

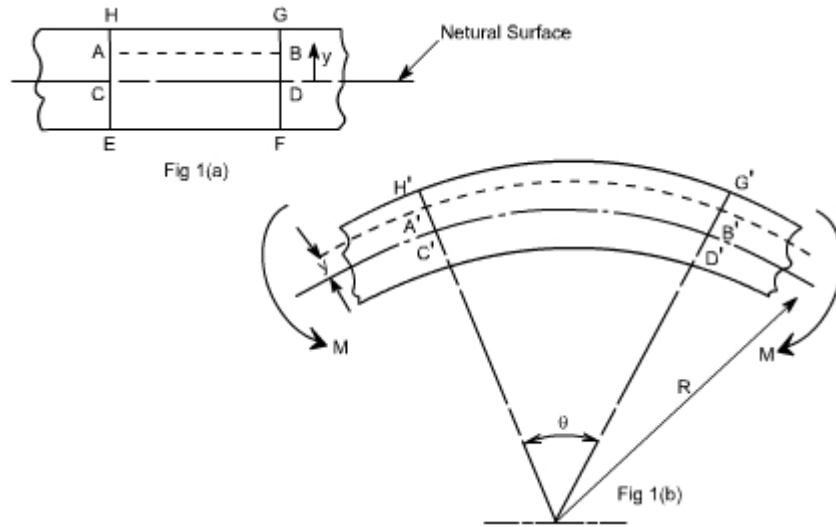
### Derivation of expression for Young's modulus

Let us consider a beam initially unstressed as shown in fig 1(a). Now the beam is subjected to a constant bending moment (i.e. 'Zero Shearing Force') along its length as would be obtained by applying equal couples at each end. The beam will bend to the radius R as shown in Fig 1(b).

As a result of this bending, the top fibers of the beam will be subjected to tension and the bottom to compression. It is reasonable to suppose, therefore, that somewhere between the two there are points at which the stress is zero. The locus of all such points is known as neutral axis. The radius of curvature R is then measured to this axis.

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  $\theta$ .

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'**

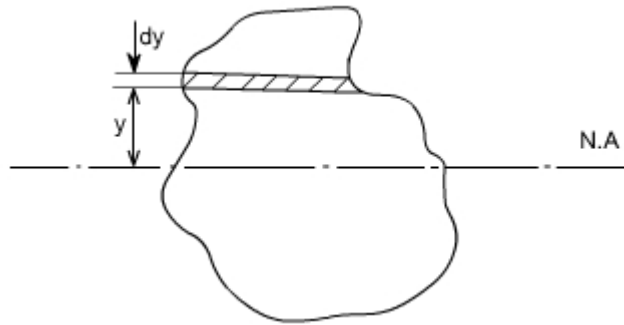


Therefore, strain in fibre  $AB = \frac{\text{change in length}}{\text{original length}} = \frac{A'B' - AB}{AB}$ . But from the figures 1(a) and 1(b),  $AB = CD$  and  $CD = C'D'$

Therefore, strain  $= \frac{A'B' - C'D'}{C'D'} = \frac{(R+y)\theta - R\theta}{R\theta} = \frac{y}{R}$ . However,  $\frac{\text{stress } (\sigma)}{\text{strain } (y)} = \text{Youngs modulus } (Y)$ .

$$\text{Therefore } \frac{\sigma}{Y} = \frac{y}{R} \quad (A1)$$

Consider any arbitrary cross section of beam as shown in Fig.2. Strain on a fibre at a distance  $y$ , from the N.A, is given by the expression  $\sigma = \frac{Y}{R}y$



**Fig.2**

If the shaded strip is of area ' $\delta A$ ' then the force on the strip is  $F = \sigma \delta A = \frac{Y}{R}y \delta A$

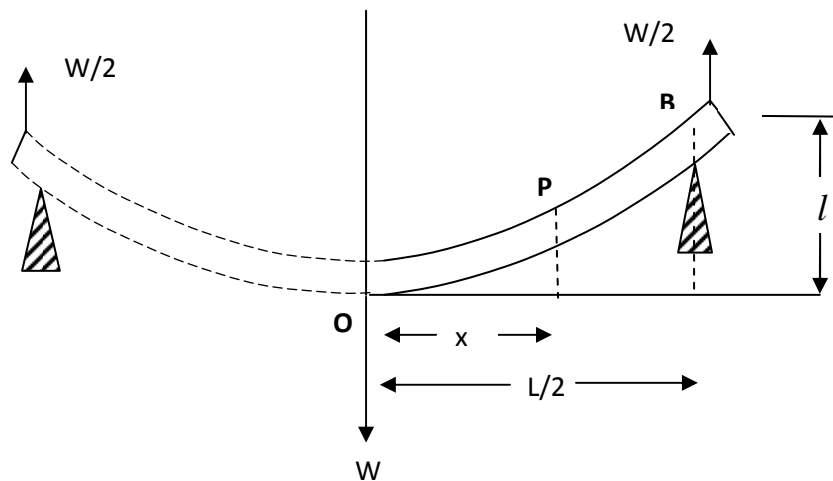
Bending moment (or the moment of resistance to bending) about the neutral axis =  $F \cdot y = \frac{Y}{R}y^2 \delta A$

The total moment for the whole cross-section is therefore equal to  $M = \sum \frac{Y}{R}y^2 \delta A = \frac{E}{R} \sum y^2 \delta A$

Now the term  $\sum y^2 \delta A$  is the property of the material and is called geometrical moment of inertia ( $I_g$ ) or second moment of inertia.

Therefore, bending moment  $M = \frac{Y}{R}I_g$  (A2)

Bending of the rod with a load at the centre is shown in Fig. 3. Consider right hand sided half portion of the rod described with solid lines. It is equivalent to a cantilever with a fixed end at O.



**Fig.3**

Considering the section PB of the cantilever OB, at a distance 'x' away from its fixed end O,

$$\text{Moment of bending couple due to load } W/2 \text{ is equal to } \frac{W}{2} \left( \frac{L}{2} - x \right) \quad (\text{A3})$$

The rod being in equilibrium, this must be balanced by bending moment (or the moment of the resistance due to bending)

$$\text{From (A2) and (A3)} \quad \frac{W}{2} \left( \frac{L}{2} - x \right) = \frac{Y}{R} I_g \quad (\text{A4})$$

For small curvatures,  $\frac{1}{R} = \frac{d^2 l}{dx^2}$  (try to derive yourself)

$$\text{By substituting for R and integrating, } \frac{dl}{dx} = \frac{W}{2YI_g} \left( L \frac{x}{2} - \frac{x^2}{2} \right) + C \quad (\text{A5})$$

Since at  $x=0$ ,  $dl/dx = 0$ , implies  $C = 0$ , substituting  $C = 0$  in (A5) and on further integrating between the limits  $x=0$ , and  $x = L/2$  gives  $l = \frac{WL^3}{48YI_g}$  (A6)

For a rectangular cross section with breadth  $b$  and depth  $d$ ,  $I_g = \frac{bd^3}{12}$  (how? clue: For a rectangular cross section bar  $I_g = \int y^2 dA$ )

$$\text{By substituting for } I_g \text{ in A6, } l = \frac{WL^3}{4Ybd^3} \text{ or } Y = \frac{WL^3}{4lb d^3}$$

**References:**

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- 2) NPTEL course notes on strength of materials <http://www.nptel.iitm.ac.in/>
- 3) Introduction to Structural Mechanics by P.S.Smith- Palgrave McMillan (2007)
- 4) Solid Mechanics by Ray Hulse, Keith Sherwin and Jack Cain, Palgrave McMillan (2004)