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Subject Name: **Strength of materials**

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Unit-II

Bending and Shearing Stresses: Theory of simple bending, Concept of pure bending and bending stress, Equation of bending, Neutral axis, Section-Modulus, Differential equation of the elastic curve, Determination of bending stresses in simply supported, Cantilever and Overhanging beams subjected to point load and uniformly distributed loading, Bending stress distribution across a section of beam, Shearing Stress and shear stress distribution across a section in Beams.

Simple Bending Theory OR Theory of Flexure for Initially Straight Beams

(The normal stress due to bending are called flexure stresses)

Preamble:

When a beam having an arbitrary cross section is subjected to a transverse loads the beam will bend. In addition to bending the other effects such as twisting and buckling may occur, and to investigate a problem that includes all the combined effects of bending, twisting and buckling could become a complicated one. Thus we are interested to investigate the bending effects alone, in order to do so, we have to put certain constraints on the geometry of the beam and the manner of loading.

Assumptions:

The constraints put on the geometry would form the **assumptions**:

1. Beam is initially **straight** , and has a **constant cross-section**.
2. Beam is made of **homogeneous material** and the beam has a **longitudinal plane of symmetry**.
3. Resultant of the applied loads lies in the plane of symmetry.
4. The geometry of the overall member is such that bending not buckling is the primary cause of failure.
5. Elastic limit is nowhere exceeded and 'E' is same in tension and compression.
6. Plane cross - sections remains plane before and after bending.

concept of pure bending:

Loading restrictions:

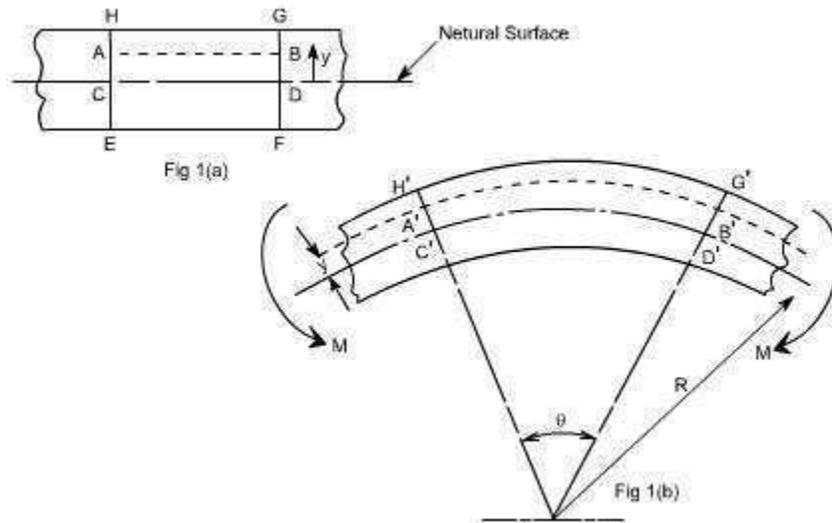
As we are aware of the fact internal reactions developed on any cross-section of a beam may consists of a resultant normal force, a resultant shear force and a resultant couple. In order to ensure that the bending effects alone are investigated, we shall put a constraint on the loading such that the resultant normal and the resultant shear forces are zero on any cross-section perpendicular to the longitudinal axis of the member,

That means $F = 0$

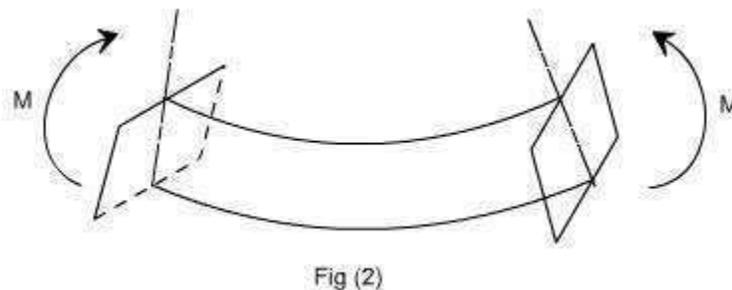
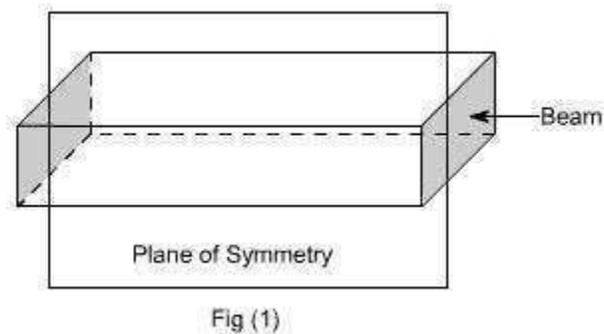
since $\frac{dM}{dX} = F = 0$ or $M = \text{constant}$.

Thus, the zero shear force means that the bending moment is constant or the bending is same at every cross-section of the beam. Such a situation may be visualized or envisaged when the beam or some portion of the beam, as been loaded only by pure couples at its ends. It must be recalled that the couples are assumed to be loaded in the plane of symmetry.

Equation of bending



In order to compute the value of bending stresses developed in a loaded beam, let us consider the two cross-sections of a beam HE and GF , originally parallel as shown in fig 1(a). when the beam is to bend it is assumed that these sections remain parallel i.e. $H'E'$ and $G'F'$, the final position of the sections, are still straight lines, they then subtend some angle q .



Consider now fiber AB in the material, at a distance y from the N.A, when the beam bends this will stretch to A'B'

Therefore,

$$\text{strain in fibre AB} = \frac{\text{change in length}}{\text{original length}}$$

$$= \frac{A'B' - AB}{AB}$$

$$\text{But } AB = CD \text{ and } CD = C'D'$$

refer to fig1(a) and fig1(b)

$$\therefore \text{strain} = \frac{A'B' - C'D'}{C'D'}$$

Since CD and C'D' are on the neutral axis and it is assumed that the Stress on the neutral axis zero. Therefore, there won't be any strain on the neutral axis

$$= \frac{(R + y)\theta - R\theta}{R\theta} = \frac{R\theta + y\theta - R\theta}{R\theta} = \frac{y}{R}$$

However $\frac{\text{stress}}{\text{strain}} = E$ where $E = \text{Young's Modulus of elasticity}$

Therefore, equating the two strains as obtained from the two relations i.e.,

$$\frac{\sigma}{E} = \frac{y}{R} \text{ or } \frac{\sigma}{y} = \frac{E}{R} \quad \dots\dots\dots(1)$$

Bending stress distribution across a section of beam, Shearing Stress and shear stress distribution across a section in Beams.

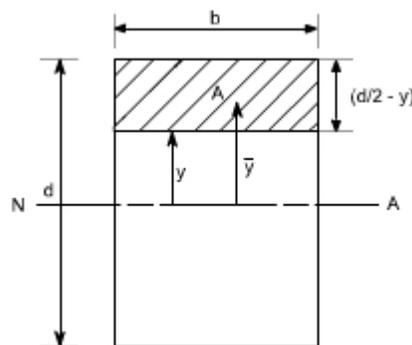


Shearing stress distribution in typical cross-sections:

Let us consider few examples to determine the shear stress distribution in a given X-sections

Rectangular x-section:

Consider a rectangular x-section of dimension b and d



A is the area of the x-section cut off by a line parallel to the neutral axis. \bar{y} is the distance of the centroid of A from the neutral axis

$$\tau = \frac{F.A.\bar{y}}{I.z}$$

for this case, $A = b\left(\frac{d}{2} - y\right)$

While $\bar{y} = \left[\frac{1}{2}\left(\frac{d}{2} - y\right) + y\right]$

i.e $\bar{y} = \frac{1}{2}\left(\frac{d}{2} + y\right)$ and $z = b; I = \frac{b.d^3}{12}$

substituting all these values, in the formula

$$\begin{aligned}\tau &= \frac{F.A.\bar{y}}{I.z} \\ &= \frac{F.b\left(\frac{d}{2} - y\right) \cdot \frac{1}{2}\left(\frac{d}{2} + y\right)}{b \cdot \frac{b.d^3}{12}} \\ &= \frac{F}{2} \cdot \frac{\left\{\left(\frac{d}{2}\right)^2 - y^2\right\}}{\frac{b.d^3}{12}} \\ &= \frac{6.F}{b.d^3} \cdot \left\{\left(\frac{d}{2}\right)^2 - y^2\right\}\end{aligned}$$

This shows that there is a parabolic distribution of shear stress with y .
The maximum value of shear stress would obviously be at the location $y = 0$.

Such that $\tau_{\max} = \frac{6.F}{b.d^3} \cdot \frac{d^2}{4}$
 $= \frac{3.F}{2.b.d}$

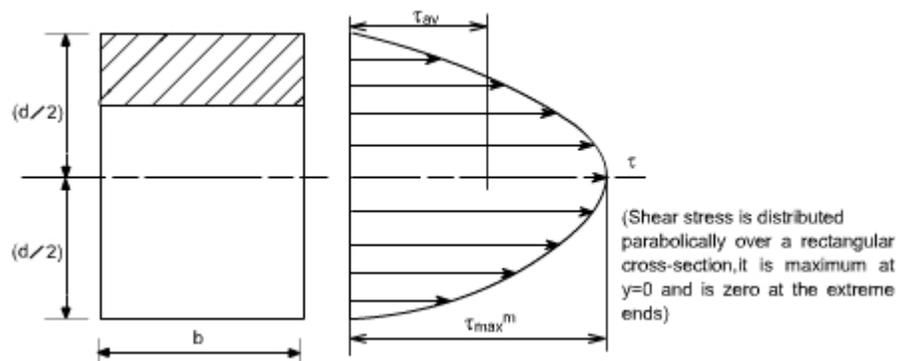
So $\tau_{\max} = \frac{3.F}{2.b.d}$ The value of τ_{\max} occurs at the neutral axis

The mean shear stress in the beam is defined as

$$\tau_{\text{mean or avg}} = \frac{F}{A} = \frac{F}{b.d}$$

So $\tau_{\max} = 1.5 \tau_{\text{mean}} = 1.5 \tau_{\text{avg}}$

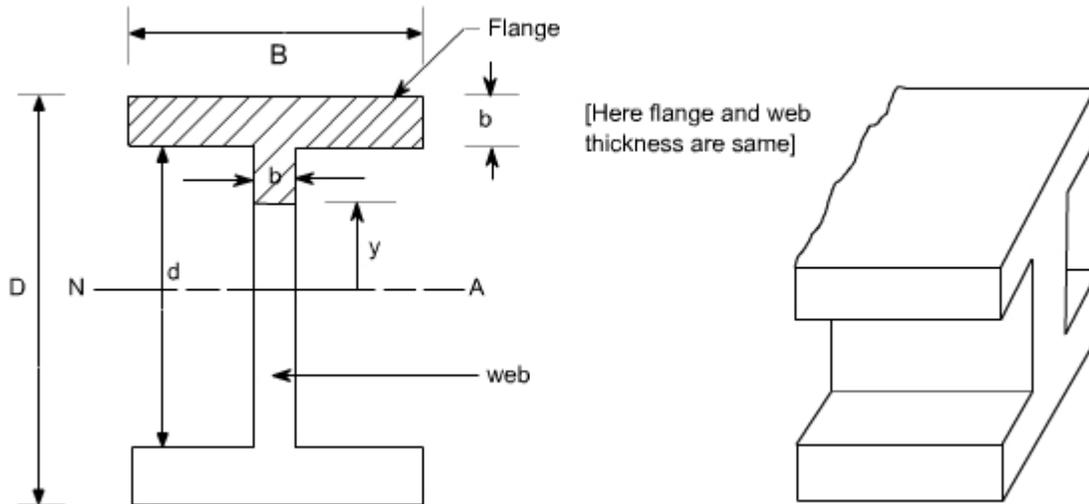
Therefore the shear stress distribution is shown as below.



It may be noted that the shear stress is distributed parabolically over a rectangular cross-section, it is maximum at $y = 0$ and is zero at the extreme ends.

I - section :

Consider an I - section of the dimension shown below.

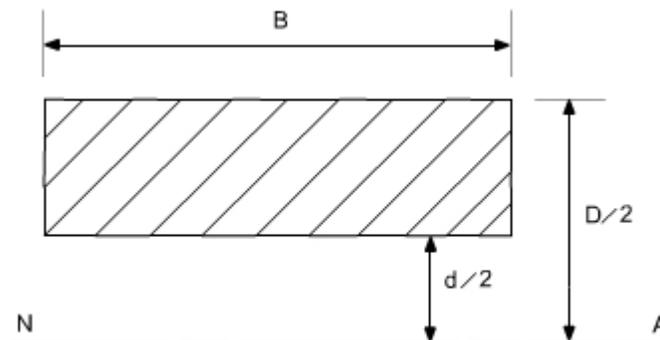


The shear stress distribution for any arbitrary shape is given as

$$\tau = \frac{F A \bar{y}}{Z I}$$

Let us evaluate the quantity $A\bar{y}$, the quantity for this case comprise the contribution due to flange area and web area

Flange area



$$\text{Area of the flange} = B \left(\frac{D-d}{2} \right)$$

Distance of the centroid of the flange from the N.A.

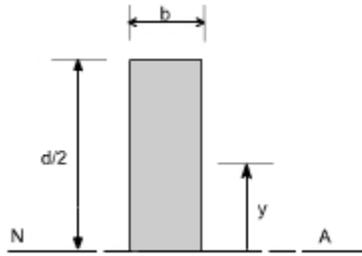
$$\bar{y} = \frac{1}{2} \left(\frac{D-d}{2} \right) + \frac{d}{2}$$

$$\bar{y} = \left(\frac{D+d}{4} \right)$$

Hence,

$$A\bar{y}|_{\text{Flange}} = B \left(\frac{D-d}{2} \right) \left(\frac{D+d}{4} \right)$$

Web Area



Area of the web

$$A = b \left(\frac{d}{2} - y \right)$$

Distance of the centroid from N.A

$$\bar{y} = \frac{1}{2} \left(\frac{d}{2} - y \right) + y$$

$$\bar{y} = \frac{1}{2} \left(\frac{d}{2} + y \right)$$

Therefore,

$$A\bar{y}|_{web} = b \left(\frac{d}{2} - y \right) \frac{1}{2} \left(\frac{d}{2} + y \right)$$

Hence,

$$A\bar{y}|_{Total} = B \left(\frac{D-d}{2} \right) \left(\frac{D+d}{4} \right) + b \left(\frac{d}{2} - y \right) \left(\frac{d}{2} + y \right) \frac{1}{2}$$

Thus,

$$A\bar{y}|_{Total} = B \left(\frac{D^2 - d^2}{8} \right) + \frac{b}{2} \left(\frac{d^2}{4} - y^2 \right)$$

Therefore shear stress,

$$\tau = \frac{F}{bI} \left[\frac{B(D^2 - d^2)}{8} + \frac{b}{2} \left(\frac{d^2}{4} - y^2 \right) \right]$$



To get the maximum and minimum values of substitute in the above relation. $y = 0$ at N. A. And $y = d/2$ at the tip.

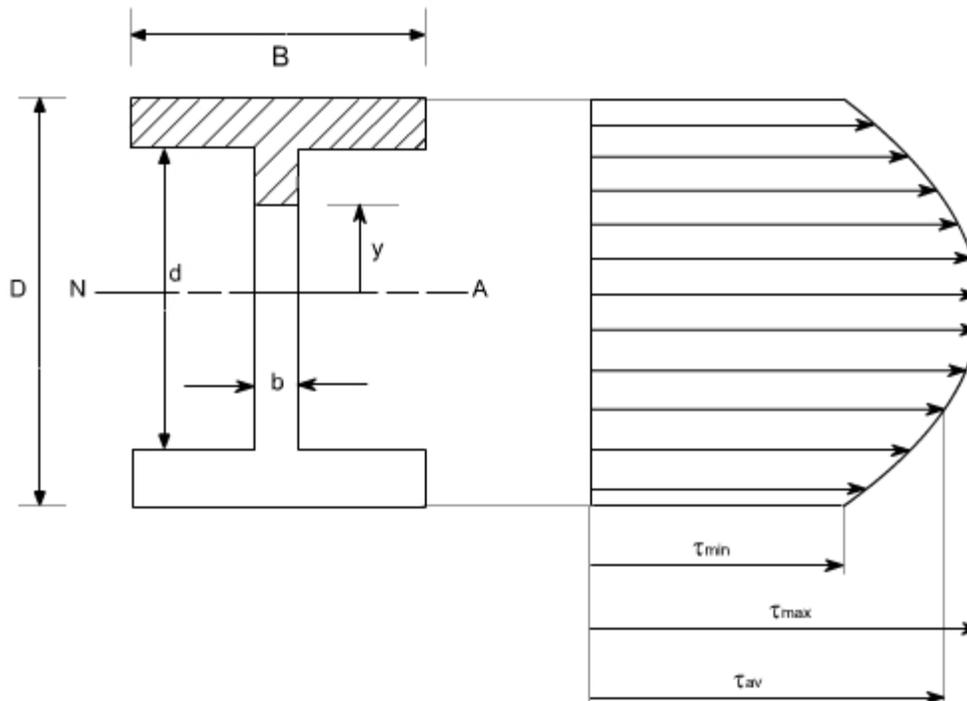
The maximum shear stress is at the neutral axis. i.e. for the condition $y = 0$ at N. A.

$$\text{Hence, } \tau_{\max} \text{ at } y=0 = \frac{F}{8bI} [B(D^2 - d^2) + bd^2] \quad \dots\dots\dots(2)$$

The minimum stress occur at the top of the web, the term bd^2 goes off and shear stress is given by the following expression

$$\tau_{\min} \text{ at } y = d/2 = \frac{F}{8bI} [B(D^2 - d^2)] \quad \dots\dots\dots(3)$$

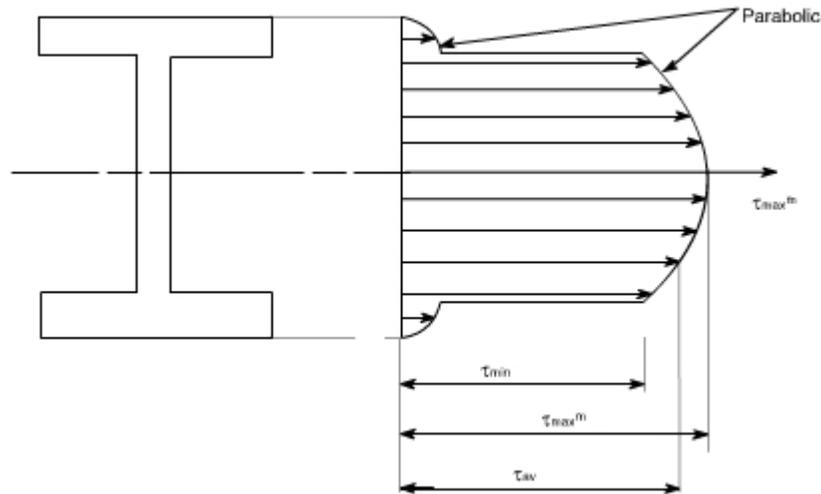
The distribution of shear stress may be drawn as below, which clearly indicates a parabolic distribution



$$\tau_{\max}^m = \frac{F}{8bI} [B(D^2 - d^2) + bd^2]$$

Note: from the above distribution we can see that the shear stress at the flanges is not zero, but it has some value, this can be analyzed from equation (1). At the flange tip or flange or web interface $y = d/2$. Obviously than this will have some constant value and than onwards this will have parabolic distribution.

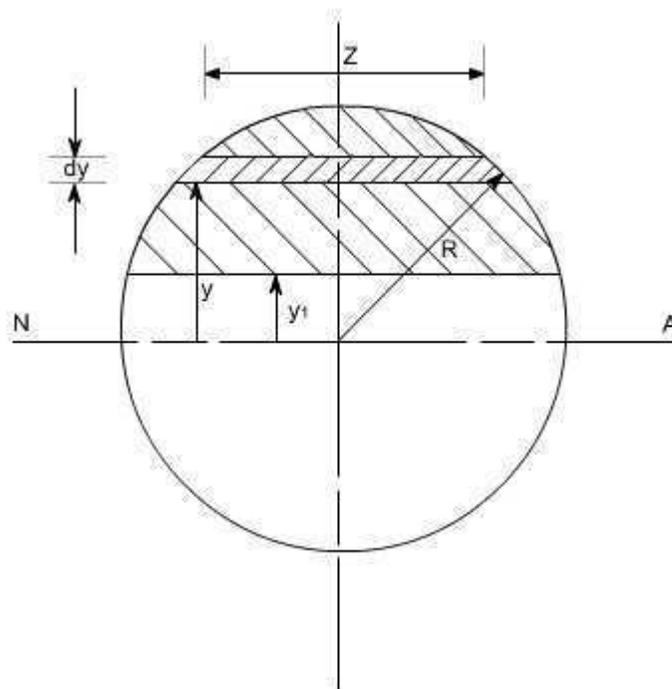
In practice it is usually found that most of shearing stress usually about 95% is carried by the web, and hence the shear stress in the flange is negligible however if we have the concrete analysis i.e. if we analyze the shearing stress in the flange i.e. writing down the expression for shear stress for flange and web separately, we will have this type of variation.



This distribution is known as the “top – hat” distribution. Clearly the web bears the most of the shear stress and bending theory we can say that the flange will bear most of the bending stress.

Shear stress distribution in beams of circular cross-section:

Let us find the shear stress distribution in beams of circular cross-section. In a beam of circular cross-section, the value of Z width depends on y.



Using the expression for the determination of shear stresses for any arbitrary shape or a arbitrary section.

$$\tau = \frac{FA \bar{y}}{Z I} = \frac{FA \int y dA}{Z I}$$

Where $\int y dA$ is the area moment of the shaded portion or the first moment of area.
re

Here in this case 'dA' is to be found out using the Pythagoras theorem

$$\left(\frac{Z}{2}\right)^2 + y^2 = R^2$$

$$\left(\frac{Z}{2}\right)^2 = R^2 - y^2 \text{ or } \frac{Z}{2} = \sqrt{R^2 - y^2}$$

$$Z = 2\sqrt{R^2 - y^2}$$

$$dA = Z dy = 2\sqrt{R^2 - y^2} \cdot dy$$

$$I_{N.A} \text{ for a circular cross-section} = \frac{\pi R^4}{4}$$

Hence,

$$\tau = \frac{FA \bar{y}}{Z I} = \frac{F}{\frac{\pi R^4}{4} \cdot 2\sqrt{R^2 - y^2}} \int_{y_1}^R 2y\sqrt{R^2 - y^2} dy$$

Where R = radius of the circle.

[The limits have been taken from y_1 to R because we have to find moment of area the shaded portion]

$$= \frac{4F}{\pi R^4 \sqrt{R^2 - y^2}} \int_{y_1}^R y\sqrt{R^2 - y^2} dy$$

The integration yields the final result to be

$$\tau = \frac{4F(R^2 - y_1^2)}{3\pi R^4}$$

Again this is a parabolic distribution of shear stress, having a maximum value when $y_1 = 0$

$$\tau_{\max} |_{y_1 = 0} = \frac{4F}{3\pi R^2}$$

Obviously at the ends of the diameter the value of $y_1 = \pm R$ thus $\tau = 0$ so this again a parabolic distribution; maximum at the neutral axis

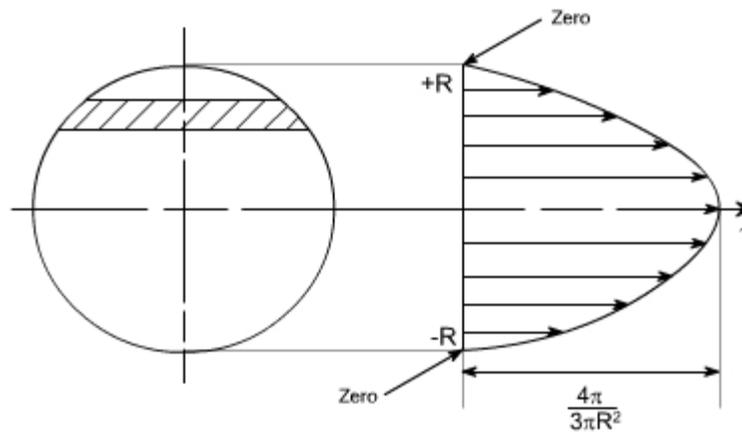
Also

$$\tau_{\text{avg}} \text{ or } \tau_{\text{mean}} = \frac{F}{A} = \frac{F}{\pi R^2}$$

Hence,

$$\tau_{\max} = \frac{4}{3} \tau_{\text{avg}}$$

The distribution of shear stresses is shown below, which indicates a parabolic distribution

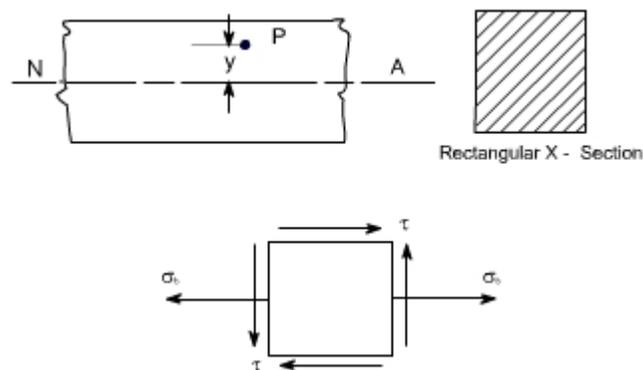


Bending stresses in simply supported, Cantilever and Overhanging beams subjected to point load and uniformly distributed loading

Principal Stresses in Beams

It becomes clear that the bending stress in beam σ_x is not a principal stress, since at any distance y from the neutral axis; there is a shear stress τ_{xy} (or τ_{yx} we are assuming a plane stress situation)

In general the state of stress at a distance y from the neutral axis will be as follows.



At some point 'P' in the beam, the value of bending stresses is given as

$$\sigma_b = \frac{My}{I} \text{ for a beam of rectangular cross-section of dimensions } b \text{ and } d; I = \frac{bd^3}{12}$$

$$\sigma_b = \frac{12 My}{bd^3}$$

whereas the value shear stress in the rectangular cross-section is given as

$$\tau = \frac{6F}{bd^3} \left[\frac{d^2}{4} - y^2 \right]$$

Hence the values of principle stress can be determined from the relations,

$$\sigma_1, \sigma_2 = \frac{1}{2}(\sigma_x + \sigma_y) \pm \frac{1}{2} \sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2}$$

Letting $\sigma_y = 0$; $\sigma_x = \sigma_b$, the values of σ_1 and σ_2 can be computed as

$$\text{Hence } \sigma_1 / \sigma_2 = \frac{1}{2} \left(\frac{12My}{bd^3} \right) \pm \frac{1}{2} \sqrt{\left(\frac{12My}{bd^3} \right)^2 + 4 \left(\frac{6F}{bd^3} \left(\frac{d^2}{4} - y^2 \right) \right)^2}$$

$$\sigma_1, \sigma_2 = \frac{6}{bd^3} \left[My \pm \sqrt{M^2 y^2 + F^2 \left(\frac{d^2}{4} - y^2 \right)^2} \right]$$

Also,

$$\tan 2\theta = \frac{2\tau_{xy}}{\sigma_x - \sigma_y} \quad \text{putting } \sigma_y = 0$$

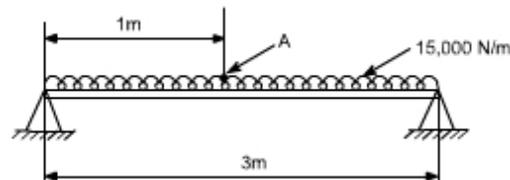
we get,

$$\tan 2\theta = \frac{2\tau_{xy}}{\sigma_x}$$

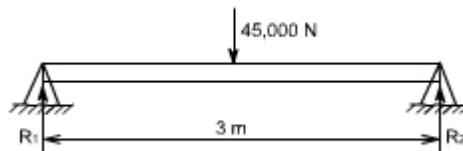
After substituting the appropriate values in the above expression we may get the inclination of the principal planes.

Illustrative examples: Let us study some illustrative examples, pertaining to determination of principal stresses in a beam

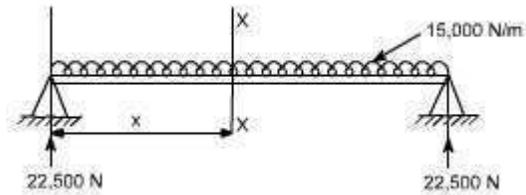
1. Find the principal stress at a point A in a uniform rectangular beam 200 mm deep and 100 mm wide, simply supported at each end over a span of 3 m and carrying a uniformly distributed load of 15,000 N/m.



Solution: The reaction can be determined by symmetry



$$R_1 = R_2 = 22,500 \text{ N}$$



consider any cross-section X-X located at a distance x from the

left end. Hence,

$$S. F \text{ at } XX = 22,500 - 15,000 x$$

$$B.M \text{ at } XX = 22,500 x - 15,000 x (x/2) = 22,500 x - 15,000 \cdot x^2 / 2$$

Therefore,

$$S. F \text{ at } X = 1 \text{ m} = 7,500$$

$$N. B. M \text{ at } X = 1 \text{ m} =$$

$$15,000 \text{ N} \quad S.F|_{x=1m} = 7,500 \text{ N}$$

$$B.M|_{x=1m} = 15,000 \text{ N.m}$$

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

$$= \frac{15,000 \times 5 \times 10^{-2} \times 12}{10 \times 10^{-12} \times (20 \times 10^{-2})^3}$$

$$\sigma_x = 11.25 \text{ MN/m}^2$$

For the computation of shear stresses

$$\tau = \frac{6F}{bd^3} \left[\frac{d^2}{4} - y^2 \right] \quad \text{putting } y = 50 \text{ mm, } d = 200 \text{ mm}$$

$$F = 7500 \text{ N}$$

$$\tau = 0.422 \text{ MN/m}^2$$

Now substituting these values in the principal stress

$$\text{equation, We get } \sigma_1 = 11.27 \text{ MN/m}^2$$

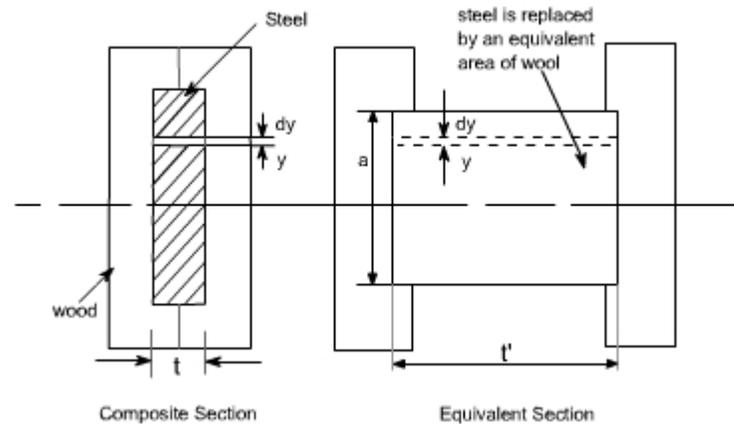
$$\sigma_2 = -0.025 \text{ MN/m}^2$$

Bending Of Composite or Fitched Beams

A composite beam is defined as the one which is constructed from a combination of materials. If such a beam is formed by rigidly bolting together two timber joists and a reinforcing steel plate, then it is termed as a fitched beam.

The bending theory is valid when a constant value of Young's modulus applies across a section it cannot be

used directly to solve the composite-beam problems where two different materials, and therefore different values of E , exist. The method of solution in such a case is to replace one of the materials by an equivalent section of the other.



Consider, a beam as shown in figure in which a steel plate is held centrally in an appropriate recess/pocket between two blocks of wood. Here it is convenient to replace the steel by an equivalent area of wood, retaining the same bending strength. i.e. the moment at any section must be the same in the equivalent section as in the original section so that the force at any given dy in the equivalent beam must be equal to that at the strip it replaces.

$$\sigma \cdot t = \sigma' \cdot t' \quad \text{or} \quad \boxed{\frac{\sigma}{\sigma'} = \frac{t'}{t}}$$

recalling $\sigma = E \cdot \varepsilon$

Thus

$$\varepsilon E t = \varepsilon' E' t'$$

Again, for true similarity the strains must be equal,

$$\varepsilon = \varepsilon' \quad \text{or} \quad E t = E' t' \quad \text{or} \quad \boxed{\frac{E}{E'} = \frac{t'}{t}}$$

Thus, $\boxed{t' = \frac{E}{E'} \cdot t}$

Hence to replace a steel strip by an equivalent wooden strip the thickness must be multiplied by the modular ratio E/E' .

The equivalent section is then one of the same materials throughout and the simple bending theory applies. The stress in the wooden part of the original beam is found directly and that in the steel found from the value at the same point in the equivalent material as follows by utilizing the given relations.

$$\frac{\sigma}{\sigma'} = \frac{t'}{t}$$

$$\frac{\sigma}{\sigma'} = \frac{E}{E'}$$

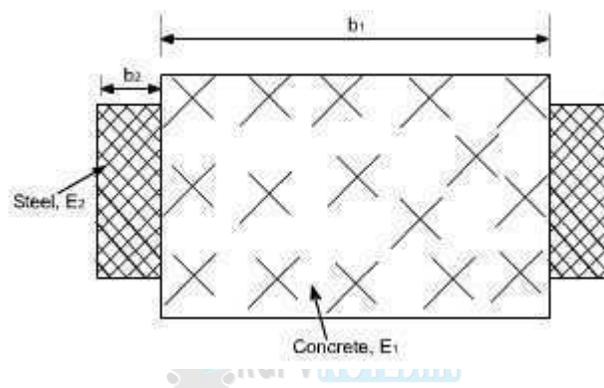
Stress in steel = modular ratio x stress in equivalent wood

The above procedure of course is not limited to the two materials treated above but applies well for any material combination. The wood and steel flitched beam was nearly chosen as a just for the sake of convenience.

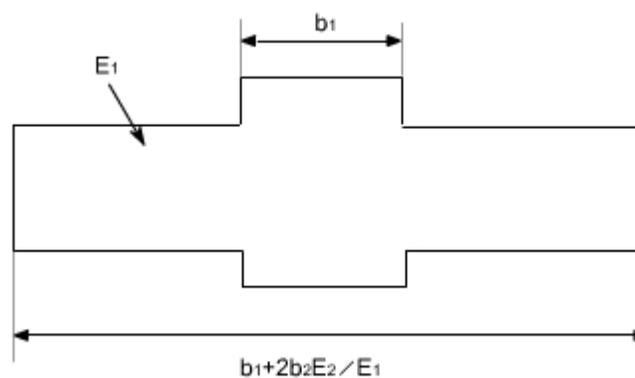
Assumption

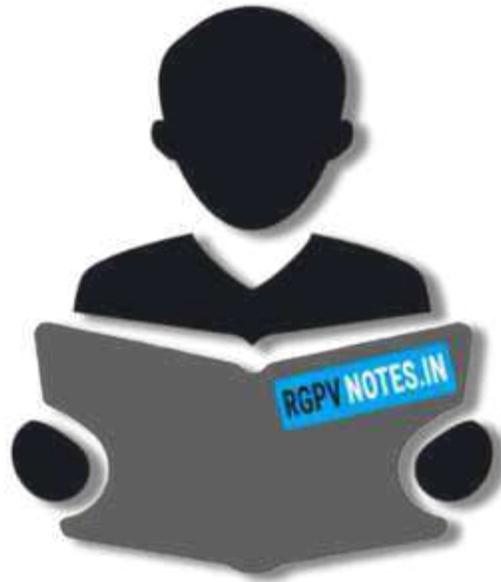
In order to analyze the behavior of composite beams, we first make the assumption that the materials are bonded rigidly together so that there can be no relative axial movement between them. This means that all the assumptions, which were valid for homogenous beams are valid except the one assumption that is no longer valid is that the Young's Modulus is the same throughout the beam.

The composite beams need not be made up of horizontal layers of materials as in the earlier example. For instance, a beam might have stiffening plates as shown in the figure below.



Again, the equivalent beam of the main beam material can be formed by scaling the breadth of the plate material in proportion to modular ratio. Bearing in mind that the strain at any level is same in both materials, the bending stresses in them are in proportion to the Young's modulus.





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