

Mechanical Engineering

Engineering Mechanics

Comprehensive Theory

with Solved Examples and Practice Questions



MADE EASY
Publications



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Engineering Mechanics

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Center of Gravity and Moment of Inertia

6.1 Center of Gravity

A point at which whole of the body assumed to be concentrated is known as center of gravity of a body. In case of uniform gravity it is the same as the centre of mass and have only one centre of gravity irrespective of its all orientation.

6.2 Centroid

The plane areas such as a triangle, quadrilateral, circle etc. have only areas, but no mass. The entire area of such plane figures may be assumed to be concentrated at a point, which is known as centroid of the area.

Centroid is used for geometrical figure like line, areas and volumes and depend only geometry of the body. While center of gravity is used for physical bodies like wires, plates and solids and depends upon the physical properties of the body.

However for plane areas, the centroid and centre of gravity are the same and can be used synonymously.

6.3 Centroid of Given Lamina

Consider the of definite area as shown in figure 6.1. The body may be considered to be composed of number of small body elements.

Let the area of the small element be a_1, a_2, \dots, a_n and the locations of the elements in $X-Y$ plane are $(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$. The area of the whole body is A and the centroid of body is G whose location in $X-Y$ plane is (\bar{X}, \bar{Y}) . Now we have to find out the values \bar{X} and \bar{Y} for locating G .

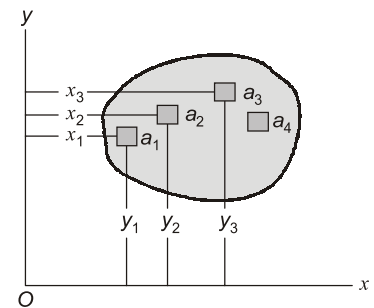


Fig.: 6.1

If G is centroid of the total area A , whose distance from the axis OY is \bar{X} , then moment of total area about OY axis is $A\bar{X}$. The moments of all the elemental area about the OY axis is

$$= a_1 x_1 + a_2 x_2 + a_3 x_3 + \dots$$

The moment of all elemental area about the axis OY must be equal to the moment of total area about the same axis. Therefore

$$A\bar{X} = a_1 x_1 + a_2 x_2 + a_3 x_3 + \dots$$

or

$$\bar{X} = \frac{a_1 x_1 + a_2 x_2 + a_3 x_3 + \dots}{A}$$

Similarly
$$\bar{Y} = \frac{a_1 y_1 + a_2 y_2 + a_3 y_3 + \dots}{A}$$

Above two equation gives the location of centroid of body. Following point should be kept in mind while determining the location of centroid of a body:

- Values of $\bar{x}_1, \bar{x}_2, \bar{x}_3, \bar{x}_4, \dots$ and $\bar{y}_1, \bar{y}_2, \bar{y}_3, \bar{y}_4, \dots$ should be measured on same side of axis of reference. If, however the figure is on both side of the axis of reference, then the distances in one direction are taken as positive and those in the opposite direction must be taken as negative.
- If given section is symmetrical about x axis or y axis, then we only have to calculate either \bar{X} or \bar{Y} because centroid or C.G. of the section lies on the axis of symmetry.

6.4 C.G. of a Uniform Rectangular Lamina

Figure 6.2 shows a rectangle $ABCD$ of width b and height h . Consider an element dy at a distance y from x axis, then the area of this element is

$$da = b dy$$

The moment about the x axis is

$$= y \cdot b dy$$

The sum of moments of all such elementary area is

$$= \int_0^h y \cdot b dy = b \int_0^h y dy$$

If \bar{Y} is distance of centroid from x axis then from principal of moment we can write

$$bh\bar{Y} = b \int_0^h y dy$$

or

$$h\bar{Y} = \left[\frac{y^2}{2} \right]_0^h = \frac{h^2}{2}$$

or

$$\bar{Y} = \frac{h}{2}$$

Similarly

$$\bar{X} = \frac{b}{2}$$

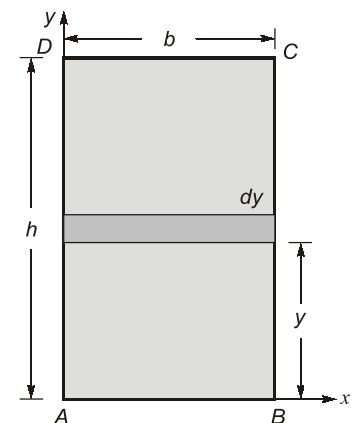


Fig.: 6.2

6.5 Centroid of Triangular Lamina

Consider a triangle ABC of base b and height h shown in figure 6.3. Consider an elemental width of dy at a distance y as shown in figure whose width is b_1 .

The area of elemental strip is given by

$$da = b_1 \cdot dy$$

Considering the triangles ABC and ADE which are equiangular, we can write

$$\frac{b_1}{b} = \frac{h-y}{h}$$

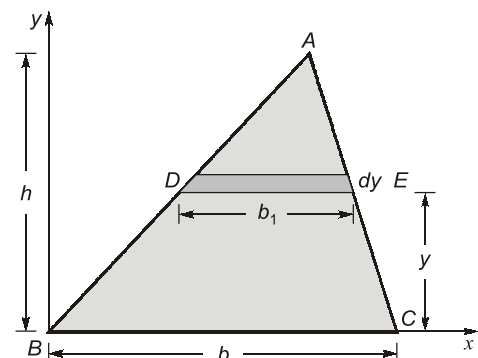


Fig.: 6.3

or
$$b_1 = \frac{b(h-y)}{h}$$

Substituting this, we get

$$da = \frac{b}{h}(h-y)dy$$

Moment of this elemental strip about x axis or base BC is

$$= \frac{b}{h}(h-y)dy \cdot y$$

The sum of the moments of all such elementary strip of the triangular lamina about base BC

$$= \int_0^h y \cdot \frac{b}{h}(h-y)dy$$

If \bar{Y} is distance of centroid from x axis then from principal of moment we can write

$$A\bar{Y} = \int_0^h y \cdot \frac{b}{h}(h-y)dy$$

or

$$\frac{1}{2}bh\bar{Y} = \int_0^h y \cdot \frac{b}{h}(h-y)dy$$

or

$$\frac{1}{2}h^2\bar{Y} = \int_0^h (hy - y^2)dy = \left[h\frac{y^2}{2} - \frac{y^3}{3} \right]_0^h$$

or

$$\frac{1}{2}h^2\bar{Y} = \frac{h^3}{6}$$

or

$$\bar{Y} = \frac{h}{3}$$

Thus height of centroid of any triangle from its base is $h/3$. If triangle is right angle then its \bar{X} can be determine the inspection only. Consider the right angle triangle $\triangle ABC$ shown in figure 6.4. As discussed above, its centroid \bar{Y} must be at $h/3$ above from its base. If we consider AB its base and BC height then its centroid must be $b/3$ from BC .

Now draw a perpendicular AN from point A on BC in triangle as shown in figure 6.5. Let $AN = h$, $NB = a$ and $NC = c$ where $a + c = b$. Now we have two right angle triangle $\triangle ANC$ and $\triangle ANB$ whose centroid are known and shown in figure.

Assume C.G. of the triangle from point B along x -axis is \bar{X} . Sum of moments of areas $\triangle ANC$ and $\triangle ANB$ about y -axis is equal to moment of area $\triangle ABC$. Therefore

$$\frac{1}{2}bh\bar{X} = \frac{1}{2}ah \times \frac{2}{3}a + \frac{1}{2}ch \left(a + \frac{c}{3} \right)$$

or

$$b\bar{X} = a \times \frac{2}{3}a + c \left(a + \frac{c}{3} \right)$$

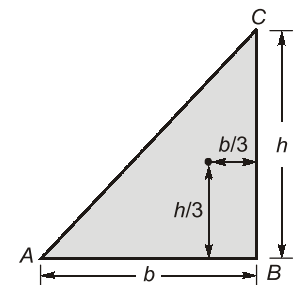


Fig.: 6.4

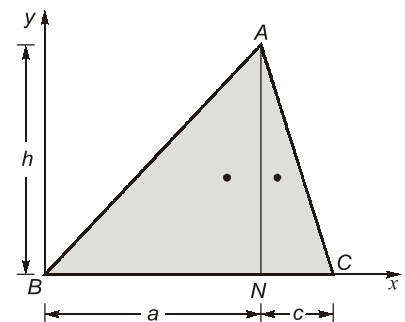


Fig.: 6.5

or
$$\bar{X} = \frac{2a^2 + 3ac + c^2}{3b} = \frac{2a^2 + 2ac + ac + c^2}{3b}$$

or
$$\bar{X} = \frac{(2a+c)(a+c)}{3(a+c)} = \frac{(2a+c)}{3}$$

or
$$\bar{X} = \frac{(2a+c)}{3} = \frac{(a+a+c)}{3} = \frac{(a+b)}{3}$$

Similarly the C.G. from the point C is $\frac{(c+b)}{3}$

6.6 Centroid of a Semicircular Lamina

Consider the semicircle shown in figure 6.6. This semicircle is symmetrical about its y axis. So centroid lie on this axis. Here $\bar{X} = 0$ and we have to determined \bar{Y} . Consider the elemental radial area OPQ at an angle θ as shown in figure 6.6 whose include angle is $d\theta$. This can be considered as a triangle with base $PQ = r \cdot d\theta$ and height r .

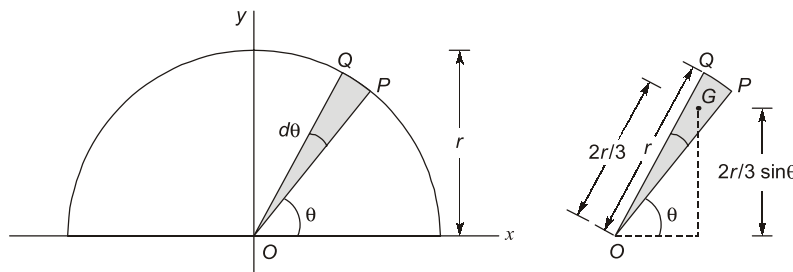


Fig. 6.6

Area of OPQ is
$$da = \frac{1}{2}(rd\theta) \cdot r = \frac{1}{2}r^2 \cdot d\theta$$

The distance C.G. of this area from the point O is $\frac{2}{3}r$. The height of centroid from x -axis

$$= \frac{2}{3}r \sin \theta$$

Moment of area OPQ about x -axis is area multiply by height. Therefore

$$= \frac{1}{2}r^2 d\theta \times \frac{2}{3}r \sin \theta = \frac{r^3}{3} \sin \theta d\theta$$

Moment of whole half circle area
$$= \int_0^{\pi} \frac{r^3}{3} \sin \theta d\theta = \frac{r^3}{3} \int_0^{\pi} \sin \theta d\theta = \frac{2}{3}r^3 \int_0^{\pi/2} \sin \theta d\theta = \frac{2}{3}r^3$$

If \bar{Y} is distance if centroid from x axis then from principal of moment we can write

$$\frac{\pi}{2}r^2\bar{Y} = \frac{2}{3}r^3 \quad \text{or} \quad \bar{Y} = \frac{4r}{3\pi}$$

6.7 C.G. of a Right Circular Cone

Consider a cone of base radius r and height h as shown in figure 6.7. The density of material is ρ . The cone is symmetrical about its y axis. So centroid lie on this axis. Thus we have to find out the position of C.G. from the base above the x axis along y axis.

Consider an element volume of thickness dy at a distance y from base as shown in figure. The weight of this elemental volume is

$$dW = \pi x^2 \cdot dy \cdot \rho$$

Considering equiangular triangles OAB and BCD, we can write

$$\frac{CD}{BC} = \frac{OA}{OB}$$

or

$$x = \frac{OA}{OB} BC = \frac{r}{h}(h - y)$$

Substituting this value we get weight of elemental volume considered

$$dW = \pi \cdot \frac{r^2}{h^2}(h - y)^2 \rho \cdot dy$$

Moment of this elemental weight about x axis

$$= \pi \rho \left(\frac{r}{h} \right)^2 (h - y)^2 y dy$$

Total moment of the given cone is

$$= \int_0^h \pi \rho \left(\frac{r}{h} \right)^2 (h - y)^2 y dy = \pi \rho \left(\frac{r}{h} \right)^2 \int_0^h [h^2 - 2hy + y^2] y dy$$

$$= \pi \rho \left(\frac{r^2}{h^2} \right) \int_0^h [h^2 y - 2hy^2 + y^3] dy$$

$$= \pi \rho \frac{r^2}{h^2} \left[h^2 \cdot \frac{y^2}{2} - 2h \frac{y^3}{3} + \frac{y^4}{4} \right]_0^h = \frac{\pi \rho r^2 h^2}{12}$$

If \bar{Y} is distance of C.G. from x axis then from principal of moment we can write

$$\frac{\pi}{3} r^2 h \cdot \rho \cdot \bar{Y} = \frac{\pi \rho}{12} r^2 h^2$$

or

$$\bar{Y} = \frac{h}{4}$$

6.8 C.G. of a Hemispherical Solid

Consider a solid hemisphere of radius r and where density of material is ρ . Consider a differential disk elementary strip of thickness dy at a distance y from x axis as shown in figure 6.8.

The weight of this elementary strip

$$dW = \rho \pi x^2 \cdot dy$$

From the geometry of figure 6.8

$$x^2 = (r^2 - y^2)$$

Thus

$$dW = \rho \pi (r^2 - y^2) \cdot dy$$

The moment of this weight of elementary strip about x axis

$$= \int_0^r \rho \pi (r^2 - y^2) y dy = \rho \pi \int_0^r (r^2 - y^2) y dy$$

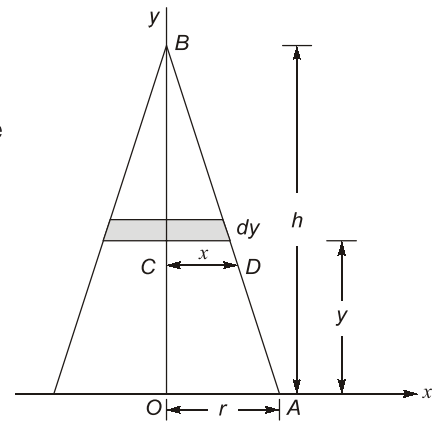


Fig: 6.7

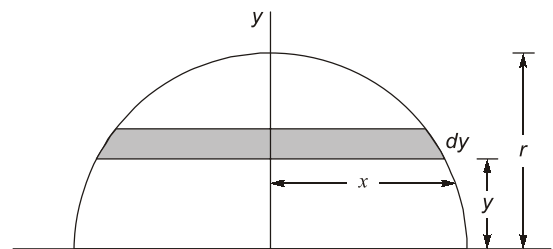


Fig.: 6.8

(\because equation of circle is: $x^2 + y^2 = r^2$)

If \bar{Y} is distance C.G. from x axis then from principal of moment, we can write

$$\left[\frac{1}{2} \left(\frac{4}{3} \pi r^3 \right) \rho \right] \cdot \bar{Y} = \rho \pi \int_0^r (r^2 - y^2) y dy$$

or
$$\frac{2}{3} r^3 \cdot \bar{Y} = \int_0^r (r^2 y - y^3) dy$$

or
$$\frac{2}{3} r^3 \cdot \bar{Y} = \left[r^2 \frac{y^2}{2} - \frac{y^4}{4} \right]_0^r = \frac{r^4}{4}$$

or
$$\bar{Y} = \frac{3}{8} r$$

6.9 Moment of Inertia

Moment of inertia is a mathematical expression which is related to a body's tendency to resist rotation. The moment of force about any point is product of the force and the perpendicular distance between them, it is also called first moment of forces. If this first moment is again multiplied by the perpendicular distance between them, then the product so obtained is called second moment of force or moment of moment of the force. If instead of force we consider the area of the lamina or mass of the body, it is called the second moment of area or second moment of mass. They are also termed broadly as moment of inertia.

6.10 Moment of Inertia of an Area

Consider an area as shown in figure 6.9. Consider an elemental area dA which is located at y from x axis, then the moment of inertia of dA about x axis is given by

$$dI_x = dA \cdot y^2$$

Total moment of inertia of given area is

$$I_x = \int dA \cdot y^2$$

Similarly

$$I_y = \int dA \cdot x^2$$

Thus, the moment of inertia of an area about the given axis is the sum of moments of inertia of an elementary area constituting the given area about the given axis.

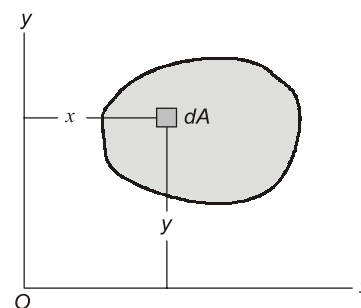


Fig.: 6.9

6.11 Theorem of Parallel Axis

This theorem states that,

The moment of inertia of lamina about any axis in the plane of the lamina equals the sum of moment of inertia of the area about a parallel centroidal axis in the plane of lamina and the product of the area of the lamina and square of the distance between two axis.

As per above statement for the given area as shown in figure 6.10. we can write

$$I_{x'} = I_G + d^2 A$$

Proof:

Figure 6.10 shows a plane lamina of area A . We have to determine moment of inertia about x' axis. Consider an elemental area dA located as shown in figure, then we can write

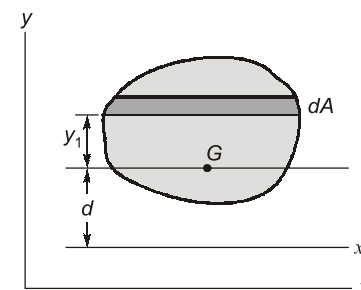


Fig.: 6.10

$$dI_G = dA \cdot y_1^2$$

or

$$I_G = \int dA \cdot y_1^2$$

The moment of inertia of dA about x' axis is

$$I_{x'} = \int (y_1 + d)^2 dA = \int dA \cdot y_1^2 + \int dA \cdot d^2 + \int 2dA y_1 d$$

or

$$= I_G + d^2 \int dA + 2d \int dA \cdot y_1$$

Here $\int dA \cdot y_1$ is the moment of area about its centroid, that is always zero. Therefore

$$I_{x'} = I_G + d^2 A$$

6.12 Theorem of Perpendicular Axis

This theorem states that,

If I_x and I_y be the moment of inertia about two mutually perpendicular x axis and y axis in the plane of the lamina and I_z be the moment of inertia of the lamina about an axis normal to the plane of lamina and passing through the point of intersection of the x axis and y axis.

As per statement of theorem

$$I_z = I_x + I_y$$

where z axis is perpendicular to x and y axes.

Consider an area dA from total area A located in the three dimensions and whose coordinates are x and y in the $x-y$ plane and its distance from z axis is r as shown in figure 6.11.

$$r^2 = x^2 + y^2$$

$$\begin{aligned} dI_z &= dA \cdot r^2 = dA (x^2 + y^2) \\ &= dA \cdot x^2 + dA \cdot y^2 \end{aligned}$$

Thus

$$I_z = \int_A dA \cdot x^2 + \int_A dA \cdot y^2$$

or

$$I_z = I_x + I_y$$

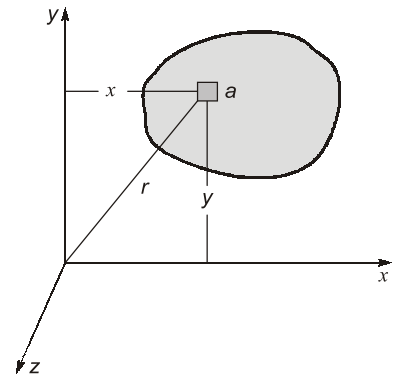


Fig.: 6.11

6.13 Radius of Gyration

The distance from the reference axis to a point where whole area of given lamina can be considered to be concentrated and produce the same moment of inertia with respect to given reference axis is known as radius of gyration.

Let I is the moment of inertia about given axis and K is the distance from axis of rotation at which whole magnitude of the given area is assumed to be concentrated to have the same moment of inertia as that of the area about that axis, then,

$$I = A \cdot K^2$$

or

$$K = \sqrt{\frac{I}{A}}$$

If the body is considered solid, then the above equations are written as

$$K = \sqrt{\frac{I_{xx}}{m}}$$

where m is the mass and I_{xx} is the mass moment of inertia of solid body considered

6.14 Moment of Inertia of a Rectangular Lamina

Consider rectangular of $b \times d$ as shown in figure 6.12, where x and y axes are located passing through the C.G. of the rectangular lamina. Consider an elemental strip of thickness dy at a distance y from x axis, then as per definition, the moment of inertia of this elemental area about x -axis is given by

$$dI = dA \cdot y^2 = (b \cdot dy) \cdot y^2$$

or

$$\begin{aligned} I_x &= \int_0^{d/2} (b \cdot dy) y^2 = 2b \int_0^{d/2} y^2 dy \\ &= 2b \left[\frac{y^3}{3} \right]_0^{d/2} = \frac{2b}{3} \left(\frac{d}{2} \right)^3 = \frac{1}{12} b d^3 \end{aligned}$$

Similarly, we can also write $I_y = \frac{1}{12} d b^3$

As per the theorem of perpendicular axis,

$$I_z = I_x + I_y$$

$$\Rightarrow I_z = \frac{1}{12} b d (b^2 + d^2)$$

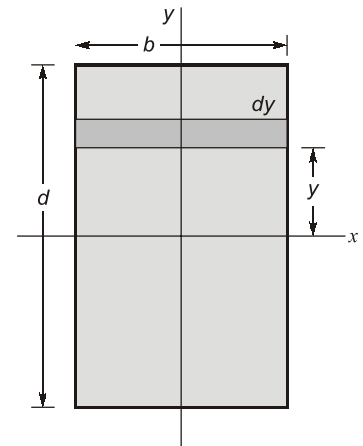


Fig.: 6.12

6.15 Moment of Inertia of a Circular Lamina

Consider a circular lamina of diameter d as shown in figure 6.13 where x and y axes are located passing through the C.G. of the circular lamina. Consider an z axis perpendicular to x and y axes and passing through O and then consider an elemental area dA at a distance r of thickness dr , then the moment of area of dA about the axis z is given by

$$dI_z = dA \cdot r^2 = (2\pi r \cdot dr) \cdot r^2 = 2\pi r^3 dr$$

$$I_z = \int_0^{d/2} 2\pi r^3 \cdot dr = 2\pi \left[\frac{r^4}{4} \right]_0^{d/2} = \frac{\pi d^4}{32}$$

But

$$I_x + I_y = I_z$$

or

$$2I_x = 2I_y = I_z$$

$$I_x = I_y = \frac{1}{2} \left(\frac{\pi d^4}{32} \right) = \frac{\pi d^4}{64}$$

If lamina is hollow with outer diameter d_2 and inner diameter d_1 , then the moment of inertia is given by

$$I_x = I_y = \frac{\pi}{64} (d_2^4 - d_1^4)$$

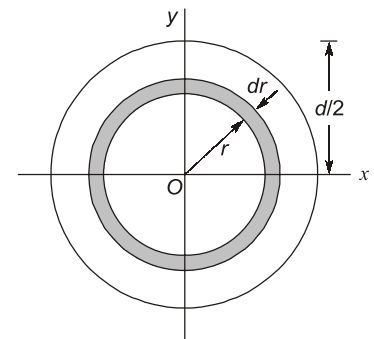


Fig.: 6.13

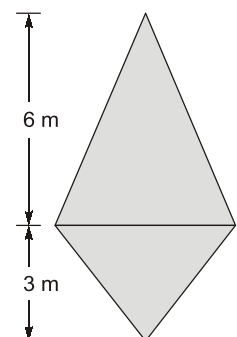
as $I_x = I_y$

Example 6.1

Two isosceles triangles having the same base b and having heights of 6 cm and 3 cm are attached to each other at the base as shown in figure. Determine the centroid of combined body.

Solution:

The figure redrawn as shown in figure. Reference axis are chosen as shown in figure. As the section is symmetrical about y axis, therefore its center of gravity will lie on this axes.



The distance of centroid from x axis is

$$\bar{Y} = \frac{A_1 \bar{y}_1 + A_2 \bar{y}_2}{A_1 + A_2}$$

where A_1 and A_2 are the area of respective triangle \bar{y}_1 and \bar{y}_2 are distance of respective center of gravity from axis x .

Thus

$$A_1 = \frac{1}{2} \times b \times 6 = 3b \text{ cm}^2$$

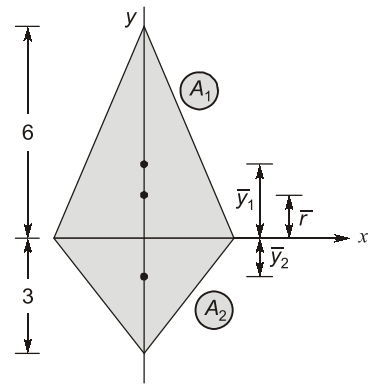
$$A_2 = \frac{1}{2} \times b \times 3 = 1.5b \text{ cm}^2$$

$$\bar{y}_1 = \frac{1}{3} \times 6 = 2 \text{ cm}$$

$$\bar{y}_2 = -\frac{1}{3} \times 3 = -1 \text{ cm}$$

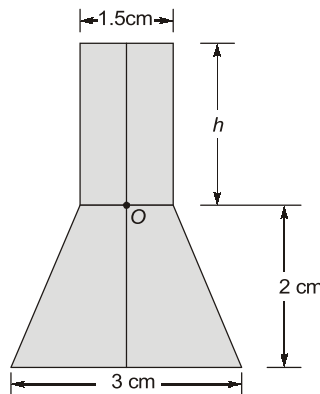
$$\bar{Y} = \frac{3b \times 2 + 1.5b \times (-1)}{3b + 1.5b} = 1 \text{ cm}$$

Thus centroid is at 1 cm above x axis.



Example 6.2

The C.G. of lamina shown in figure lie at the point O . Determine the height of the rectangle.



Solution:

The figure has been redrawn as shown in figure. Here G_1 and G_2 are the C.G. of the rectangle A_1 and Trapezium A_2 . Here O is the center of gravity G also.

Thus

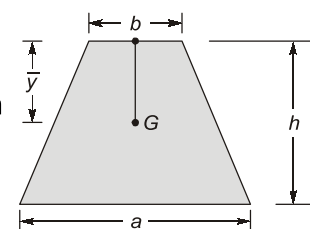
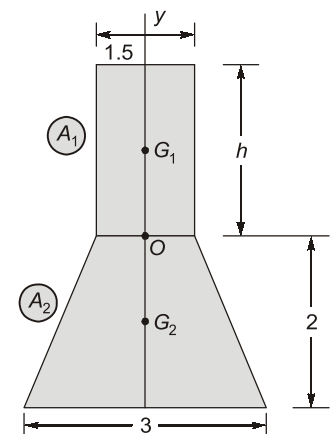
$$OG_1 = GG_1 = \frac{h}{2}$$

C.G. of Trapezium, $\bar{y} = \frac{h}{3} \left(\frac{2a+b}{a+b} \right)$

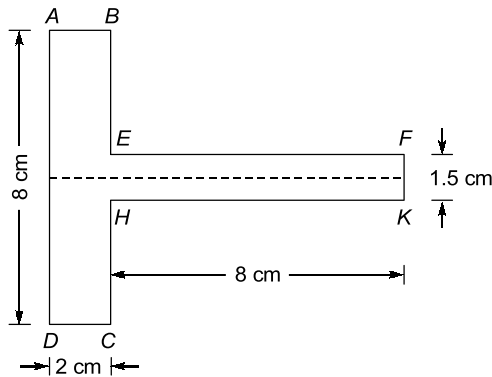
$$OG_2 = GG_2 = \frac{h}{3} \left(\frac{2a+b}{a+b} \right) = \frac{2}{3} \left(\frac{2 \times 3 + 1.5}{1.5 + 3} \right) = \frac{10}{9} \text{ cm}$$

$$A_1 = h \times 1.5 = 1.5h$$

$$A_2 = \left(\frac{a+b}{2} \right) h = \left(\frac{3+1.5}{2} \right) \times 2 = 4.5 \text{ cm}$$



Q.3 In a thin uniform lamina having symmetrical central axis as shown in figure. The distance of centre of gravity from AD is



- (a) 3 cm (b) $\frac{22}{7}$ cm
(c) $\frac{23}{7}$ cm (d) $\frac{24}{7}$ cm

ANSWERS

1. (c) 2. (c) 3. (b)

Hints & Explanation

1. (c)

$$\bar{x} = 0.636R.$$

2. (c)

$$\bar{y} = \frac{A \cdot 2 - \frac{A}{4} \times 4}{\frac{3A}{4}} = \frac{4A}{3A} = \frac{4}{3}, \quad A = \text{area of triangle}$$

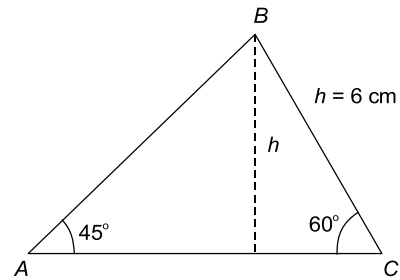
3. (b)

$$\bar{x} \text{ from } AD = \frac{16 \times 1 + 12 \times 6}{28} = \frac{88}{28} = \frac{22}{7}$$



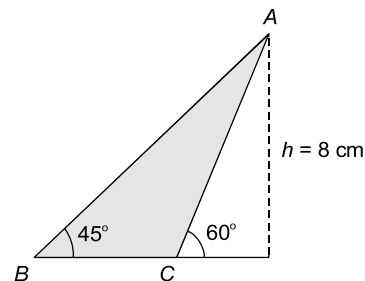
**Student's
Assignments**

Q.1 A triangle ABC , has altitude $h = 6$ cm. What moment is of inertia about centroidal axis which is parallel to base AC ?



- (a) 56.77 cm^4 (b) 113.54 cm^4
(c) 170.35 cm^4 (d) None of these

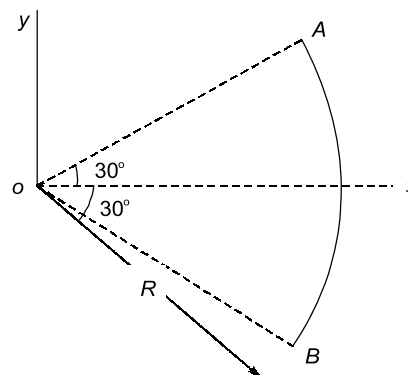
Q.2 What is moment of inertia of triangle ABC as shown in figure about base BC ?



- (a) 48.13 cm^4 (b) 144.26 cm^4
(c) 341.3 cm^4 (d) None of these.

Q.3 What is \bar{x} of circular arc A , subtending an angle of 60° at O ?

- (a) $0.985R$ (b) $0.955R$
(c) $0.866R$ (d) $0.75R$



■■■■