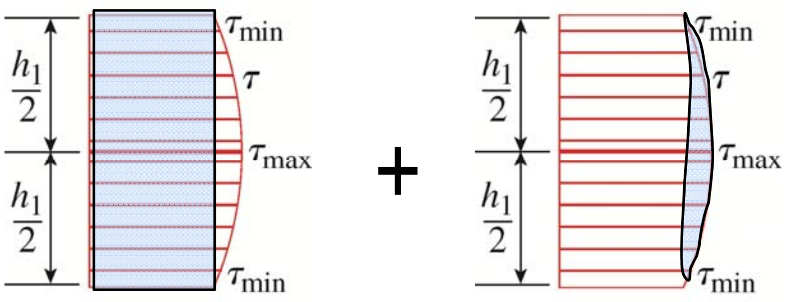


- Area of shear stress diagram

$$h_1\tau_{\min} + \frac{2}{3}h_1(\tau_{\max} - \tau_{\min})$$

- Total shear force in the web

$$V_{web} = \frac{th_1}{3}(2\tau_{\max} + \tau_{\min})$$

  – 90 ~ 98% of the total shear force for beams of typical proportion;

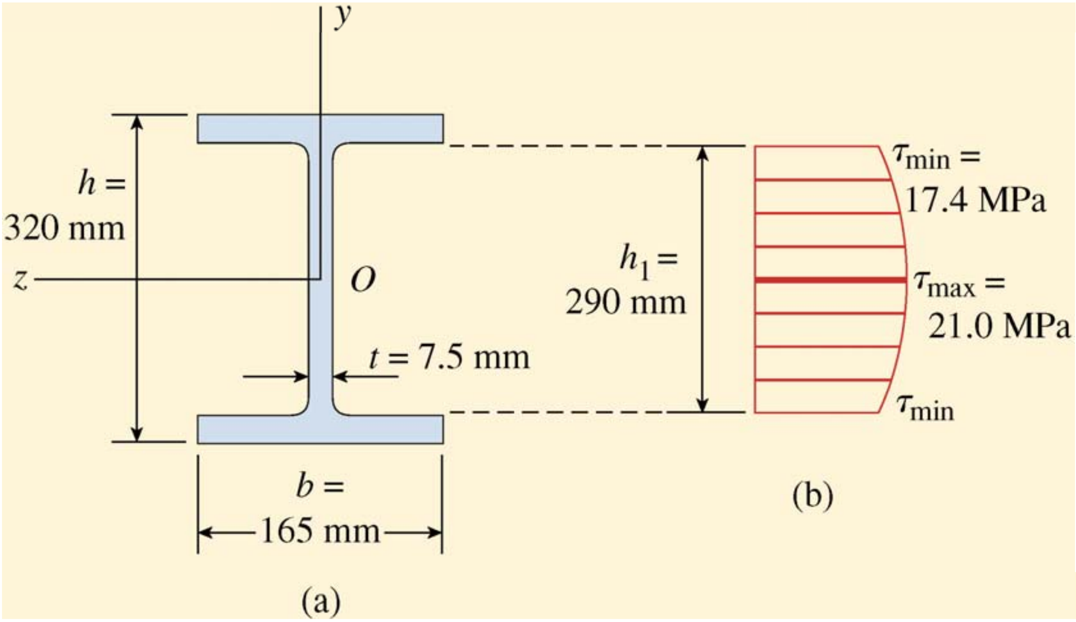
- Average shear stress in the web assuming the web carries all of the shear force

$$\tau_{aver} = \frac{V}{th_1}$$

  – Within + - 10% of the maximum shear stress

Shear Stresses in the Webs of Beams with Flanges
Example 5-14

- Vertical shear force = 45 kN. Maximum & minimum shear stress? Total shear force in the web?



Summary

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- Introduction
- Pure Bending and Nonuniform Bending
- Curvature of Beam
- Longitudinal Strains in Beams
- Normal Stress in Beams $\sigma_x = -\frac{My}{I}$
- Design of Beams for Bending Stresses
- Nonprismatic Beams
- Shear Stresses in Beams of Rectangular Cross Section $\tau = \frac{VQ}{Ib}$
- Shear Stresses in Beams of Circular Cross Section
- Shear Stresses in the Webs of Beams with Flanges