ENGINEERING MECHANICS

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Moment of Inertia

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- **Area moment of inertia**
- Rectangular moment of inertia/ second moment of inertia
- Polar moment of inertia
- Radius of Gyration(Rectangular radius of gyration and polar radius of gyration)
- **Parallel axis Theorem**
- **Derivation of moment of inertia for different geometric figures**

Importance of centroid/centre of gravity

- **First area moment of inertia is either positive or negative or zero**
- **Second area moment of inertia is the Moment of first area moment of inertia**
- **but Second area moment of inertia is always positive about the axis**
- **Second moment of inertia is denoted by capital ‘I’**
- **Unit of second area moment of inertia is mm4**

Rectangular Area moment of inertia and polar moment of inertia

Rectangular and Polar Moments of Inertia

Consider the area A in the x-y plane, Fig. A/2. The moments of inertia of the element dA about the x- and y-axes are, by definition, $dI_x = y^2\,dA$ and $dI_y = x^2\,dA$, respectively. The moments of inertia of A about the same axes are therefore

$$I_x = \int y^2\,dA$$
$$I_y = \int x^2\,dA \qquad \text{(A/1)}$$

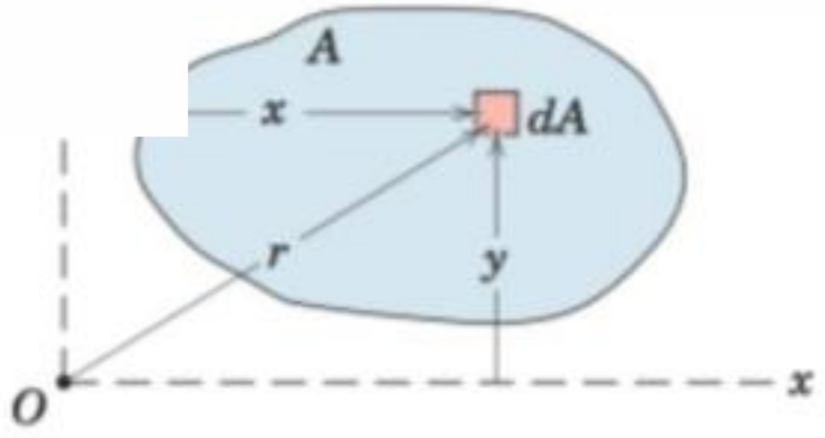


Figure A/2

Rectangular Area moment of inertia and polar moment of inertia

The moment of inertia of dA about the pole O (z-axis) is, by similar definition, $dI_z = r^2\,dA$. The moment of inertia of the entire area about O is

$$\boxed{I_z = \int r^2\,dA} \qquad \text{(A/2)}$$

The expressions defined by Eqs. A/1 are called *rectangular* moments of inertia, whereas the expression of Eq. A/2 is called the *polar* moment of inertia.* Because $x^2 + y^2 = r^2$, it is clear that

$$\boxed{I_z = I_x + I_y} \qquad \text{(A/3)}$$

Radius of gyration

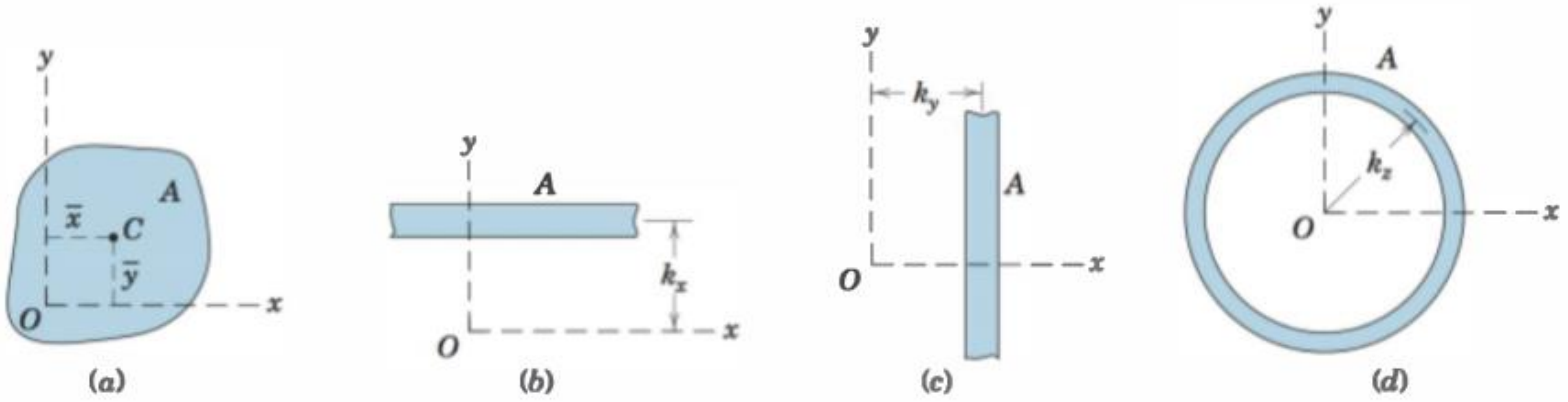


Figure A/3

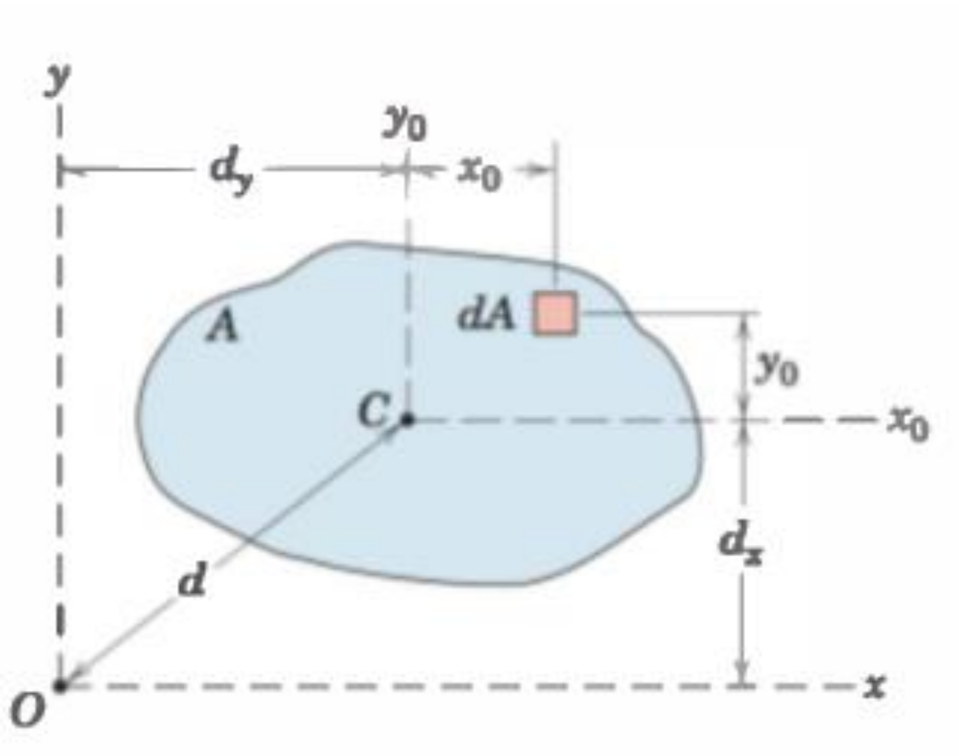
$$I_x = k_x^2 A$$
$$I_y = k_y^2 A$$
$$I_z = k_z^2 A$$

or

$$k_x = \sqrt{I_x/A}$$
$$k_y = \sqrt{I_y/A}$$
$$k_z = \sqrt{I_z/A}$$

$$k_z^2 = k_x^2 + k_y^2$$

Transfer axis theorem



- The moment of inertia of an area about a non centroidal axis may be easily expressed in terms of the moment of inertia about a parallel centroidal axis.

Transfer axis theorem

- By definition, the moment of inertia of the element dA about the x-axis is given by

$$dI_x = (y_0 + d_x)^2\, dA$$

Expanding and integrating give us

$$I_x = \int y_0^2\, dA + 2d_x \int y_0\, dA + d_x^2 \int dA$$

Transfer axis theorem

- We see that the first integral is by definition the moment of inertia $\bar{I}_x$ about the centroidal x_0-axis. The second integral is zero, since $\int y_0\, dA = A\bar{y}_0$ and $\bar{y}_0$ is automatically zero with the centroid on the x_0-axis. The third term is simply $Ad_x{}^2$. Thus, the expression for I_x and the similar expression for I_y become

$$\boxed{\begin{aligned} I_x &= \bar{I}_x + Ad_x{}^2 \\ I_y &= \bar{I}_y + Ad_y{}^2 \end{aligned}} \qquad \textbf{(A/6)}$$

By Eq. A/3 the sum of these two equations gives

$$I_z = \bar{I}_z + Ad^2 \qquad \textbf{(A/6}a\textbf{)}$$

Transfer axis theorem

- We see that the first integral is by definition the moment of inertia $\bar{I}_x$ about the centroidal x_0-axis. The second integral is zero, since $\int y_0 \, dA = A\bar{y}_0$ and $\bar{y}_0$ is automatically zero with the centroid on the x_0-axis. The third term is simply Ad_x^2. Thus, the expression for I_x and the similar expression for I_y become

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By Eq. A/3 the sum of these two equations gives

$$I_z = \bar{I}_z + Ad^2 \qquad \textbf{(A/6a)}$$

Transfer axis theorem

- **Conditions for parallel axis theorem**

1. **two axis should be there and two axis must be parallel to each other**
2. **Between two axis, one axis has to pass through the centroidal axis**

Transfer axis theorem

$[I_x = \int y^2 \, dA]$ $\qquad \bar{I}_x = \int_{-h/2}^{h/2} y^2 b \, dy = \frac{1}{12} bh^3$ *Ans.*

By interchange of symbols, the moment of inertia about the centroidal y_0-axis is

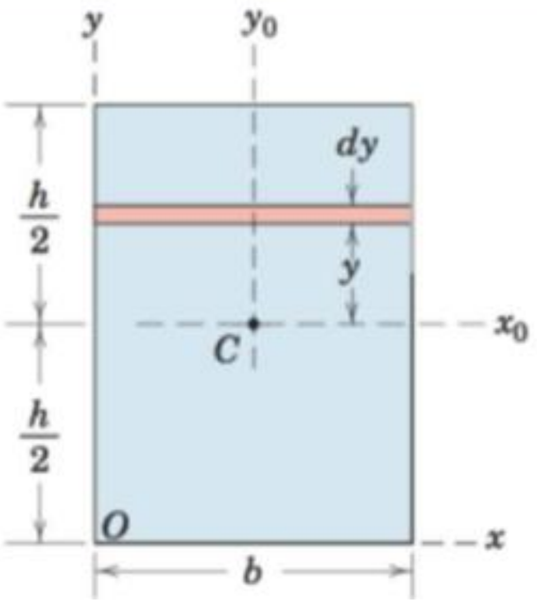
$$\bar{I}_y = \frac{1}{12} hb^3 \qquad \textit{Ans.}$$

The centroidal polar moment of inertia is

$[\bar{I}_z = \bar{I}_x + \bar{I}_y]$ $\qquad \bar{I}_z = \frac{1}{12}(bh^3 + hb^3) = \frac{1}{12} A(b^2 + h^2)$ *Ans.*

By the parallel-axis theorem, the moment of inertia about the x-axis is

$[I_x = \bar{I}_x + Ad_x^2]$ $\qquad I_x = \frac{1}{12} bh^3 + bh\left(\frac{h}{2}\right)^2 = \frac{1}{3} bh^3 = \frac{1}{3} Ah^2$ *Ans.*



Transfer axis theorem

Solution. A strip of area parallel to the base is selected as shown in the figure, and it has the area $dA = x\,dy = [(h - y)b/h]\,dy$. By definition

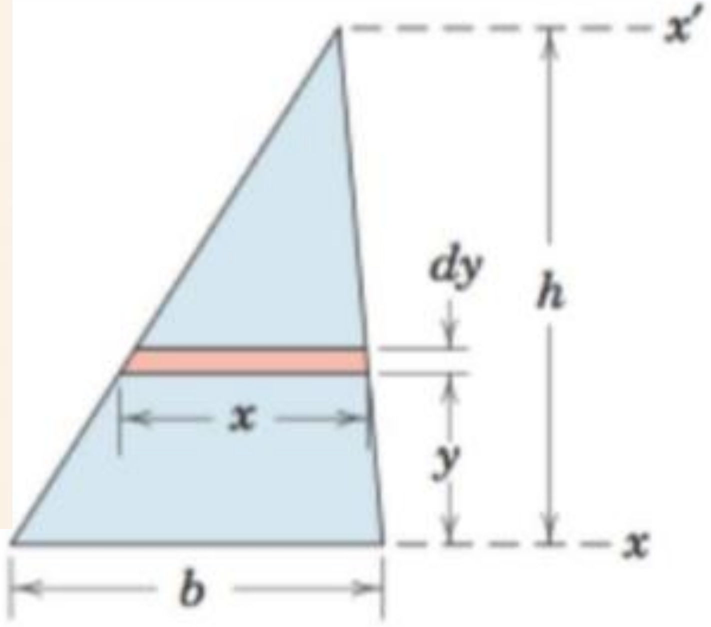
$$[I_x = \int y^2\,dA] \qquad I_x = \int_0^h y^2 \frac{h-y}{h} b\,dy = b\left[\frac{y^3}{3} - \frac{y^4}{4h}\right]_0^h = \frac{bh^3}{12} \qquad \textit{Ans.}$$

By the parallel-axis theorem, the moment of inertia $\bar{I}$ about an axis through the centroid, a distance $h/3$ above the x-axis, is

$$[\bar{I} = I - Ad^2] \qquad \bar{I} = \frac{bh^3}{12} - \left(\frac{bh}{2}\right)\left(\frac{h}{3}\right)^2 = \frac{bh^3}{36} \qquad \textit{Ans.}$$

A transfer from the centroidal axis to the x'-axis through the vertex gives

$$[I = \bar{I} + Ad^2] \qquad I_{x'} = \frac{bh^3}{36} + \left(\frac{bh}{2}\right)\left(\frac{2h}{3}\right)^2 = \frac{bh^3}{4} \qquad \textit{Ans.}$$



Transfer axis theorem

Solution. A differential element of area in the form of a circular ring may be used for the calculation of the moment of inertia about the polar z-axis through O since all elements of the ring are equidistant from O. The elemental area is $dA = 2\pi r_0\, dr_0$, and thus,

$$[I_z = \int r^2\, dA] \qquad I_z = \int_0^r r_0^{\,2}(2\pi r_0\, dr_0) = \frac{\pi r^4}{2} = \tfrac{1}{2}Ar^2 \qquad \textit{Ans.}$$

The polar radius of gyration is

$$\left[k = \sqrt{\frac{I}{A}}\right] \qquad k_z = \frac{r}{\sqrt{2}} \qquad \textit{Ans.}$$

By symmetry $I_x = I_y$, so that from Eq. A/3

$$[I_z = I_x + I_y] \qquad I_x = \tfrac{1}{2}I_z = \frac{\pi r^4}{4} = \tfrac{1}{4}Ar^2 \qquad \textit{Ans.}$$

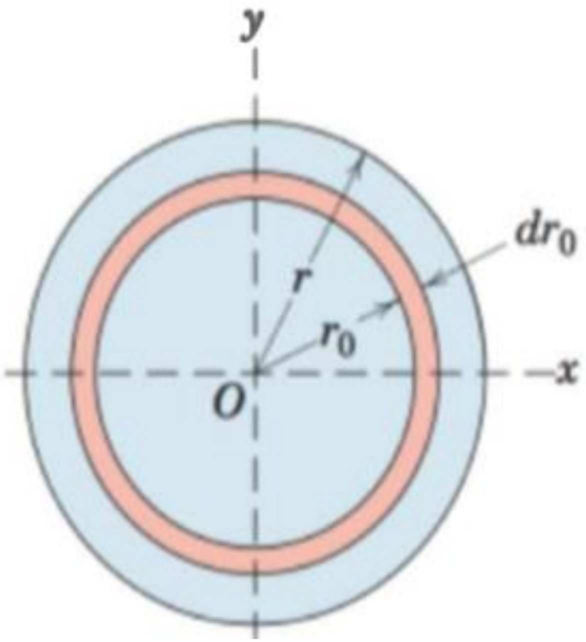


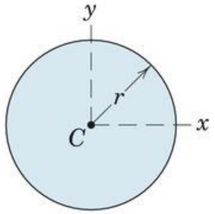
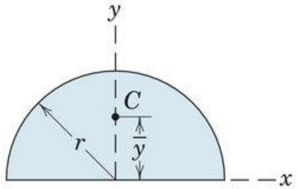
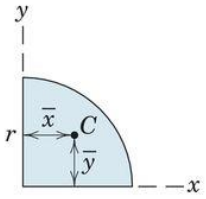
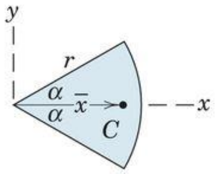
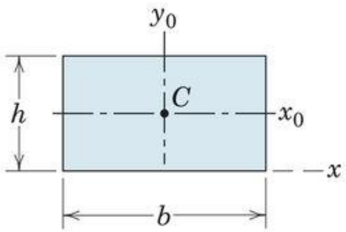
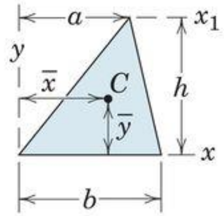
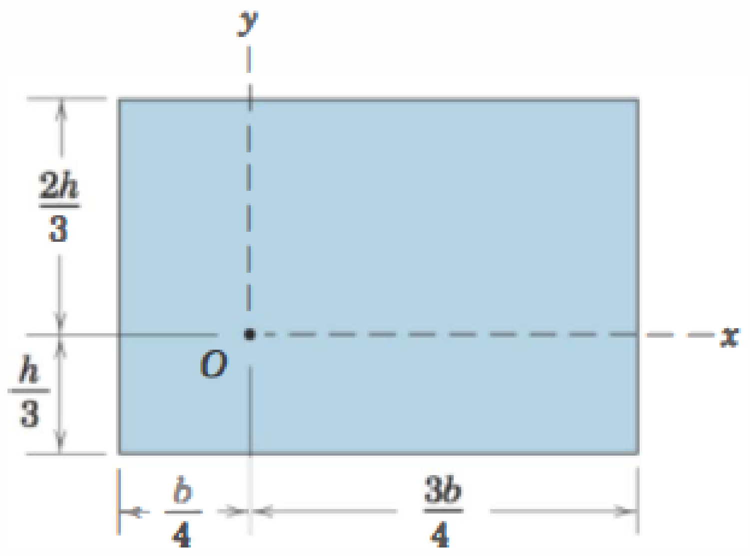
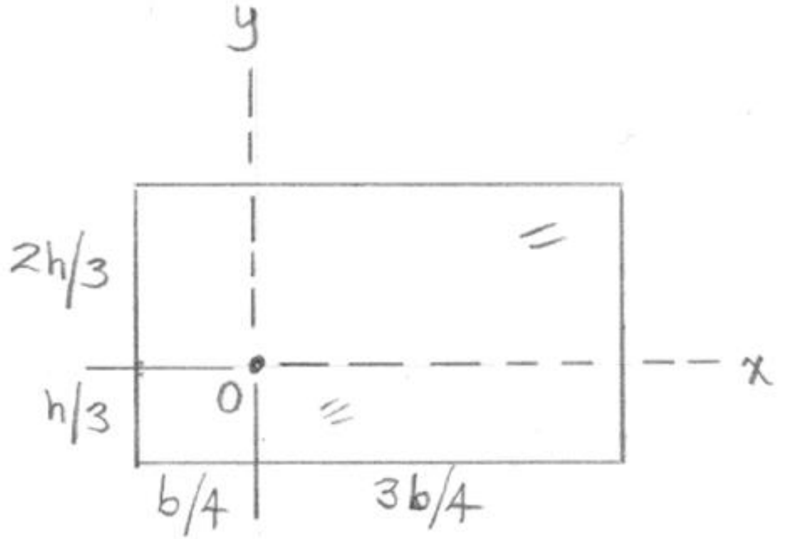
FIGURE		AREA MOMENTS OF INERTIA
Circular Area		$I_x = I_y = \frac{\pi r^4}{4}$ $I_z = \frac{\pi r^4}{2}$
Semicircular Area		$I_x = I_y = \frac{\pi r^4}{8}$ $\bar{I}_x = \left(\frac{\pi}{8} - \frac{8}{9\pi}\right) r^4$ $I_z = \frac{\pi r^4}{4}$
Quarter-Circular Area		$I_x = I_y = \frac{\pi r^4}{16}$ $\bar{I}_x = \bar{I}_y = \left(\frac{\pi}{16} - \frac{4}{9\pi}\right) r^4$ $I_z = \frac{\pi r^4}{8}$
Area of Circular Sector		$I_x = \frac{r^4}{4}(\alpha - \frac{1}{2}\sin 2\alpha)$ $I_y = \frac{r^4}{4}(\alpha + \frac{1}{2}\sin 2\alpha)$ $I_z = \frac{1}{2} r^4 \alpha$

FIGURE		AREA MOMENTS OF INERTIA
Rectangular Area		$I_x = \frac{bh^3}{3}$ $\bar{I}_x = \frac{bh^3}{12}$ $\bar{I}_z = \frac{bh}{12}(b^2 + h^2)$
Triangular Area		$I_x = \frac{bh^3}{12}$ $\bar{I}_x = \frac{bh^3}{36}$ $I_{x_1} = \frac{bh^3}{4}$

A/1 Determine the moments of inertia of the rectangular area about the x- and y-axes and find the polar moment of inertia about point 0.





$$I_x = \bar{I}_x + A d_x^2 = \frac{1}{12} bh^3 + bh\left(\frac{h}{6}\right)^2$$

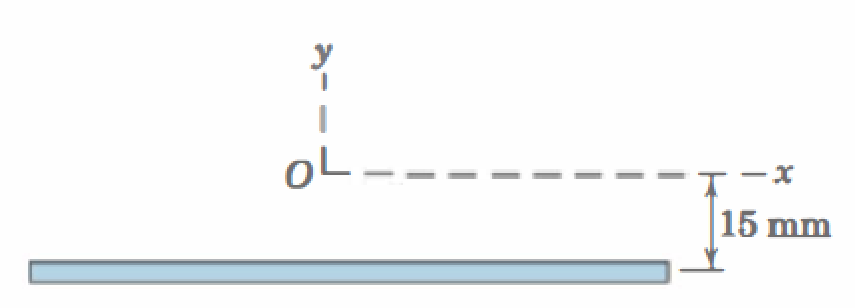
$$= \underline{\frac{1}{9} bh^3}$$

$$I_y = \bar{I}_y + A d_y^2 = \frac{1}{12} hb^3 + bh\left(\frac{b}{4}\right)^2$$

$$= \underline{\frac{7}{48} hb^3}$$

$$I_z = I_x + I_y = \underline{bh\left(\frac{h^2}{9} + \frac{7b^2}{48}\right)}$$

A/3 The narrow rectangular strip has an area of 300 mm^2, and its moment of inertia about the y-axis is 35(10^3) mm^4. Obtain a close approximation to the polar radius of gyration about point 0.

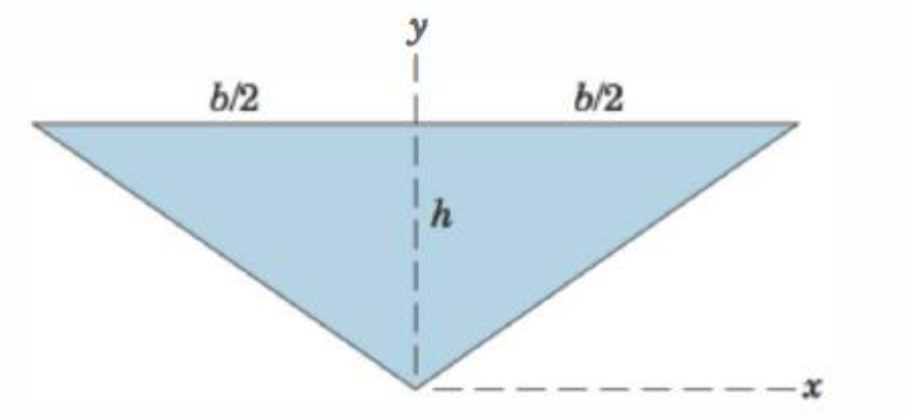


$$I_x \approx Ad^2 = 300(15)^2 = 67.5(10^3)\ \text{mm}^4$$

$$J_o = I_x + I_y = 67.5(10^3) + 35(10^3) = 102.5(10^3)\ \text{mm}^4$$

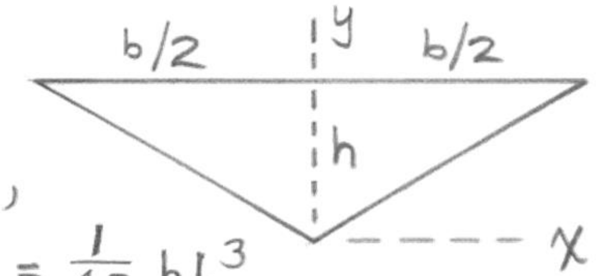
$$k_o = \sqrt{J_o/A} = \sqrt{\frac{102.5(10^3)}{300}} = \underline{18.48\ \text{mm}}$$

A/4 Determine the ratio b/h such that Ix = Iy for the area of the isosceles triangle.



A/4

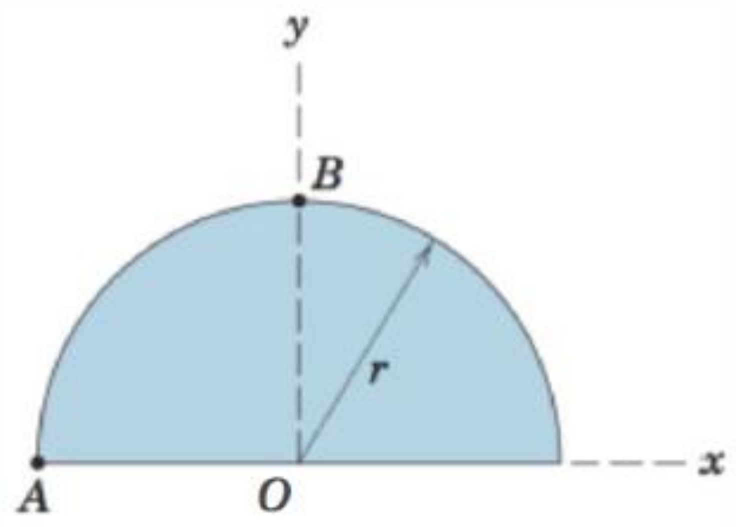
From Sample Problem A/2,

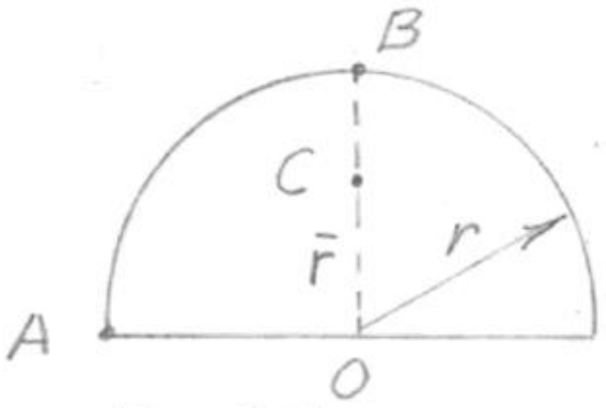


$I_x = \frac{1}{4}bh^3$, $I_y = 2\left\{\frac{1}{12}h\left(\frac{b}{2}\right)^3\right\} = \frac{1}{48}hb^3$

$I_x = I_y$ if $\frac{1}{4}bh^3 = \frac{1}{48}hb^3$, $\underline{\frac{b}{h} = 2\sqrt{3}}$

A/6 Determine the polar moments of inertia of the semicircular area about points A and B.





$\bar{r} = 4r/3\pi$

For complete circle

$$I_A = I_0 + Ar^2 = \frac{1}{2}Ar^2 + Ar^2$$
$$= \frac{3}{2}Ar^2$$

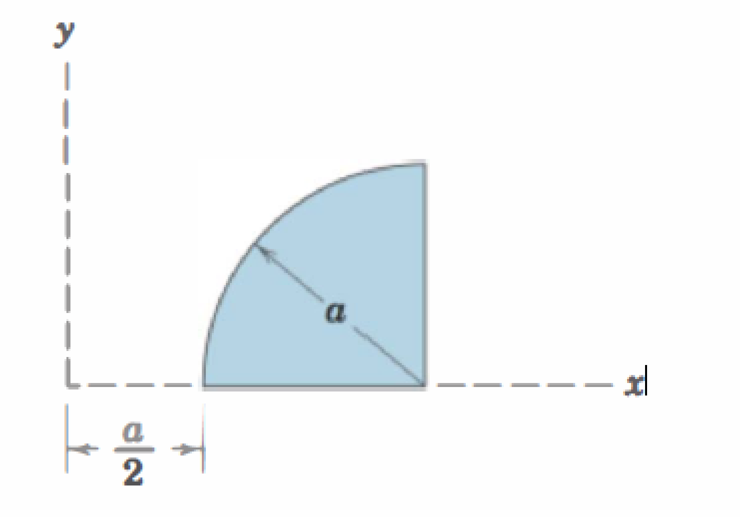
For half circle

$$I_A = \frac{1}{2}\left(\frac{3}{2}\pi r^4\right) = \underline{\frac{3}{4}\pi r^4}$$

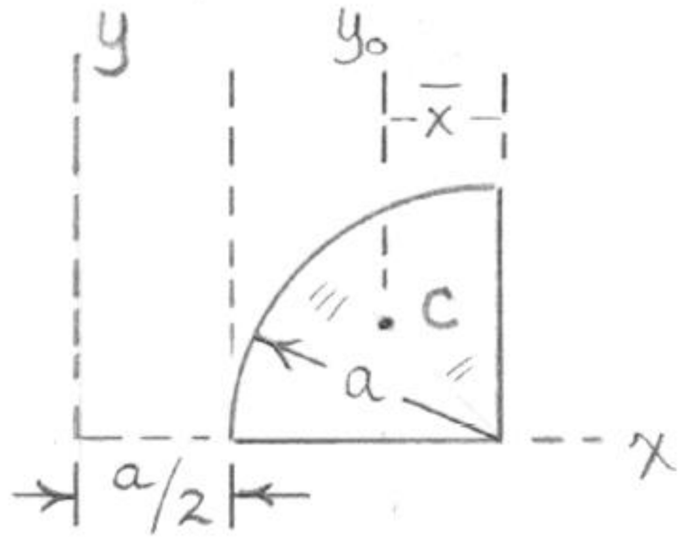
For half circle, $I_0 = \frac{1}{4}\pi r^4$

$$I_B = I_C + A(r-\bar{r})^2 = I_0 - A\bar{r}^2 + A(r-\bar{r})^2$$
$$= I_0 + A(r^2 - 2r\bar{r})$$
$$= \frac{1}{4}\pi r^4 + \frac{\pi r^4}{2}\left(1 - \frac{8}{3\pi}\right) = r^4\left(\frac{3\pi}{4} - \frac{4}{3}\right)$$

A/7 Determine the moment of inertia of the quarter circular area about the y-axis.



A/7



From Table D/3:

$$\bar{I}_y = \left(\frac{\pi}{16} - \frac{4}{9\pi}\right) a^4$$

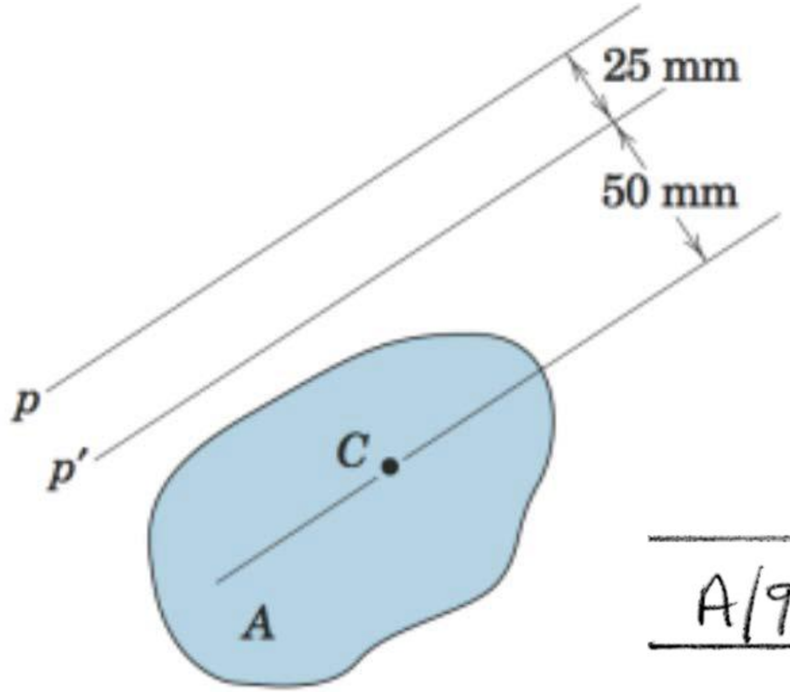
$$\bar{x} = \frac{4a}{3\pi}$$

$$I_y = \bar{I}_y + A d_y^2$$

$$= \left(\frac{\pi}{16} - \frac{4}{9\pi}\right) a^4 + \frac{\pi a^2}{4}\left[\frac{a}{2} + \left(a - \frac{4a}{3\pi}\right)\right]^2$$

$$= \left[\frac{5\pi}{8} - 1\right] a^4$$

A/9 The moments of inertia of the area A about the parallel p- and p'-axes differ by $15(10^6)$ mm^4. Compute the area A, which has its centroid at C.



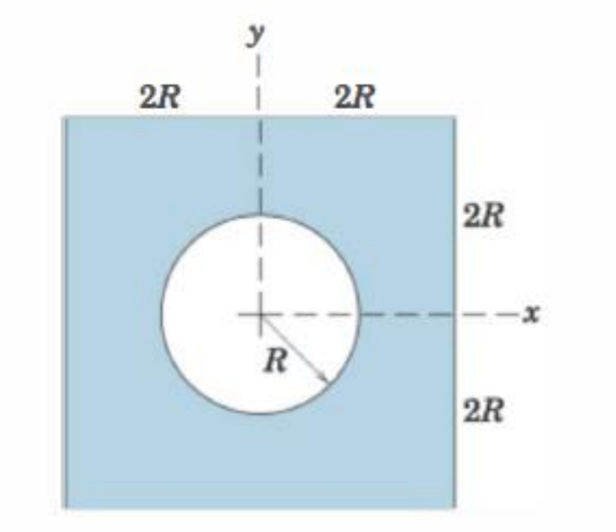
A/9

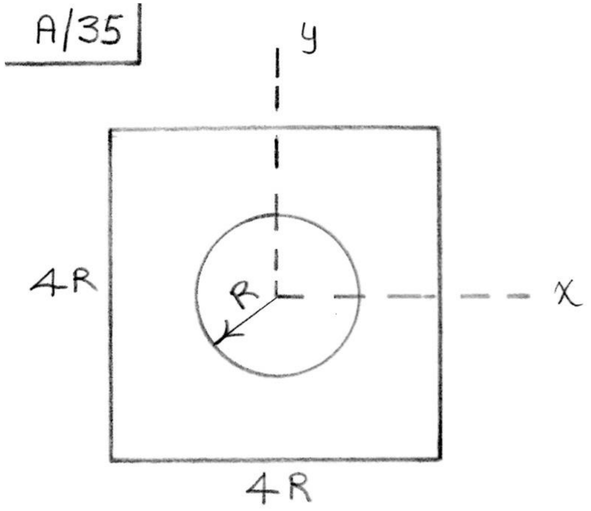
$$I_p = I_C + A(75)^2, \quad I_{p'} = I_C + A(50)^2$$

$$I_p - I_{p'} = 15(10^6) = A[(75)^2 - (50)^2]$$

$$\underline{A = 4800 \text{ mm}^2}$$

A/35 Determine the moment of inertia about the x-axis of the square area without and with the central circular hole.





Without hole, $I_x = \frac{1}{12}(4R)(4R)^3 = \frac{64}{3}$

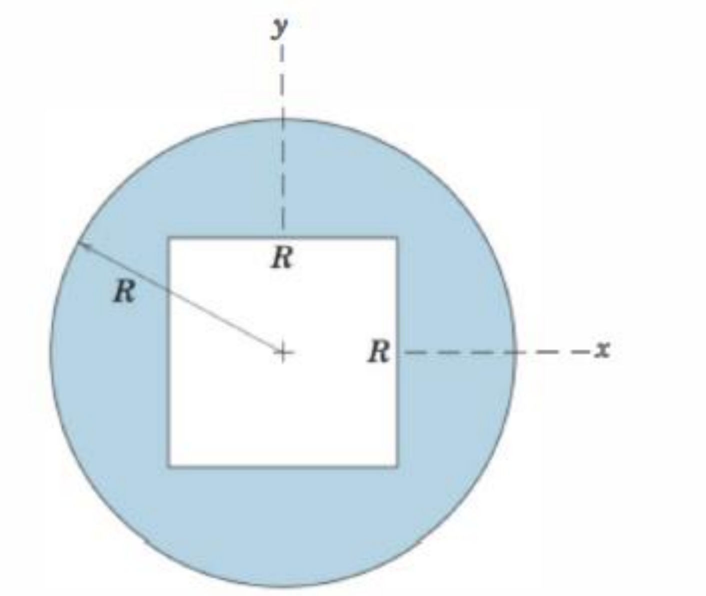
$\underline{(21.3R^4)}$

With hole, $I_x = \frac{64}{3}R^4 - \frac{1}{4}(\pi R^2)R^2$

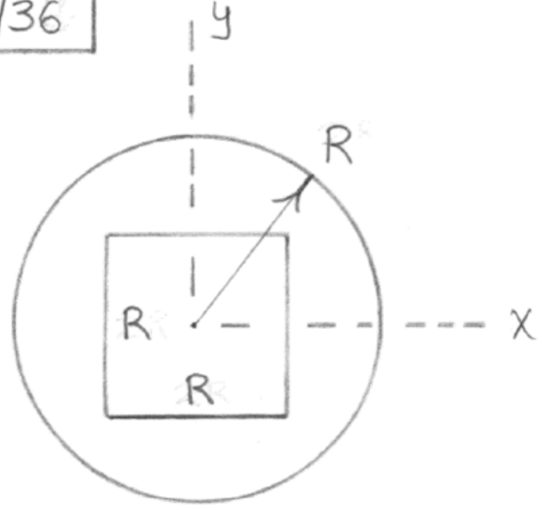
$= \underline{20.5R^4}$

(a 3.68% reduction)

A/36 Determine the polar moment of inertia of the circular area without and with the central square hole.



A/36



Without square hole:

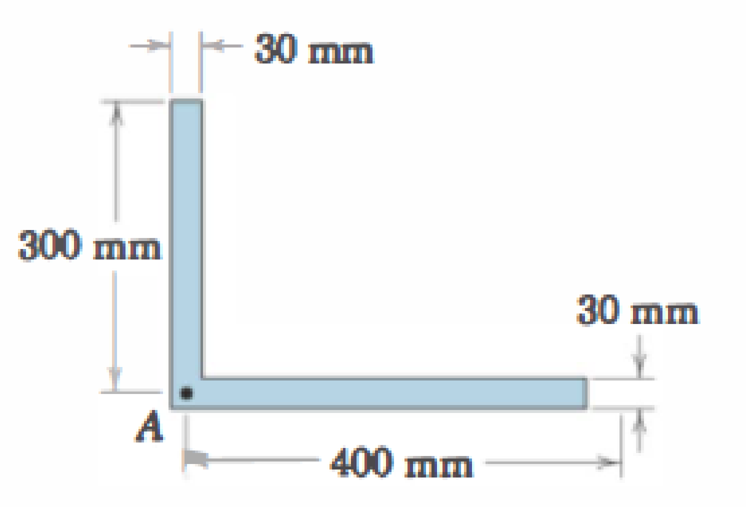
$$I_z = 2I_x = 2\left(\tfrac{1}{4}\pi R^2 \cdot R^2\right) = \underline{1.571 R^4}$$

With hole:

$$I_z = 1.571R^4 - 2\left(\tfrac{1}{12} R \cdot R^3\right) = \underline{1.404 R^4}$$

(a reduction of 10.61%)

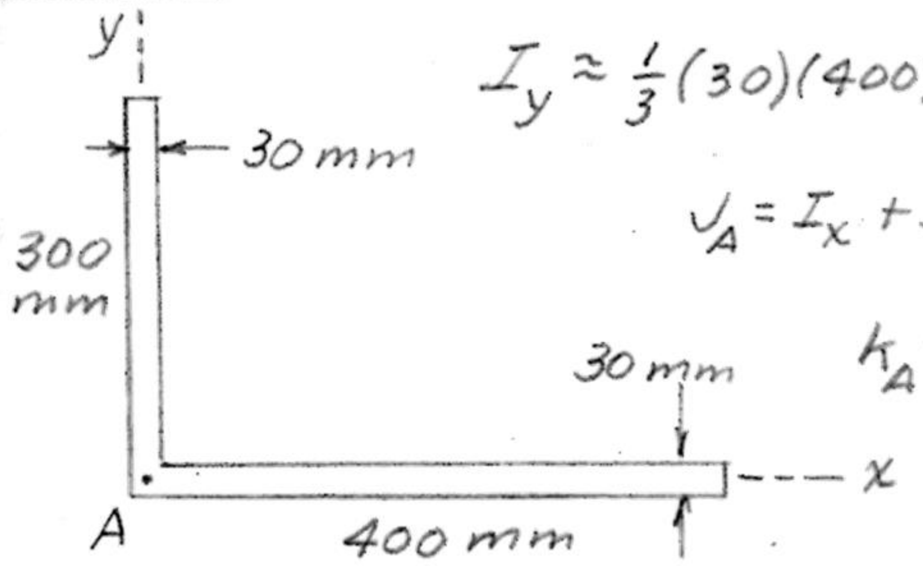
A/37 Calculate the polar radius of gyration of the area of the angle section about point A Note that the width of the legs is small compared with the length of each leg.



A/37

$$I_x \approx \frac{1}{3}(30)(300)^3 + 0 = 270(10)^6\ mm^4$$

$$I_y \approx \frac{1}{3}(30)(400)^3 + 0 = 640(10)^6\ mm^4$$

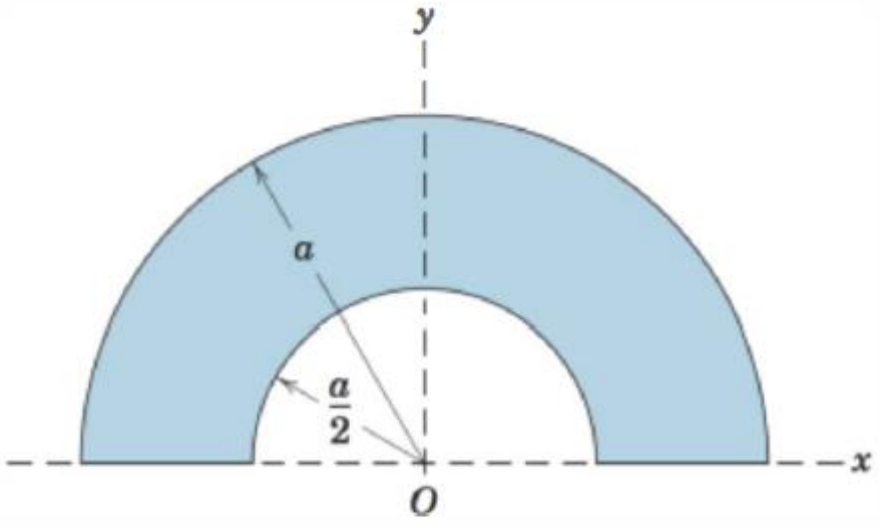


$$J_A = I_x + I_y = 910(10)^6\ mm^4$$

$$k_A = \sqrt{J_A / A} = \sqrt{\frac{910(10)^6}{30(300+400)}}$$

$$k_A = \underline{208\ mm}$$

A/38 Calculate the polar radius of gyration of the area of the angle section about point A Note that the width of the legs is small compared with the length of each leg.



A/38

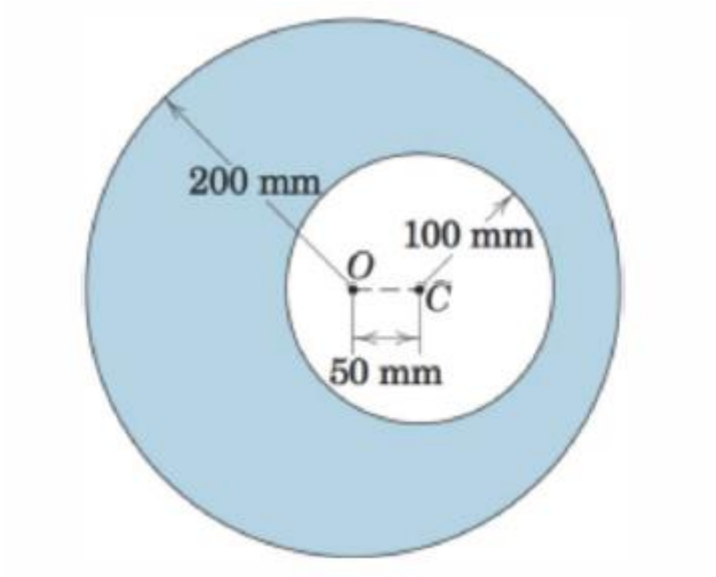
$$I_z = \frac{1}{2}\left[\frac{\pi a^4}{2} - \frac{\pi\left(\frac{a}{2}\right)^4}{2}\right] = \frac{15}{64}\pi a^4$$

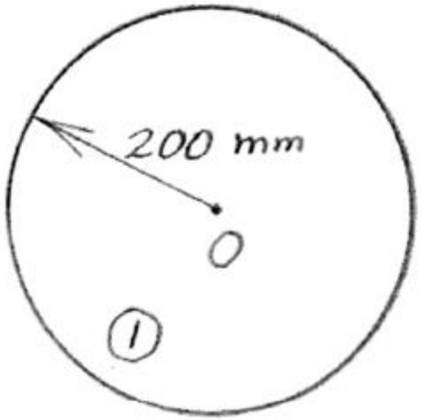
$$k_z = \sqrt{\frac{I_z}{A}} = \sqrt{\frac{\frac{15}{64}\pi a^4}{\frac{3}{8}\pi a^2}} = \underline{\frac{\sqrt{10}}{4}a}$$

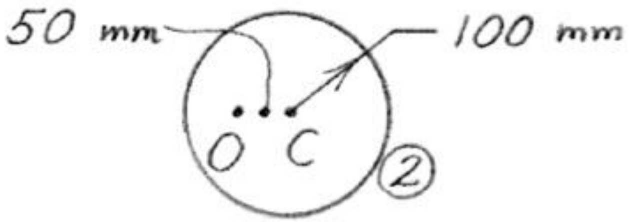
From $k_x^2 + k_y^2 = k_z^2$ and the fact that $k_x = k_y$ for the present case,

$$2k_x^2 = \left(\frac{\sqrt{10}}{4}a\right)^2, \quad k_x = k_y = \underline{\frac{\sqrt{5}}{4}a}$$

A/39 Calculate the polar radius of gyration of the shaded area about the center 0 of the larger circle.







Area $A = A_1 - A_2 = \pi(200^2 - 100^2) = 3(10^4)\pi \text{ mm}^2$

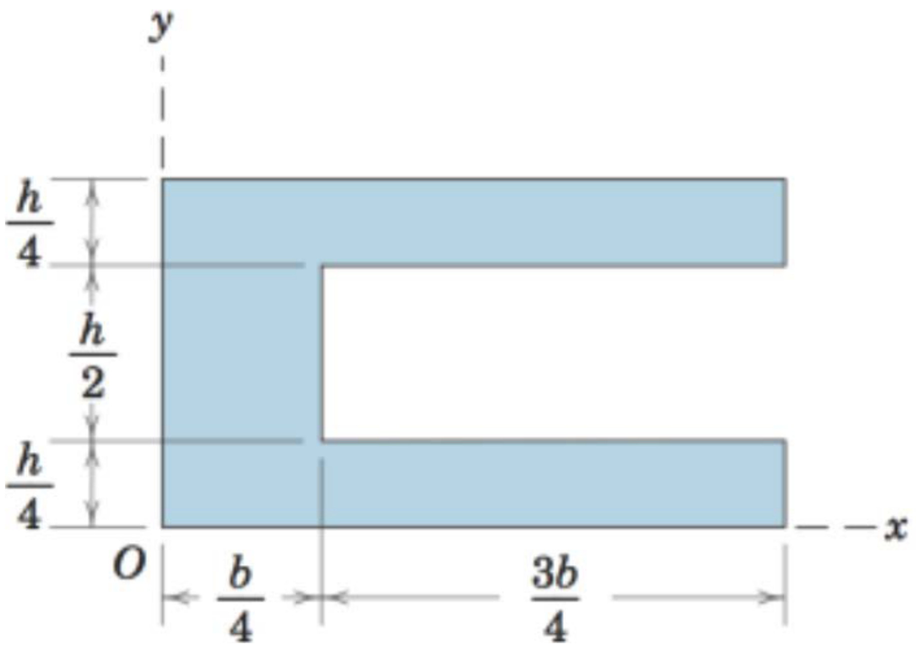
① $I_{O_1} = \frac{1}{2}(\pi \cdot 200^2)(200^2) = 8(10^8)\pi \text{ mm}^4$

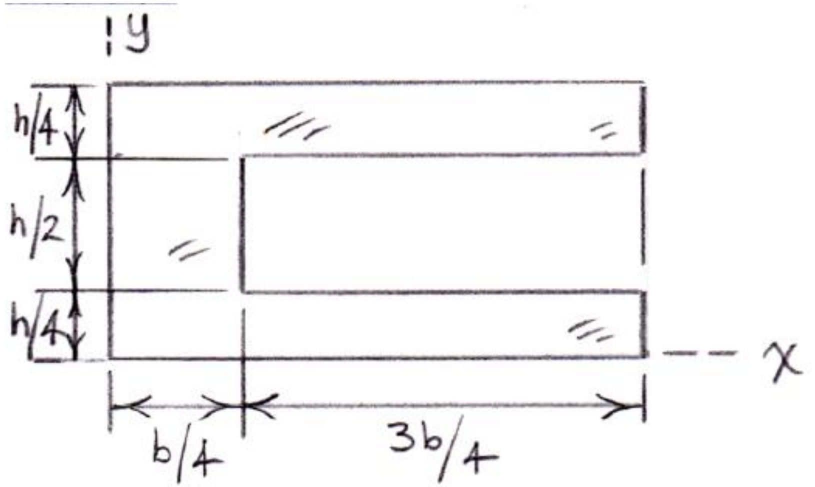
② $I_{O_2} = \frac{1}{2}(\pi \cdot 100^2)(100^2) + \pi(100^2)(50^2) = 0.75(10^8)\pi \text{ mm}^4$

So $I_O = I_{O_1} - I_{O_2} = 7.25(10^8)\pi \text{ mm}^4$

$k_O = \sqrt{I_O/A} = \sqrt{\frac{7.25(10^8)\pi}{3(10^4)\pi}} = \underline{155.5 \text{ mm}}$

A/40 Determine the percent reductions in both area and area moment of inertia about the y-axis caused by removal of the rectangular cutout from the rectangular plate of baseband height h.





Full rectangle : $A = bh, \quad I_y = \frac{1}{3}hb^3$

With cutout : $A = bh - \frac{3b}{4}\left(\frac{h}{2}\right) = \frac{5}{8}bh$

$$I_y = \frac{1}{3}hb^3 - \left[\frac{1}{12}\frac{h}{2}\left(\frac{3b}{4}\right)^3 + \frac{3}{8}bh\left(\frac{b}{4}+\frac{3b}{8}\right)^2\right]$$

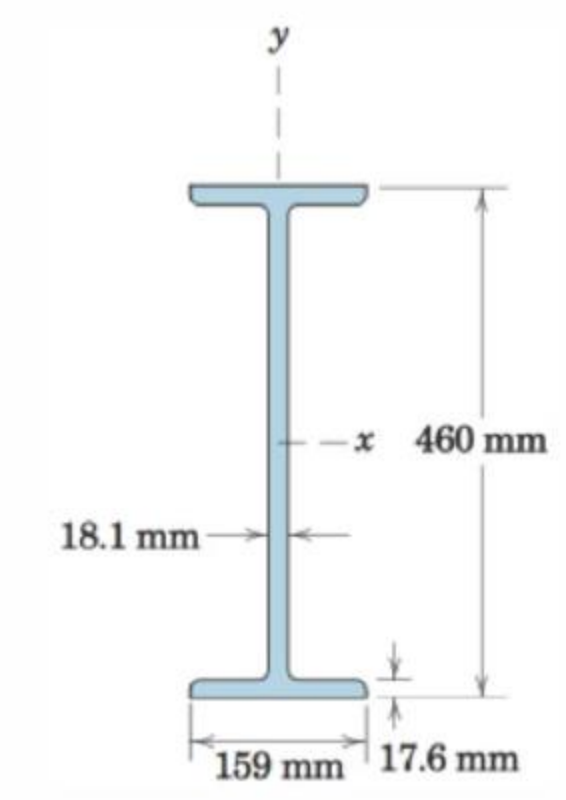
$$= \frac{65}{384}hb^3$$

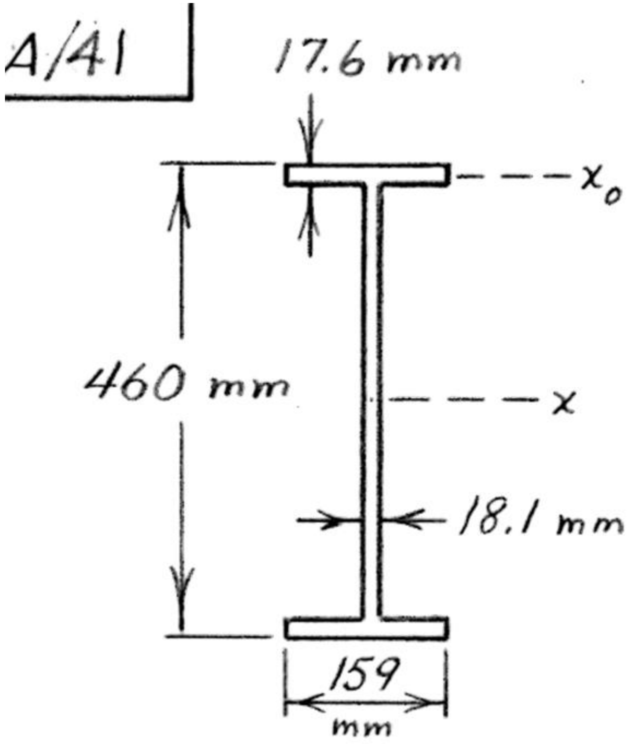
Percent reductions :

$$n_A = \frac{bh - \frac{5}{8}bh}{bh}(100\%) = \underline{37.5\%}$$

$$n_{I_y} = \frac{\frac{1}{3}hb^3 - \frac{65}{384}hb^3}{\frac{1}{3}hb^3} = \underline{49.2\%}$$

A/41 The cross-sectional area of an I-beam has the dimensions shown. Obtain a close approximation to the handbook value of $I_x = 385(10^6)\ \text{mm}^4$ by treating the section as being composed of three rectangles.





Flanges: $\bar{I}_x = I_{x_o} + Ad^2$

$$= 2\left\{\frac{1}{12}(159)(17.6^3) + 159(17.6)\left(230 - \frac{17.6}{2}\right)^2\right\}$$

$$= 2\left\{7.22(10^4) + 1.369(10^8)\right\}\ \text{mm}^4$$

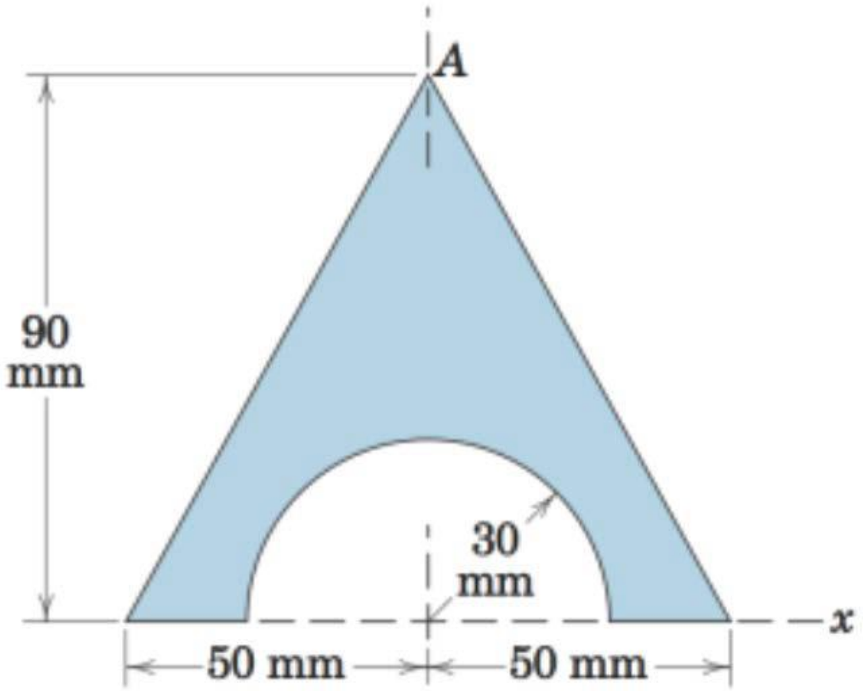
$$= 2.74(10^8)\ \text{mm}^4$$

Web: $\bar{I}_x = \frac{1}{12}(18.1)(460 - 2[17.6])^3$

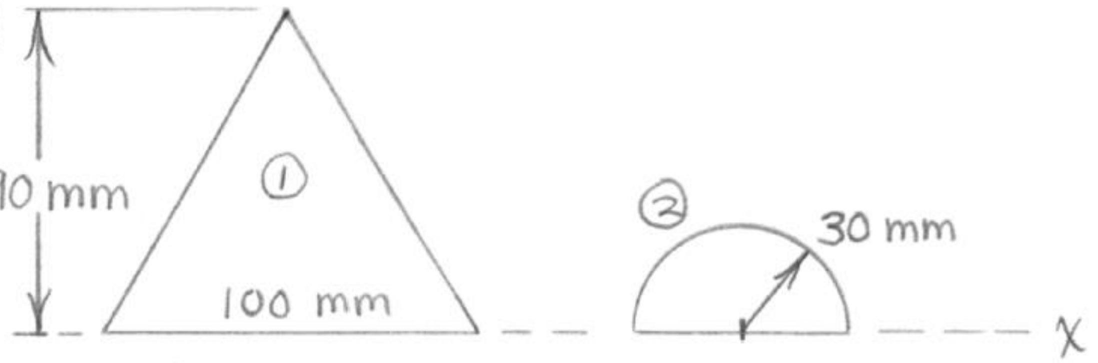
$$= 1.156(10^8)\ \text{mm}^4$$

Total $\bar{I}_x = 3.90(10^8)\ \text{mm}^4$

A/42 Calculate the moment of inertia of the shaded area about the x-axis.



A/42

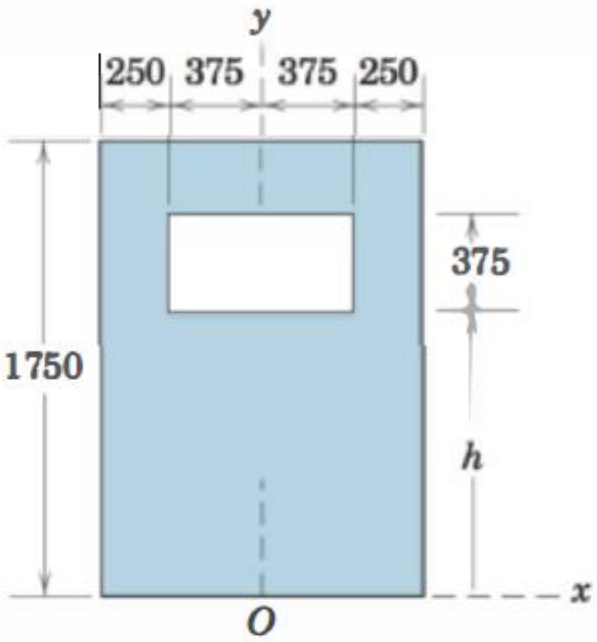


$$I_{x_1} = \frac{1}{12}(100)(90^3) = 6.08(10^6)\ mm^4$$

$$I_{x_2} = -\frac{\pi(30^4)}{8} = -0.318(10^6)\ mm^4$$

So $I_x = (6.08 - 0.318)10^6 = \underline{5.76(10^6)\ mm^4}$

A/43 The variable h designates the arbitrary vertical location of the bottom of the rectangular cutout within the rectangular area. Determine the area moment of inertia about the x-axis for (a) h = 1000 mm and (b) h = 1500 mm.



Dimensions in millimeters

(a) h = 1000 mm (hole complete)

$$I_x = \frac{1}{3}(1250)(1750^3) - \left[\frac{1}{12}(750)(375)^3 + 750(375)\left(1000 + \frac{375}{2}\right)^2\right]$$

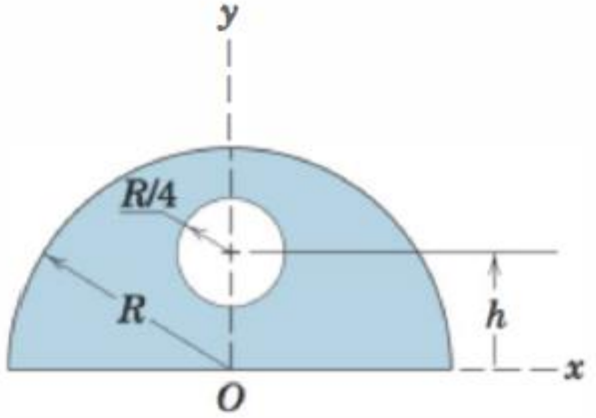
$$= \underline{1.833(10^{12})\ mm^4} \text{ or } \underline{1.833\ m^4}$$

(b) h = 1500 mm (250 mm of hole in play)

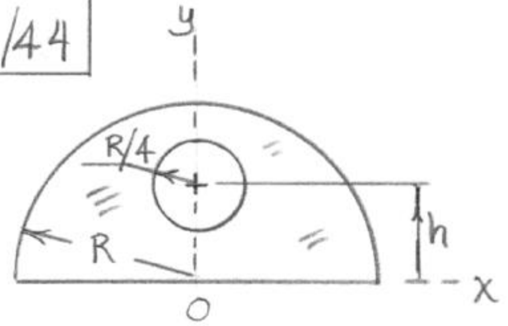
$$I_x = \frac{1}{3}(1250)(1750^3) - \left[\frac{1}{12}(750)(250)^3 + 750(250)\left(1500 + \frac{250}{2}\right)^2\right]$$

$$= \underline{1.737(10^{12})\ mm^4 \text{ or } 1.737\ m^4}$$

A/44 The variable h designates the arbitrary vertical location of the center of the circular cutout within the semicircular area. Determine the area moment of inertia about the x-axis for (a) h = 0 and (b) h = R/2.



A/44



(a) $h = 0$ (One-half of hole considered)

$$I_x = \frac{\pi R^4}{8} - \frac{\pi (R/4)^4}{8} = \frac{255}{2048}\pi R^4$$

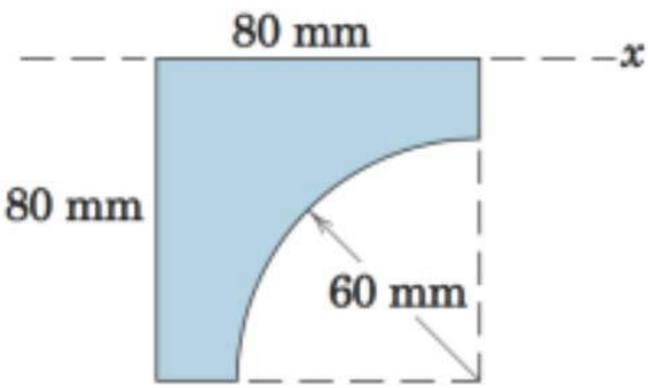
$$(0.391 R^4)$$

(b) $h = \frac{R}{2}$ (Entire hole now in play)

$$I_x = \frac{\pi R^4}{8} - \left[\frac{\pi (R/4)^4}{4} + \pi\left(\frac{R}{4}\right)^2\left(\frac{R}{2}\right)^2\right]$$

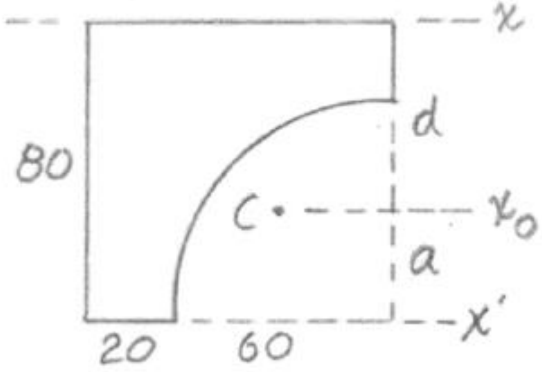
$$= \frac{111}{1024}\pi R^4 \quad (0.341 R^4)$$

A/45 Calculate the moment of inertia of the shaded area about the x-axis.



A/45

Dimen. in mm



Square: $I_x = \frac{1}{3}b^4 = \frac{1}{3}(80)^4 = 13.65(10^6)\ \text{mm}^4$

Quarter-circle: $a = \frac{4r}{3\pi} = \frac{4(60)}{3\pi}$

$= 25.46\ \text{mm}$

$d = 80 - 25.46 = 54.54\ \text{mm}$

$$I_x = I_{x_0} + Ad^2 = I_{x'} - Aa^2 + Ad^2$$

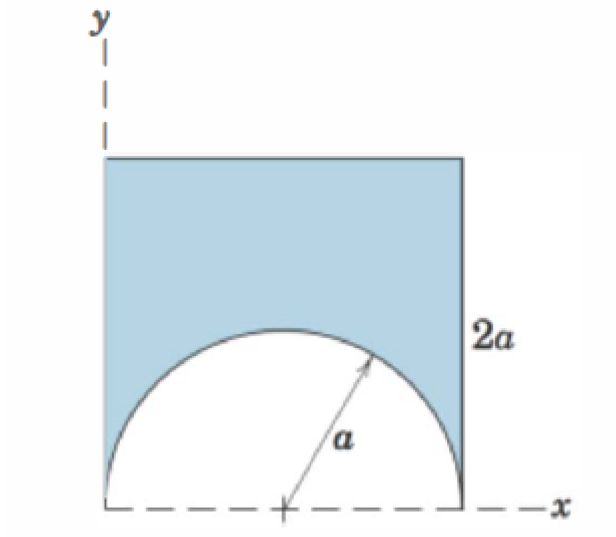
$$= -\frac{1}{4}\frac{\pi r^4}{4} - \frac{\pi r^2}{4}(d^2 - a^2) = -\frac{\pi r^2}{4}\left(\frac{r^2}{4} + d^2 - a^2\right)$$

$$= -\frac{\pi(60)^2}{4}\left[\frac{60^2}{4} + (54.54)^2 - (25.46)^2\right]$$

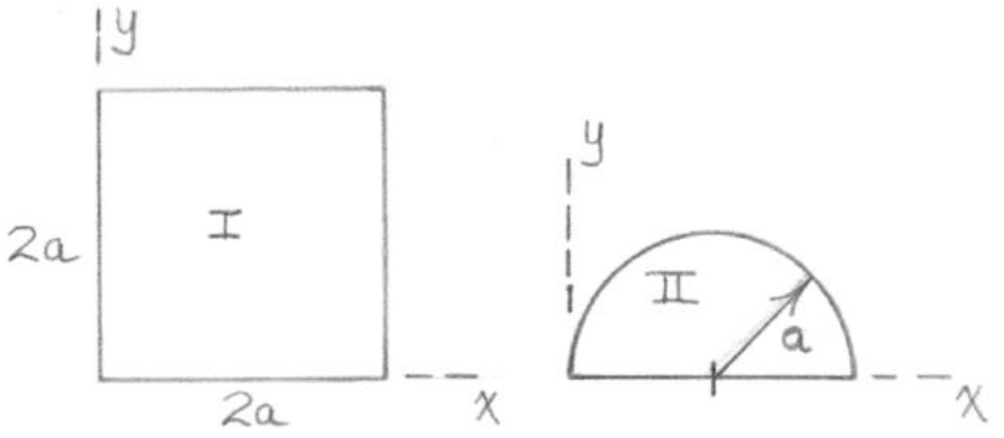
$$= -9.120(10^6)\ \text{mm}^4$$

Total $I_x = (13.65 - 9.120)(10^6) = \underline{4.53(10^6)\ \text{mm}^4}$

A/46 Determine the moments of inertia of the shaded area about the x- and y-axes.



A/46



I. Square $I_x = I_y = \frac{1}{3}(4a^2)(2a)^2 = \frac{16}{3}a^4$

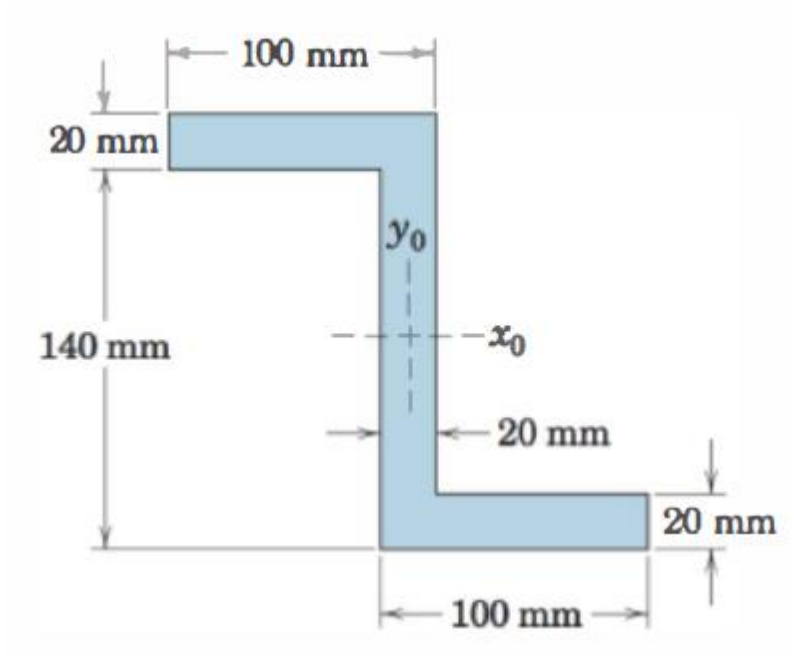
II. Semicircle $I_x = \frac{1}{8}\pi a^4$

$$I_y = \frac{1}{8}\pi a^4 + \frac{1}{2}\pi a^2(a^2) = \frac{5}{8}\pi a^4$$

Combined: $I_x = \frac{16}{3}a^4 - \frac{\pi}{8}a^4 = \underline{4.94a^4}$

$$I_y = \frac{16}{3}a^4 - \frac{5}{8}\pi a^4 = \underline{3.37a^4}$$

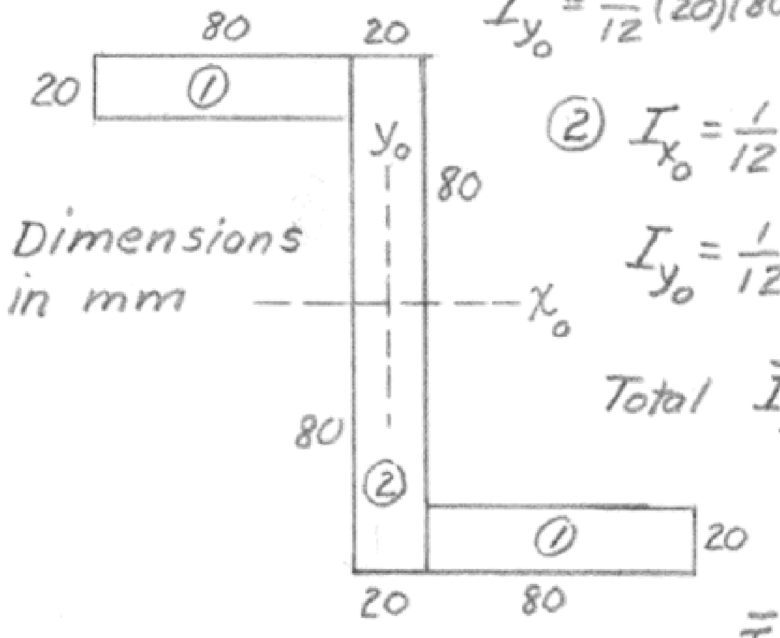
A/48 Determine the moments of inertia of the Z-section about its centroidal xo- and yo-axes.



A/48

① $I_{x_0} = \frac{1}{12}(80)(20)^3 + (80)(20)(70)^2 = 7.89(10^6)\ mm^4$

$I_{y_0} = \frac{1}{12}(20)(80)^3 + (20)(80)(50)^2 = 4.85(10^6)\ mm^4$



② $I_{x_0} = \frac{1}{12}(20)(160)^3 = 6.83(10^6)\ mm^4$

$I_{y_0} = \frac{1}{12}(160)(20)^3 = 0.1067(10^6)\ mm^4$

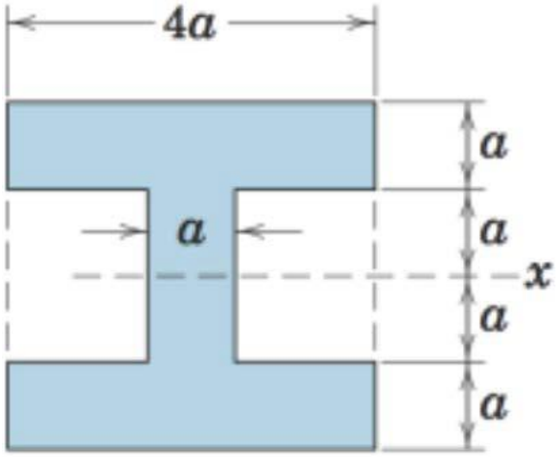
Total $\bar{I}_x = [2(7.89) + 6.83](10^6)$

$= 22.6(10^6)\ mm^4$

$\bar{I}_y = [2(4.85) + 0.1067](10^6)$

$= 9.81(10^6)\ mm^4$

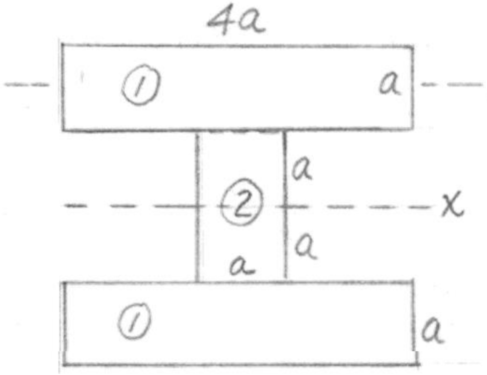
A/49 Determine the moment of inertia of the shaded area about the x-axis in two different ways.



A/49

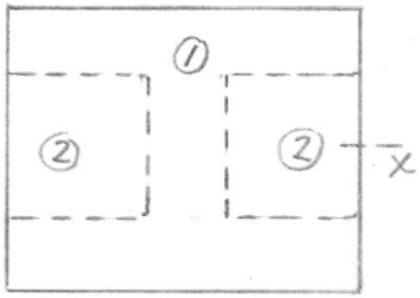
Sol. I

$$I_{①} = 2\left[\frac{1}{12}4a(a^3) + 4a^2\left(\frac{3a}{2}\right)^2\right] = \frac{56}{3}a^4$$



$$I_{②} = \frac{1}{12}a(2a)^3 = \frac{2}{3}a^4$$

Total $\underline{I_x = \frac{58}{3}a^4}$



Sol. II

$$I_{①} = \frac{1}{12}(4a)(4a)^3 = \frac{64}{3}a^4$$

$$I_{②} = -\frac{1}{12}(3a)(2a)^3 = -2a^4$$

$$\text{Total} = \left(\frac{64}{3} - \frac{6}{3}\right)a^4 = \underline{\frac{58}{3}a^4}$$

THANK YOU

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