UNIT 5 COLUMNS

Structure

5.1 Introduction

Objectives

5.2 Determination of Effective Length

5.3 Design of Axially Loaded Columns

5.3.1 Design of Axially Loaded Short Columns with Lateral Ties

5.3.2 Design of Axially Loaded Short Circular Columns with Helical Reinforcement

5.4 Detailing of Reinforcements

5.4.1 Detailing of Longitudinal Reinforcement

5.4.2 Detailing of Transverse Reinforcements

5.5 Summary

5.6 Answers to SAQs

5.1 INTRODUCTION

Column is primarily a compression member. The gravity and lateral loads of a structure are transferred to it, which subsequently transfer them to the foundation. The loads on the column may be concentric or eccentric (i.e. axial load with uniaxial or biaxial bending moments). Even if the load is concentric – which is rarely a case – it is designed as an eccentric column with a *minimum eccentricity* prescribed by IS Code to take care of any accidental load, movement of imposed load from one position to other, etc.

If the length of a column is less than three times its least lateral dimension $\left(\text{i.e. } \frac{l_{ef}}{b} < 3\right)$, it is called a *pedestal*. Depending upon length and its lateral dimensions, a column may be a short or slender one. More specifically, if both the slenderness ratios $\frac{l_{ex}}{D}$ and $\frac{l_{ey}}{b} \leq 12$, the column is a *short* column; otherwise, i.e. for $\frac{l_{ex}}{D}$ or $\frac{l_{ey}}{b} > 12$, it is a *slender* column in respect of major or minor axis, respectively. If both slenderness ratios are greater than 12, it is slender column in respect of both axes.

Here, l_{ex} = Effective length of column in respect of the major axis,

D = Depth in respect of the major axis,

l_{ey} = Effective length of column in respect of minor axis, and

b = Width of the member.

The unsupported length (l) of a column with *end restraints* shall not exceed 60 b, where b = least lateral dimension. If, in any given plane, one end of a column is unrestrained, its unsupported length (l) shall not exceed $\frac{100\,b^2}{D}$.

where b = Width of that cross section, and

D = Depth of cross section measured in the plane under consideration.

A column has two types of reinforcements – longitudinal or main reinforcement and transverse or lateral reinforcement.

The longitudinal reinforcement resists axial load and bending moment; whereas transverse reinforcement resists shear force, shares a small fraction of axial load if provided in the form of helical reinforcement, keeps main reinforcement in position and prevents longitudinal bars from buckling.

Columns with axial loads only will be designed in this Unit, as design of columns with axial load and bending moments becomes very complex by Limit State Method. However, design of a columns with axial load and uniaxial bending of uncracked section has been dealt with in Working Stress Method (Unit 9).

Objectives

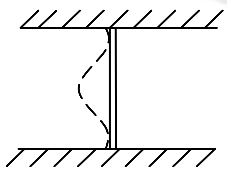
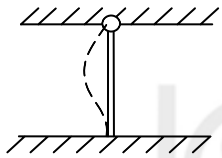
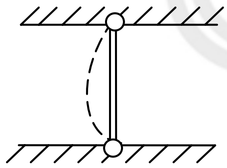
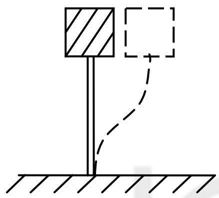
After studying this unit, you should be able to

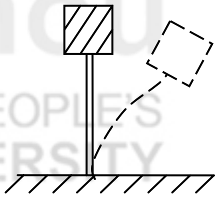
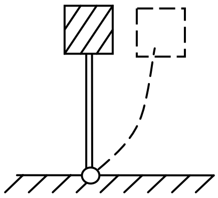
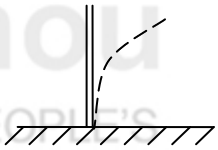
- describe the design and detailing of axially loaded rectangular and circular columns.

5.2 DETERMINATION OF EFFECTIVE LENGTH

The effective length of a column (l_{ef}) is not equal to its unsupported length (l) in all cases. It depends upon *end conditions*. For normal usage, the values of effective lengths for different end conditions are given in Table 5.1.

Table 5.1 : Effective Length of Columns for Different End Conditions

Degree of End Restraint of Compression Members	**Symbol**	**Recommended Value of Effective Length**
(1)	(2)	(3)
Effectively held in position and restrained against rotation in both ends		$0.65\ \ell$
Effectively held in position at both ends, restrained against rotation at one end		$0.80\ \ell$
Effectively held in position at both ends, but not restrained against rotation		$1.00\ \ell$
Effectively held in position and restrained against rotation at one end, and at the other restrained against rotation but not held in position		$1.20\ \ell$

Effectively held in position and restrained against rotation at one end, and at the other partially restrained against rotation but not held in position		1.50 ℓ
Effectively held in position at one end but not restrained against rotation, and at the other end restrained against rotation but not held in position		2.00 ℓ
Effectively held in position and restrained against rotation at one end, but not held in position nor restrained against rotation at the other end		2.00 ℓ

5.3 DESIGN OF AXIALLY LOADED COLUMNS

As mentioned in Section 5.1, bending moment due to *minimum eccentricity* of axial load shall be considered in design.

The minimum eccentricity shall be

(a) $\dfrac{\text{Unsupported length of column } (\ell)}{500} + \dfrac{\text{Lateral diamensions}}{30}$, or

(b) 20 mm, or

whichever is more.

The value of the minimum eccentricity so obtained shall not exceed 0.05 times the lateral dimension.

5.3.1 Design of Axially Loaded Short Columns with Lateral Ties

Design axial load,

$$P_u = 0.4\, f_{ck} A_c + 0.67\, f_y A_{sc} \qquad \ldots (5.1)$$

where, A_c = Area of concrete, and

A_{sc} = Area of longitudinal reinforcement for the column.

The minimum eccentricity requirement mentioned above may deemed to have been incorporated in the above equation.

In Eq. (5.1), for given values of P_u, f_{ck} and f_y, *two unknown quantities* A_c and A_{sc} may be put in terms of gross area of concrete, A_g, i.e. in terms of only *one unknown* as follows :

$$A_{sc} = \frac{p}{100} A_g$$

where p = Percentage of reinforcement, and

$$A_c = A_g - A_{sc} = A_g - \frac{p}{100} A_g = A_g \left(1 - \frac{p}{100}\right)$$

Putting these two values in Eq. (5.1)

$$P_u = 0.4\, f_{ck}\, A_g \left(1 - \frac{p}{100}\right) + 0.67\, f_y\, \frac{p}{100}\, A_g$$

or, $$\frac{P_u}{A_g} = 0.4\ f_{ck} \left(1 - \frac{p}{100}\right) + 0.67\, f_y\, \frac{p}{100}$$

or, $$\frac{P_u}{A_g} = 0.4\, f_{ck} + \frac{p}{100}\,(0.67\, f_y - 0.4\, f_{ck}) \qquad \ldots (5.2)$$

Eq. (5.2) is more convenient in solving problems.

There may be two types of problems :

(a) To determine area of reinforcement (A_{sc}) for given values of P_u, A_g, f_{ck} and f_y, and

(b) To determine cross sectional area for given values of P_u, f_{ck} and f_y.

All types of problems may *also* be solved using *'Interaction Diagrams'*. Interaction Diagrams for f_y = 250 N/mm^2 (Figure 5.1) and for f_y = 415 (Figure 5.2) are given to illustrate their use in *practice*.

Figure 5.1 : Interaction Diagram for Axially Loaded Short Columns for f_y = 250 N/mm^2

For solving Type (a) problems, a horizontal line is drawn from P_u in the upper diagram to intersect the line for given A_g. From the point of intersection, a vertical line is drawn to intersect the line for given f_{ck} in the lower diagram. From this intersection point, a horizontal line is drawn to get desired value of p or A_{sc}. This process is illustrated in Figure 5.1 by dotted lines for Example 5.1. Alternatively, from $\frac{P_u}{A_g}$ value a vertical line is drawn to intersect the line for given f_{ck} and then a horizontal line is drawn to get A_{sc} in terms of p.

Similarly, for Type (b) problems, Example 5.2 is illustrated on Figure 5.2.

Figure 5.2 : Interaction Diagram for Axially Loaded Short Columns for f_y = 415 N/mm^2

Example 5.1

Design a column of unsupported length of 2.75 m effectively held in position but not restrained against rotation. The column has a rectangular cross section 350 × 400 and carries a factored load of 2000 kN. Determine area of longitudinal bars. Design parameters are : P_u = 2000 kN N/mm^2; f_y = 250 N/mm^2; f_{ck} = 25 N/mm^2 and diameter of longitudinal bar = 25 mm.

Solution

$$l_{ef} = 1.00\ \ell = 1.00 \times 2.75 = 2.75 \text{ m} \qquad \text{(Table 5.1)}$$

$$\frac{l_{ef}}{b} = \frac{2.75 \times 10^3}{350} = 7.86 < 12$$

Hence, the column will be designed as a short column.

$$P_u = 0.4\, f_{ck} \left(A_g - \frac{pA_g}{100} \right) + 0.67\, f_y\, \frac{pA_g}{100}$$

or, $\frac{P_u}{A_g} = 0.4 \times 25 \times \left(1 - \frac{p}{100}\right) + 0.67 \times 250 \times \left(\frac{p}{100}\right)$

or, $\frac{P_u}{A_g} = 10 - \left(\frac{p}{10}\right) + 1.675\, p \quad \frac{2000 \times 10^3}{350 \times 400} = 10 + 1.575\, p$

or, $14.29 = 10 + 1.575\, p$

or, $p = 2.72\% > 0.8\%$ and $< 6\%$

or, $A_{sc} = \frac{2.72 \times 350 \times 400}{100} = 3808 \text{ mm}^2$

Hence, provided 8 ϕ 25 ($A_{st} = 3928 > 3808 \text{ mm}^2$) (Figure 5.3)

Figure 5.3 : Designed Section

Check for Minimum Eccentricity

$$e_{\min} = \frac{\ell}{500} + \frac{D}{30} = \frac{2.75 \times 1000}{500} + \frac{400}{30} = 18.83 < (0.05\, D = 20)$$

$$e_{\min} = \frac{\ell}{500} + \frac{b}{30} = \frac{2.75 \times 1000}{500} + \frac{350}{30} = 17.17 < (0.05\, b = 17.5)$$

Check by Interaction Diagram

For $P_u = 2{,}000$ kN and

$A_g = 350 \times 400 = 140{,}000 \text{ mm}^2 = 1400 \text{ cm}^2$

From Interaction Diagram, for $f_y = 250$ N/mm^2 and $f_{ck} = 25$ N/mm^2

$\frac{100\ A_s}{A_g} = 2.8$ (Figure 5.1)

or, $A_s = \frac{2.8 \times A_g}{100} = \frac{2.8 \times 140{,}000}{100} = 3920 \text{ mm}^2$

Hence, provided 8 ϕ 25 ($A_{st} = 8 \times 491 = 3928 \text{ mm}^2 > 3920 \text{ mm}^2$)

Hence, O.K.

Example 5.2

Design longitudinal reinforcement for a circular column of diameter 350 mm with lateral ties for a factored load of 1800 kN and effective length 2.75 m for the following design parameters.

$f_y = 415$; and $f_{ck} = 20$

Solution

$$\frac{l_{ef}}{D} = \frac{2.75 \times 10^3}{350} = 7.86 < 12,$$

Hence, short column

$$P_u = 0.4\, f_{ck} \left(A_g - \frac{p \times A_g}{100} \right) + 0.67\, f_y \, \frac{pA_g}{100}$$

$$\frac{P_u}{A_g} = 0.4\, f_{ck} \left(1 - \frac{p}{100} \right) + 0.67\, f_y \, \frac{p}{100}$$

$$\frac{1800 \times 10^3}{\frac{\pi}{4} \times 350^2} = 0.4 \times 20 \times \left(1 - \frac{p}{100} \right) + 0.67 \times 415 \times \frac{p}{100}$$

or, $18.71 = 8 - 0.08\, p + 2.78\, p$

or, $10.71 = 2.7\, p$

or, $p = \dfrac{10.71}{2.7} = 3.97\%$

or, $A_{sc} = \dfrac{3.97}{100} \times \dfrac{\pi}{4} \times 350^2 = 3820 \text{ mm}^2$

Provided 8 ϕ 25 ($A_{sc} = 3928 > 3820 \text{ mm}^2$) (Figure 5.4)

Hence, O.K.

Figure 5.4 : Designed Section

Check for Eccentricity

$$e_{\min} = \frac{\ell}{500} + \frac{D}{30}$$

$$= \frac{2.75 \times 10^3}{500} + \frac{350}{30} = 17.17 < 0.05\, D\ (= 17.5)$$

Check by Interaction Diagram (Figure 5.2).

For $P_u = 1800$ kN and

$$A_g = \frac{\pi}{4} \times 350^2 = 96211.28 \text{ mm}^2$$

$$= 962.11 \text{ cm}^2$$

From Interaction Diagram for $f_y = 415 \text{ N/mm}^2$ and $f_{ck} = 20 \text{ N/mm}^2$

$$\frac{100\ A_s}{A_g} = 3.95$$

or $A_s = \dfrac{3.95 \times A_g}{100} = \dfrac{3.95 \times 96211.28}{100} = 3800 \text{ mm}^2$

Provided 8 ϕ 25 ($A_s = 8 \times 491 = 3928 \text{ mm}^2 > 3800 \text{ mm}^2$) (Figure 5.4)

Hence, O.K.

5.3.2 Design of Axially Loaded Short Circular Columns with Helical Reinforcement

The *design load* for this type of column shall be taken as 1.05 times the strength of similar member with lateral ties provided the ratio of the volume of helical reinforcement to the volume of the core shall be not less than

$$0.36 \left(\frac{A_g}{A_c} - 1 \right) \frac{f_{ck}}{f_y} \qquad \ldots (5.3)$$

where A_g = Gross area of the section, and

A_c = Area of core of helically reinforced section measured to the outside diameter of the helix.

Example 5.3

Design longitudinal reinforcement for the circular column with helical reinforcement as transverse reinforcement of ϕ 8 @ 45 c/c for Example 5.2.

Solution

$$\frac{P_u}{1.05} = 0.4\, f_{ck} \left(A_g - \frac{pA_g}{100} \right) + 0.67\, f_y\, \frac{pA_g}{100}$$

or, $$\frac{1800 \times 10^3}{1.05 \times \frac{\pi}{4} \times 350^2} = 0.4 \times 20 \times \left(1 - \frac{p}{100}\right) + 0.67 \times 415 \times \frac{p}{100}$$

or, $17.82 = 8 - 0.08\, p + 2.78\, p$

or, $9.82 = 2.7\, p$

or, $p = \frac{9.82}{2.7} = 3.64\%$

or, $A_{sc} = \frac{3.64}{100} \times \frac{\pi}{4} \times 350^2 = 3502 \text{ mm}^2$

Provided 12 ϕ 20 (A_{sc} = 3768 > 3502 mm^2) (Figure 5.5)

Check for Eccentricity

$$e_{\min} = \frac{\ell}{500} + \frac{D}{30} = \frac{2.75 \times 10^3}{500} + \frac{350}{30} = 17.17 < 0.05\, D\ (= 17.5)$$

Volume of Helical Reinforcement

Minimum volume of helical reinforcement per unit length of column

$$= 0.36 \left(\frac{A_g}{A_c} - 1 \right) \frac{f_{ck}}{f_y} = 0.36 \times \left(\frac{\frac{\pi}{4} \times 350^2}{\frac{\pi}{4} \times 270^2} - 1 \right) \times \frac{20}{415}$$

= 0.0118 (Assuming nominal cover = 40).

For pitch of helical reinforcement = ϕ 8 @ 45.

$\therefore$ Volume of helical reinforcement per metre length

$$= \frac{\pi}{4} \times 8^2 \times \frac{1000}{45} \times (\pi \times 262)$$

$$\frac{\text{Volume of helical reinforcement per metre length}}{\text{Volume of core/metre length}} = \frac{\frac{\pi}{4} \times 8^2 \times \frac{1000}{45} \times (\pi \times 262)}{\frac{\pi}{4} \times 270^2 \times 1000}$$

$$= 0.016 \nless 0.0118$$

Hence, O.K.

Figure 5.5 : Circular Column with Helical Reinforcement

SAQ 1

(a) Why 'minimum eccentricity requirement' is necessary for an axially loaded column?

(a) Define 'Pedestal' and a short column.

(b) How the effective length of a column is evaluated?

(c) How will you determine the area of longitudinal bars for given design load and gross cross sectional area of a column?

5.4 DETAILING OF REINFORCEMENTS

5.4.1 Detailing of Longitudinal Reinforcement

Development Length

Development length of compression bars may be calculated by the same formula which is used for tensile bars

i.e. $L_d = \dfrac{\phi \sigma_s}{4\tau_{bd}}$

But for compression bars

(a) τ_{bd} = 1.25 times the bond stress of bars in tension, and

(b) the *projected* length of hooks, bends and straight lengths beyond bends, if provided, shall *only* be considered.

Lap Splice

The lap length in compression member shall be equal to the development length (L_d) but not less than 24 ϕ (Figures 5.6(a) and (b)).

Distance between Individual Bars

The minimum horizontal spacing between two parallel main bars shall be diameter of larger bar or maximum size of coarse aggregate plus 5 mm. The maximum spacing of longitudinal bars measured along the periphery of the column shall not exceed 300 mm. At least four bars, one at each corner, shall be provided in column having rectangular section. A circular column must have at least six bars.

Nominal Cover

Nominal cover in case of a column shall not be less than 40 mm or the diameter of longitudinal bar whichever is greater.

However, for columns of width 800 mm or less and longitudinal bar of 12 mm diameter, the nominal cover may be taken equal to 25 mm.

Cross Sectional Area of Longitudinal Bars

The cross sectional area of longitudinal bars in a column shall not be more than 6% nor less than 0.8% of the gross sectional area of the column.

5.4.2 Detailing of Transverse Reinforcements

Pitch and Diameter

(a) *Pitch of Lateral Ties* (*Figures 5.6*(*a*) *and* (*b*))

The pitch of lateral ties shall not be more than the *least* of the following :

(i) The least lateral dimension of compression member;

(ii) Sixteen times the smallest diameter of the longitudinal bar; and

(iii) 300 mm.

(a) Splice with Lower Bars Cranked into Position Inside Upper Bars (Intermediate Floor)

(b) Splicing at the Floor Level when the Relative Displacement of Column Faces is more than 75 mm

Figure 5.6

(b) *Pitch of Helical Reinforcement* (*Figure 5.7*)

Pitch of the helical turns shall not be more than 75 mm nor more than one-sixth of core diameter nor less than 25 mm and nor less than three times the diameter of bar of helical reinforcement.

Figure 5.7 : Circular Column with Helical Reinforcement

The diameter of transverse reinforcing bar shall not be less than one-forth of the diameter of longitudinal reinforcing bar and in no case less than 6 mm.

Arrangement of Lateral Ties

(a) If the longitudinal bars are not spaced more than 75 mm on either side, transverse reinforcement need only to go round corner and alternate bars for the purpose of providing effective lateral supports (Figure 5.8).

Figure 5.8 : Transverse Reinforcement

(b) If the longitudinal bars spaced at a distance of not exceeding 48 times the diameter of the tie are effectively tied in two directions, additional longitudinal bars in between these bars need to be tied in one direction by open ties (Figure 5.9).

Figure 5.9 : Transverse Reinforcement

SAQ 2

(a) Write short notes on detailing of longitudinal reinforcement in a column.

(b) What are the considerations for pitch of lateral ties as well as for helical reinforcement?

(c) Explain with sketches the detailing of lateral ties for a column.

5.5 SUMMARY

The design load on an axially loaded short column with lateral ties is determined by the formula

$$P_u = 0.4\, f_{ck} A_c + 0.67\, f_y A_{st}$$

For a circular column with helical reinforcement, the design load shall be 1.05 times the design strength of similar column with lateral ties, provided

$$\frac{\text{Volume of Helical Reinforcement}}{\text{Volume of Core}} \nless 0.36 \left(\frac{A_g}{A_c} - 1 \right) \frac{f_{ck}}{f_y}$$

A column is a short one if

$$\frac{l_{ef}}{b \text{ or } D \text{ or dia. of column}} \ngtr 12$$

where l_{ef} shall be obtained from Table 5.1.

The detailing of longitudinal and transverse reinforcements have been explained in text as well as in examples.

5.6 ANSWERS TO SAQs

SAQ 1

(a) Refer Section 5.1.

(b) Refer Section 5.1.

(c) Refer Section 5.2.

(d) Refer Section 5.3.

SAQ 2

(a) Refer Section 5.4.1.

(b) Refer Section 5.4.2.

(c) Refer Section 5.4.2.