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Study on the Behaviour of Rectangular Column with Unequally Spaced Longitudinal Reinforcement

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***Abstract*— Resisting moment or ultimate moment carrying capacity is criterion which gives strength to the column section against bending. The importance of ultimate moment carrying capacity can be studied and understood by limiting strain diagram and interaction curve diagram. The interaction curve will be obtained by fixing the neutral axis at different distances inside as well as outside the section column from the edge of the column. The stress and strain exerted on the each row of the bars are calculated. The values of ultimate load (Pu) and ultimate moment (Mu) capacities are obtained and taken along Y axis and X axis respectively.**

***Keywords*— Rectangular concrete column, limiting strain diagram, interaction diagram, longitudinal reinforcement, neutral axis (Xu).**

I. INTRODUCTION

The usual practice is in use while designing the rectangular and circular column is by spacing of longitudinal reinforcement equally in the column section. In case of rectangular column longitudinal reinforcement is spaced equally along the width & depth of the column. The various structural characteristics of rectangular column with equally spaced longitudinal reinforcement can easily be analysed since the axis of centre of gravity lies within the section of these columns. However centre of gravity will remain inside the section in case of rectangular column with longitudinal reinforcement spaced unequally along depth of the section, but the unequal reinforcement is provided to increase the resisting moment in the section. Therefore this study deals with the study and analysis of strength parameters and nature of different types of rectangular column with respect to the location of neutral axis. Thus the section with maximum resisting moment can be achieved.

The present code of design of column does not allow the unequal spacing of longitudinal reinforcements. Up to now, the design of column is done based on equally spaced reinforcement. To investigate the effects of unequally spaced reinforcement on resisting moment capacity of the column, an analytical study is carried out. The study on unequally spaced longitudinal reinforcements gives higher resisting moments compared to the column with equally spaced longitudinal reinforcements.

II. IMPORTANT FEATURES OF INTERACTION CURVE

The typical Pu-Mu interaction curve diagram for a column section is given in Fig 1. The curve represents various pairs of values of design Pu-Mu values for different eccentricities.

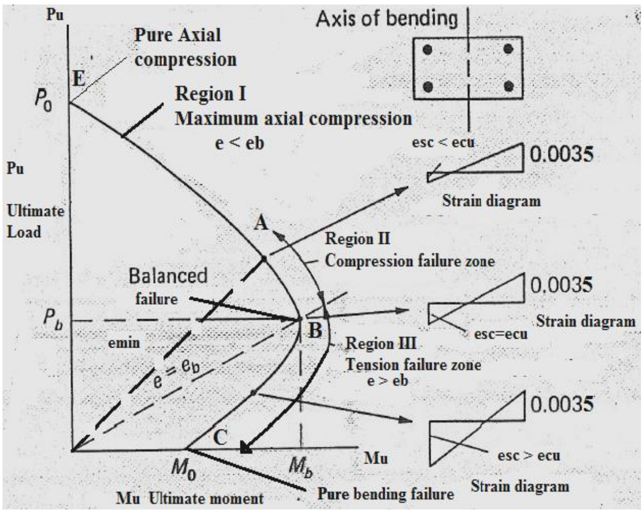


Fig.1 Pu-Mu Interaction curve Diagram

There are 3 prominent regions in the curve which represents the various modes of failure:
Region I: minimum eccentricity
Region II: compression failure zone
Region III: tension failure zone
When values Pu and Mu are such that entire column is under compression so that the neutral axis lies outside the section.

This zone is called as compression zone. When values of Pu and Mu are such that a part of the section is in tension then the zone is called tension zone. Here compressive strain in concrete reaches 0.0035.
Region I can be divided into 2 parts. First part is e=emin. The point A in the interaction curve diagram shows that region. Second part is e<emin. This is the region between EA in interaction curve. So the area between EA is maximum axial compression. The point E in the curve is having pure axial compression.
Region II is called as compression failure zone. It is the region between AB. Here resisting moment starts increasing. The point B shows the balanced failure zone. Here maximum resisting moment is obtained.
The region BC is called as tension failure zone. Here neutral axis lies inside the section. Here in this region the axial load carrying capacity rapidly decreases and also the eccentricity increases. The point c is the point where axial load becomes zero.

III. METHODOLOGY

The research includes the design of rectangular column section having unequal spacing of longitudinal reinforced bars using limit state design. This is a plastic design method. This method is based on ensuring sufficient safety margin. Limit state or load resistant factor uses the ultimate strength of the member going beyond initial yielding to determine the allowable strength. The useful benefit of the limit state design is that it gives more economical design compared to the working stress method. Also it gives more consistent factor across all the elements.

A. *Important assumptions in Limit State Method*

a) The maximum strain in concrete at the outermost compression fibre is taken as 0.0035.
b) The tensile strength of the concrete is ignored.
c) The maximum compression strain in concrete in concrete in axial compression is taken as 0.002.
d) The maximum compressive strain at the highly compressed extreme fibre in concrete subjected to axial compression and bending and when there is no tension on the section shall be 0.0035 minus 0.75 times the strain at the least compressed fibre.
e) The maximum strain in the tension reinforcement in the section at failure shall not be less than = (Fy/1.15Es)+ 0.002

B. *Limiting strain diagram for different depths of Neutral axis inside & outside the section*

To study the behaviour of rectangular column can be explained with the help of limiting strain diagram and interaction curve. The limiting strain diagram shows the different strain profiles depending on the position of neutral axis while the interaction curve shows the ultimate load bearing capacity and resisting moment of the column depending on the position of neutral axis.

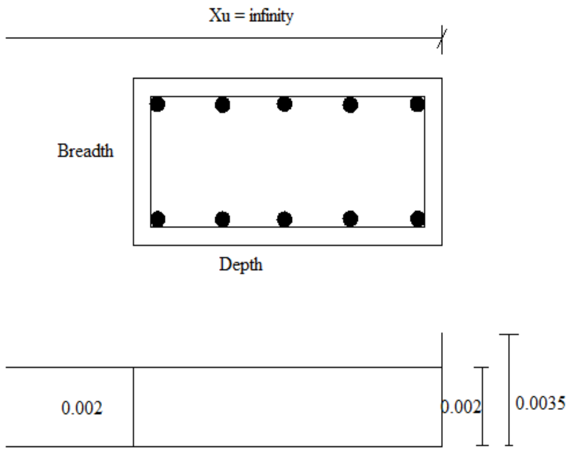


Fig. 2 limiting strain diagram for neutral axis at infinite distance

The Fig. 2 shows strain profile for neutral axis at infinite distance. When neutral axis is at infinite distance then it attains maximum axial compression strain of 0.002 at highly compressed edge as well as least compressed edge.

The point A in the Fig. 1 shows the region of pure axial compression.

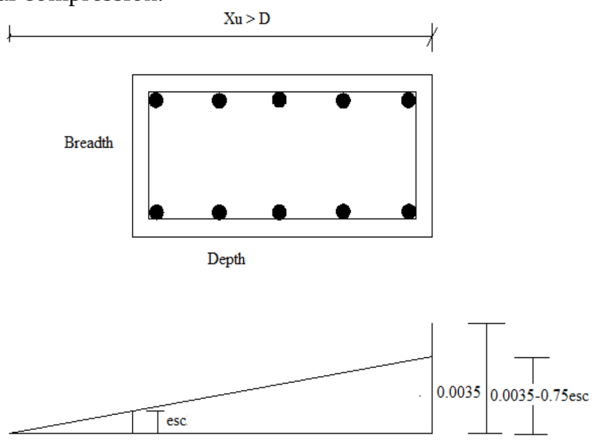


Fig. 3 limiting strain diagram for neutral axis outside the section

The Fig. 3 shows the limiting strain profile for neutral axis outside the section. Here the strain at the maximum compressive edge is taken as 0.0035-0.75esc. The axial compressive stain in least compressed edge will be less than 0.002.

The region AB in the Fig. 1 shows the axial compression region where the strain decreases from 0.002 to 0.

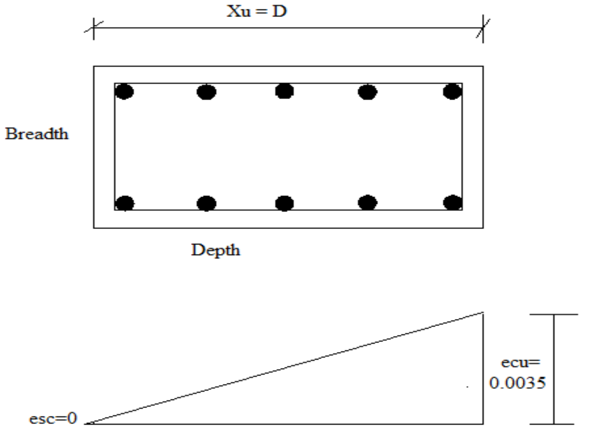


Fig. 4 limiting strain diagram for neutral axis at distance equal to the depth

The Fig. 4 shows the limiting strain diagram which shows the attainment of maximum compressive strain in concrete at the highly compressed edge is 0.0035 and zero strain at the least compressed edge.

The point B in the Fig. 1 of interaction curve is the point where the axial compressive strain becomes zero. It is the point where there will be no compressive strain or tensile strain. As per the assumptions of limit state of collapse it is also the point due to which the compressive strain in the concrete will reaches its maximum compressive strain of 0.0035. This strain remains same for all the neutral axis positions inside the section.

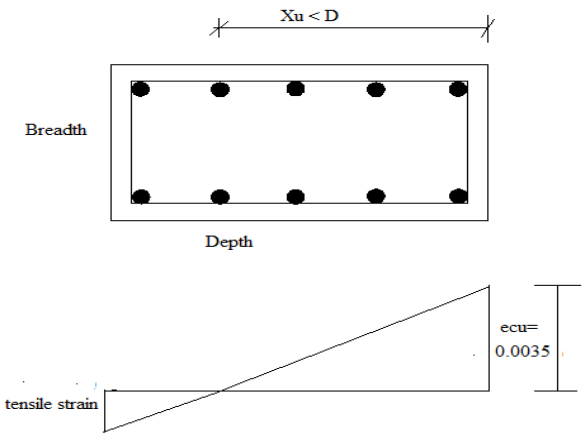


Fig. 5 limiting strain diagram for neutral axis inside the section

The Fig. 5 shows the limiting strain diagrams for the compressive failure zone. Here the tensile strain in steel is attained at the least compressed edge of the steel. The tensile strain will range from zero to 0.0035. The values Pu & Mu in compressive failure zone is taken to design a column because compressive failure zone gives under reinforced section. The steel fails before concrete developing cracks in the concrete giving enough indications of failure.

The region between B to c in Fig. 1 of interaction curve shows the compression failure region because the compressive strain dominates.

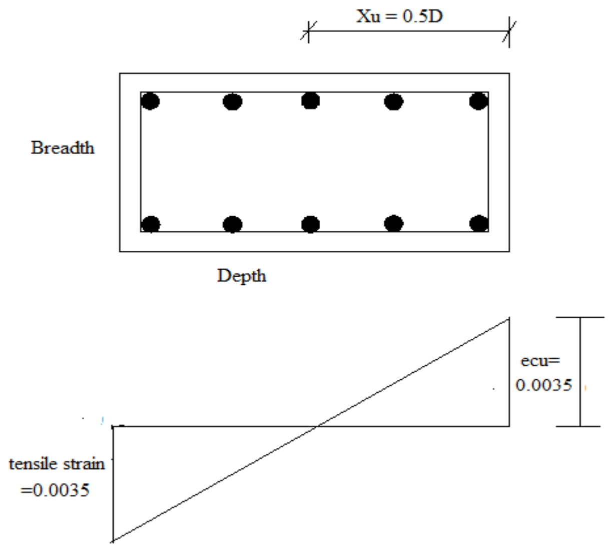


Fig. 6 limiting strain diagram for balanced section

The Fig. 6 shows the limiting strain diagram for the balanced failure of the section. It is the point where both compressive strain at the most compressed edge and tension strain at the least compressed edge fiber becomes same. That is both ends will attain the strain of 0.0035.

The point C in Fig 1 of interaction curve shows the balanced failure zone.

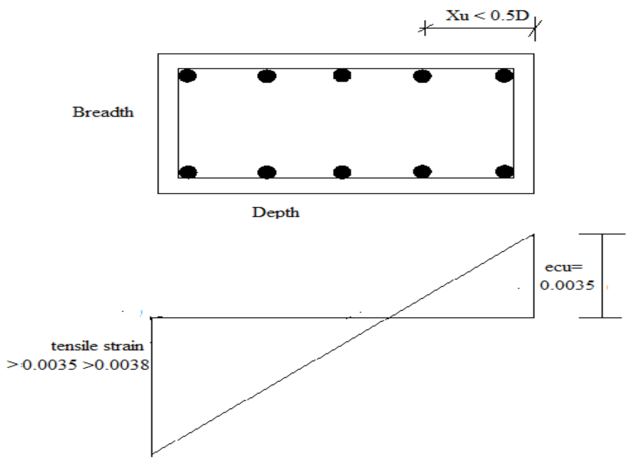


Fig. 7 limiting strain diagram for tension failure zone

The Fig. 7 shows limiting strain diagram for the tension failure zone. In this zone the tension failure dominates. In this zone the tensile stain exceeds 0.0035. Tensile failure zone gives over reinforced section which will results in the failure of concrete before steel in the column. This will results in catastrophic results. So to the design column the values of ultimate load and ultimate moment are not taken from this region.

The region between C to D from Fig. 1 of interaction curve shows the tension failure region. In this region flexure failure take place by bending. The point D shows the point of pure bending which is Mo. As per the assumption the tension strain will not exceed 0.0038 which is the allowable strain in tension 0.446fck.

IV. Design Procedure

A. *Neutral axis lies inside the column section, (Xu = or < D)*

b= width of the section
D= depth of the section
f_{ck}= characteristic strength of the concrete
f_y= characteristic strength of the steel
d'= end cover
Cc= coefficient for area for the stress block
e_{cb}= Strain at least compressed edge
e_{cu}= Strain at extremely compressed edge

Step 1:
Find Axial load carrying capacity of concrete:
P_c = Cc x f_{ck} x b x D kN

Step 2:
Find Axial load carrying capacity of steel:
Strain in the steel e_{sc}:

$$e_{sc} = 0.0035 \times \frac{(D-d')}{D}$$

Stress in the steel f_{sc} :
f_{sc} is found out by interpolating the values given in Table H of IS: 456-1976
Stress in concrete f_{cc}:
f_{cc} = 0.446 x f_{ck} when e_{sc} >0.002
f_{cc} = 446 x e_{sc} x f_{ck} x (1-(250 x e_{sc})) when e_{sc} <0.002
Axial load in steel:
P_s= (f_{sc} - f_{cc}) x Area of the steel

Step 3:
Total Axial load, P_u:
P_u= P_c + P_s

Step 4:
Ultimate moment, M_u:
Ultimate moment carrying capacity of the concrete M_c:
M_c = Cc x b x Xu x ((0.5 x D) x (0.416 x Xu))
Ultimate moment carrying capacity of the steel M_s:
M_s= Ps x ((0.5 x D) – Each row distance)
Total Ultimate moment, Mu:
Mu = M_c + M_s

B. *Neutral axis lies outside the column section, (Xu > D)*

Step 1:
Find Axial load carrying capacity of concrete:
P_c = Cc x f_{ck} x b x D kN

Step 2:
Find Axial load carrying capacity of steel:
Strain at least compressed edge can be calculated by

$$\frac{(0.0035-0.75^{*}e_{cb})}{Xu} = \frac{e_{cb}}{(Xu-D)}$$

Strain at the extreme compressed edge
e_{cu}= 0.0035 - 0.75 e_{cb}
Strain in the steel e_{sc}:

$$e_{sc} = e_{cu} \times \frac{(D-d')}{D}$$

Stress in the steel f_{sc} :
f_{sc} is found out by interpolating the values given in Table H of IS: 456-1976
Stress in concrete f_{cc}:
f_{cc} = 0.446 x f_{ck} when e_{sc} >0.002
f_{cc} = 446 x e_{sc} x f_{ck} x (1-(250 x e_{sc})) when e_{sc} <0.002
Axial load in steel:
P_s= (f_{sc} - f_{cc}) x Area of the steel

Step 3:
Total Axial load, P_u:
P_u= P_c + P_s

Step 4:
Ultimate moment, M_u:
Ultimate moment carrying capacity of the concrete M_c:
M_c = Cc x b x Xu x ((0.5 x Xu) x (0.416 x Xu))
Ultimate moment carrying capacity of the steel M_s:
M_s= Ps x ((0.5 x D) – Each row distance)
Total Ultimate moment, Mu:
Mu = M_c + M_s

V. Worked Out Example

This study explains achieving better resisting moments at deferent points in the column section by varying the positions of reinforcements throughout the section. The following example of two standard sections of dimension 230mmX450mm with equally spaced longitudinal reinforcements and same section with varied spacing of longitudinal reinforcement shows the increase in resisting moments by drawing interaction curves for both the sections.
Example 1:
Calculating ultimate loads and ultimate moments and drawing interaction curve for the section with equally spaced longitudinal reinforcements.

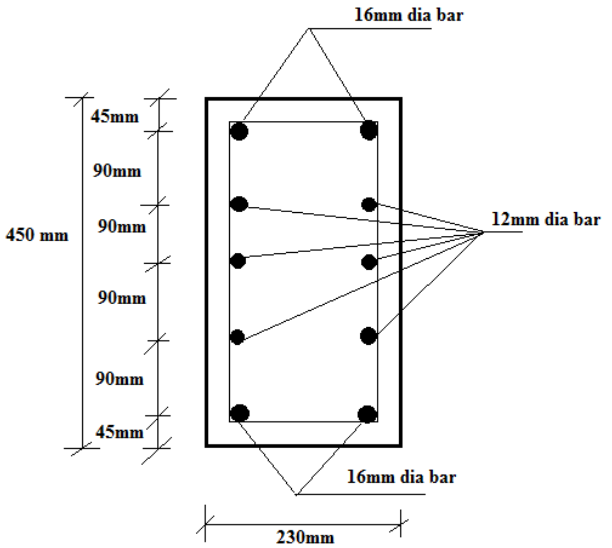


Fig. 8 Column section with equally spaced longitudinal reinforcement

Data:
Steel reinforcement at four corners of the section= 4 bars of 16 mm diameter
Steel reinforcement in the middle of the section= 6 bars of 12 mm diameter

Grade of concrete f_{ck} = 20N/mm^2
Grade of steel f_y = 415N/mm^2
Effective cover = 45mm
Area of the section = 230 X 450= 103500mm^2
Area of the steel in the section
= $((\prod*16^2/4)*4) + ((\prod*12^2/4)*6 = 1482.83mm^2$

Solution:

When neutral axis lies inside the section (Xu< or =D):

When neutral axis Xu @ level of 450mm
Axial load carrying capacity of concrete, P_c= 747.27 kN
Strain different rows of reinforcement:
Row 1: e_{sc}=0.0035
Row 2: e_{sc}=0.00245
Row 3: e_{sc}=0.00175
Row 4: e_{sc}=0.00105
Row 5: e_{sc}=0.00035
Stress in Steel & Concrete:

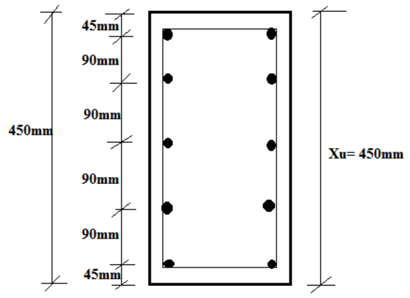
f_{sc}= 355.21 N/mm^2 f_{cc} = 8.92 N/mm^2

f_{sc}= 348.83 N/mm^2 f_{cc} = 8.92 N/mm^2

f_{sc}= 314.18 N/mm^2 f_{cc} = 8.78 N/mm^2

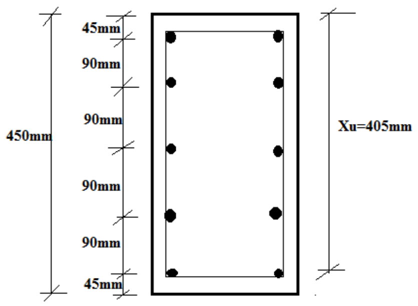
f_{sc}= 210.51 N/mm^2 f_{cc} = 6.91 N/mm^2

f_{sc}= 70.170 N/mm^2 f_{cc} = 2.85 N/mm^2



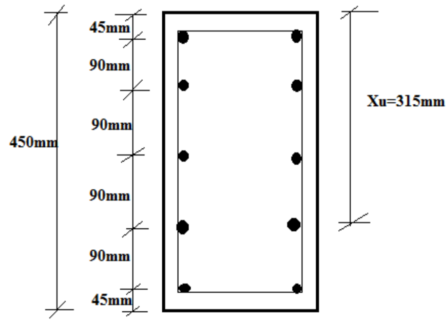
Ultimate load Pu= 1104.47 kN
Ultimate Moment Mu= 51.11 kN-m

Same way the ultimate load & ultimate moment are found at every row of reinforcement:
When neutral axis Xu @ level of 405mm

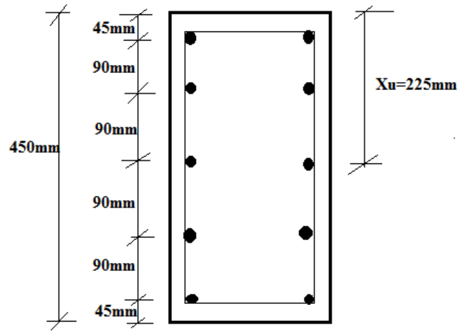


Ultimate load Pu= 986.402 kN
Ultimate Moment Mu= 66.73 kN-m

When neutral axis Xu @ level of 315mm

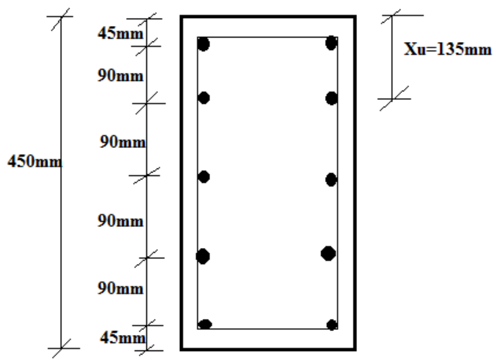


Ultimate load Pu= 697.14 kN
Ultimate Moment Mu= 95.12 kN-m
When neutral axis Xu @ level of 225mm



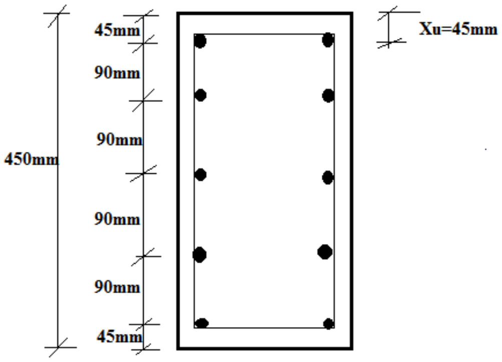
Ultimate load Pu= 346.45 kN
Ultimate Moment Mu= 112.97 kN-m

When neutral axis Xu @ level of 135mm



Ultimate load Pu= 48.79 kN
Ultimate Moment Mu= 85.69 kN-m

When neutral axis Xu @ level of 45mm



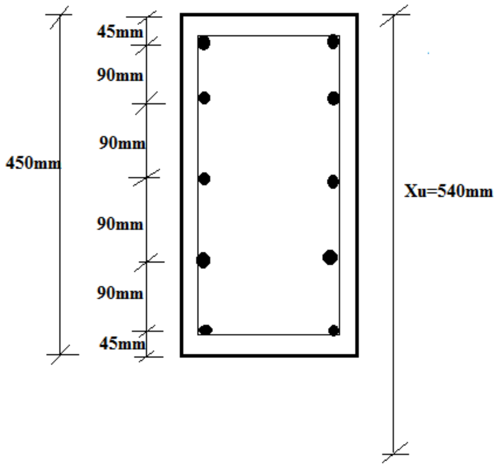
Ultimate load Pu= -135.45 kN
Ultimate Moment Mu= 41.54 kN-m

When neutral axis Xu @ level of 45mm

Ultimate load Pu= -535.368 kN
Ultimate Moment Mu= 0 kN-m

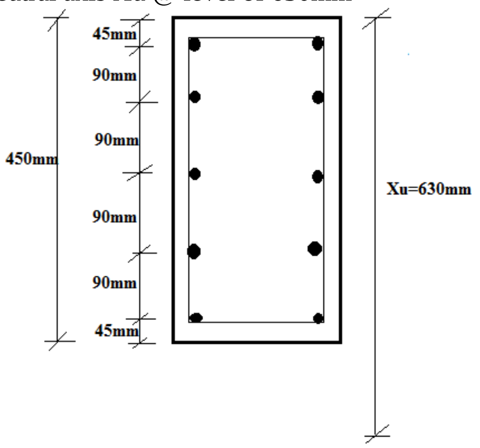
When neutral axis is outside the section, (Xu>D):

When neutral axis Xu @ level of 540mm



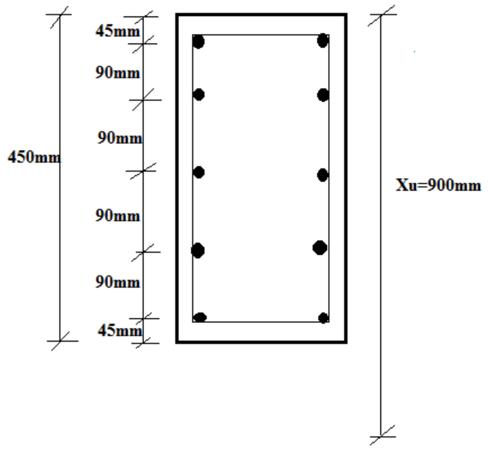
Ultimate load Pu= 1186.003 kN
Ultimate Moment Mu= 33.205 kN-m

When neutral axis Xu @ level of 630mm



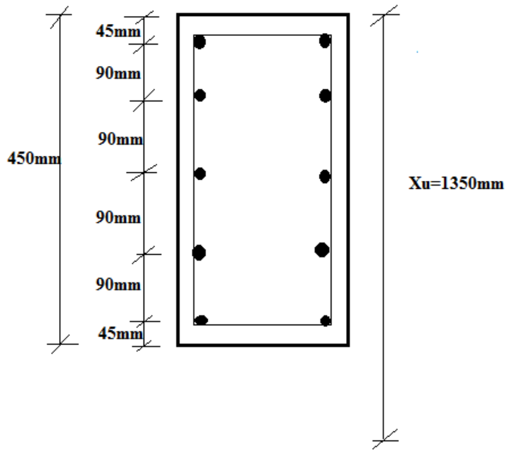
Ultimate load Pu= 1253.40 kN
Ultimate Moment Mu= 22.92 kN-m

When neutral axis Xu @ level of 900mm



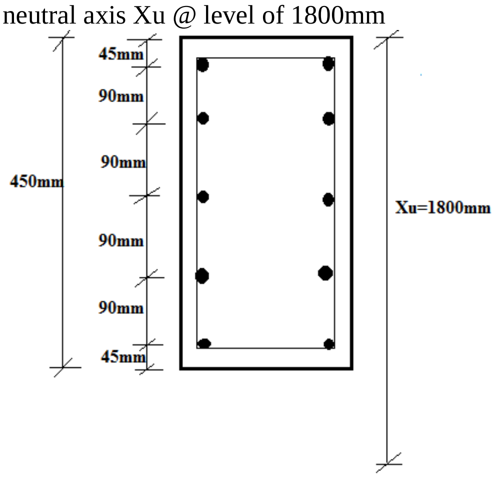
Ultimate load Pu= 1337.99 kN
Ultimate Moment Mu= 9.88 kN-m

When neutral axis Xu @ level of 1350mm



Ultimate load Pu= 1374.71 kN
Ultimate Moment Mu= 3.918 kN-m

When neutral axis Xu @ level of 1800mm



Ultimate load Pu= 1383.74 kN
Ultimate Moment Mu= 2.210 kN-m

When neutral axis Xu @ a distance that Mu=0

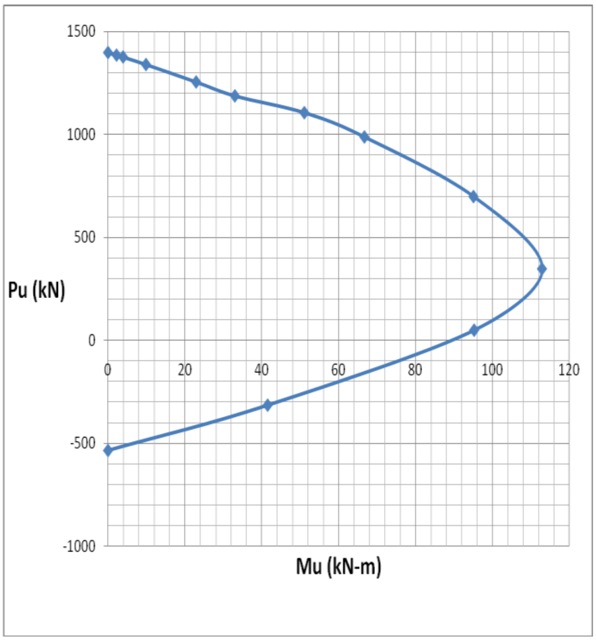
Pu = (0.446 x f_{ck} x b x D) + ((0.79 x f_y) x (0.446 x f_{ck})) x Total area of the steel

= (0.446 x 20 x 230 x 450) + ((0.79 x 415) x (0.446 x 20) x 1482.83
Pu = 1396.14 kN

The following table shows calculated results Pu along y axis and Mu along x axis for different rows of reinforcements

Y-axis Pu (kN)	X-axis Mu (kN-m)	Xu Distance (mm)
-535.37	0	0
-315.46	41.54806224	45
48.7896	95.29668017	135
346.454	112.9710827	225
697.139	95.12119936	315
986.403	66.73138072	405
1104.48	51.11203575	450
1186	33.02595665	540
1253.4	22.92623364	630
1337.99	9.882724387	900
1374.71	3.91829456	1350
1383.74	2.21040534	1800
1396.14	0	Infinity

Table 1: Values of Pu & Mu for equally spaced longitudinal reinforcements



Graph 1: Interaction curve for the section with equally spaced reinforcements

Calculating ultimate loads and ultimate moments and drawing interaction curve for the same section with unequally spaced longitudinal reinforcements.

Data:
Steel reinforcement at four corners of the section= 4 bars of 16 mm diameter
Steel reinforcement in the middle of the section= 6 bars of 12 mm diameter
Grade of concrete f_{ck} = 20N/mm^2
Grade of steel f_y = 415N/mm^2
Effective cover= 45mm
Area of the section = 230 X 450= 103500mm^2
Area of the steel in the section
= ((∏*16^2/4)*4) + ((∏*12^2/4)*6 = 1482.83mm^2

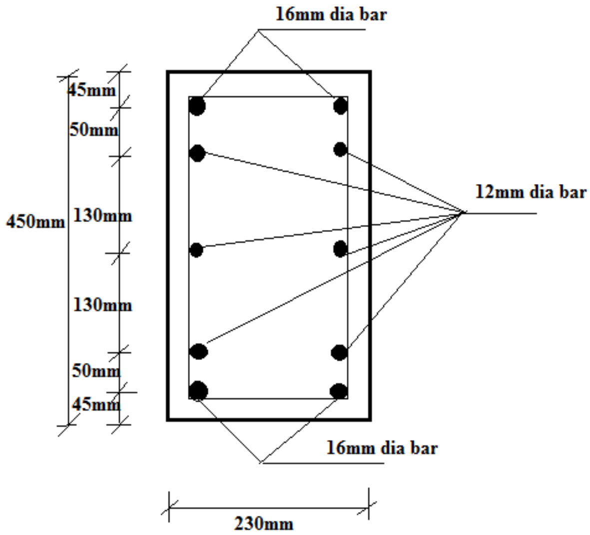
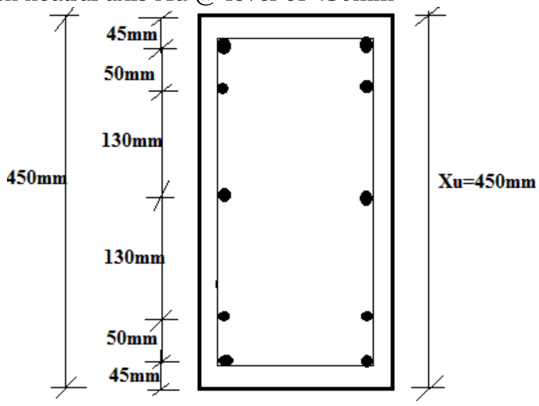


Fig. 9 Column section with unequally spaced longitudinal reinforcement

Solution:

When neutral axis lies inside the section (Xu< or =D):

When neutral axis Xu @ level of 450mm



Axial load carrying capacity of concrete, P_c= 747.27 kN
Strain different rows of reinforcement:
Row 1: e_{sc}=0.0035
Row 2: e_{sc}=0.00276
Row 3: e_{sc}=0.00175
Row 4: e_{sc}=0.00073
Row 5: e_{sc}=0.00035
Stress in Steel & Concrete:
f_{sc}= 355.21 N/mm^2 f_{cc} = 8.92 N/mm^2

f_{sc}= 351.81 N/mm^2 f_{cc} = 8.92 N/mm^2

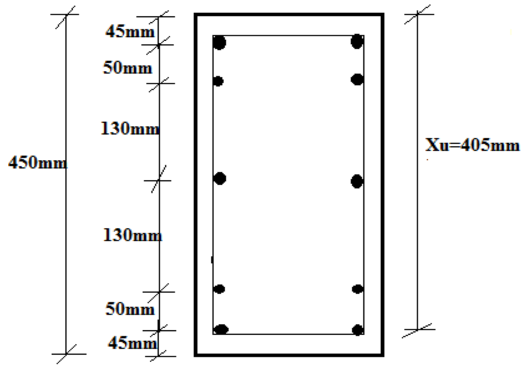
f_{sc}= 314.18 N/mm^2 f_{cc} = 8.78 N/mm^2

f_{sc}= 148.13 N/mm^2 f_{cc} = 5.37 N/mm^2

f_{sc}= 70.170 N/mm^2 f_{cc} = 2.85 N/mm^2

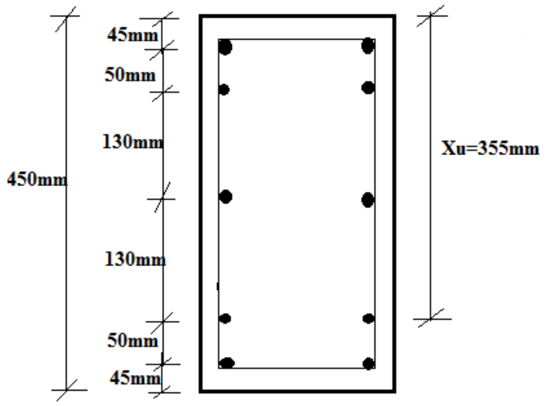
Ultimate load Pu= 1092.52 kN
Ultimate Moment Mu= 54.32 kN-m

Same way the ultimate load & ultimate moment are found at every row of reinforcement:
When neutral axis Xu @ level of 405mm



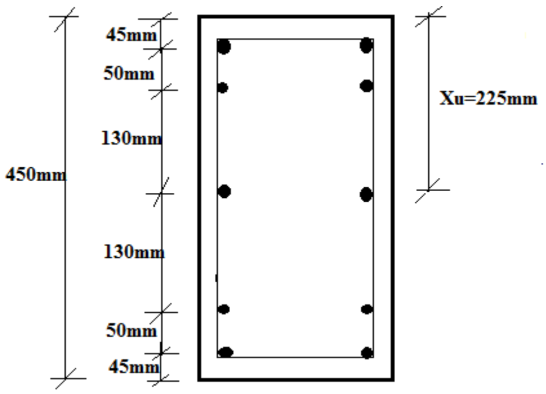
Ultimate load Pu= 973.41 kN
Ultimate Moment Mu= 70.627 kN-m

When neutral axis Xu @ level of 355mm



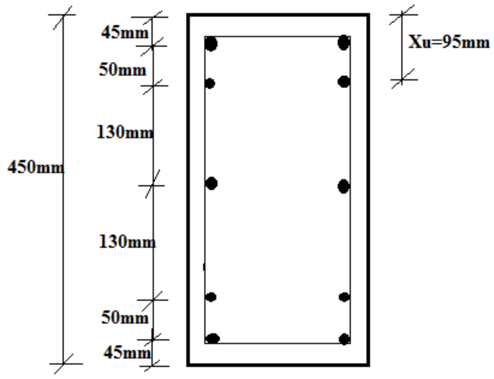
Ultimate load Pu= 821.46 kN
Ultimate Moment Mu= 87.673 kN-m

When neutral axis Xu @ level of 355mm



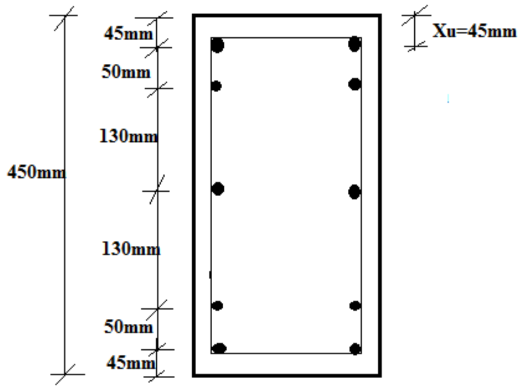
Ultimate load Pu= 357.10 kN

Ultimate Moment Mu= 120.08 kN-m
When neutral axis Xu @ level of 95mm



Ultimate load Pu= -25.674 kN
Ultimate Moment Mu= 88.52 kN-m

When neutral axis Xu @ level of 45mm



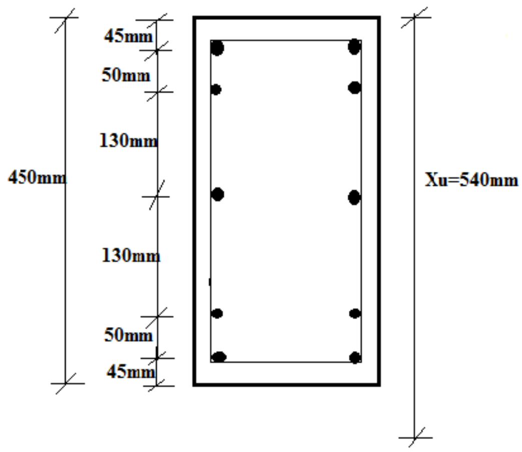
Ultimate load Pu= -315.45 kN
Ultimate Moment Mu= 41.54 kN-m

When neutral axis Xu @ level of 0mm

Ultimate load Pu= -535.36 kN
Ultimate Moment Mu= 0 kN-m

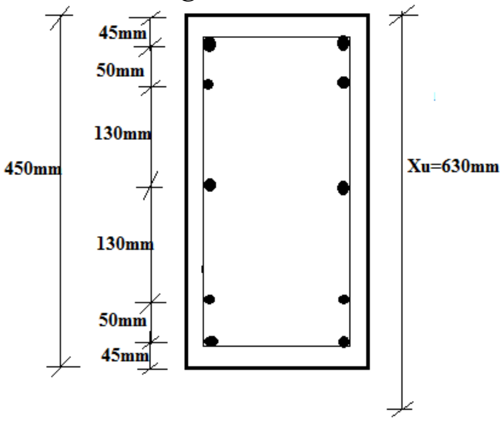
When neutral axis is outside the section, (Xu>D):

When neutral axis Xu @ level of 540mm



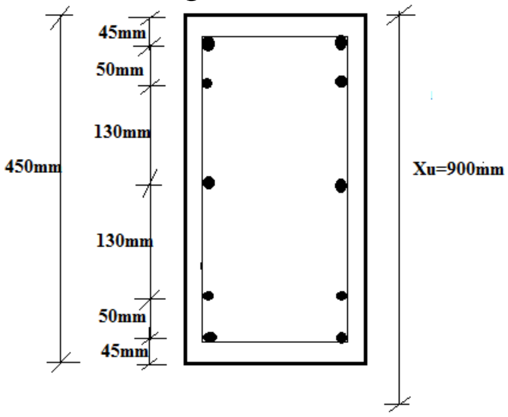
Ultimate load Pu= 1179.71 kN
Ultimate Moment Mu= 35.336 kN-m

When neutral axis Xu @ level of 630mm



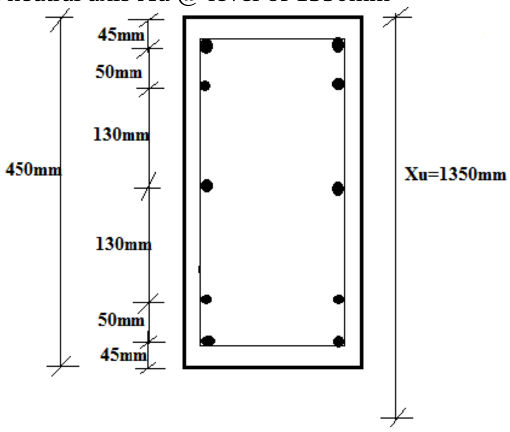
Ultimate load Pu= 1247.87 kN
Ultimate Moment Mu= 24.708kN-m

When neutral axis Xu @ level of 900mm



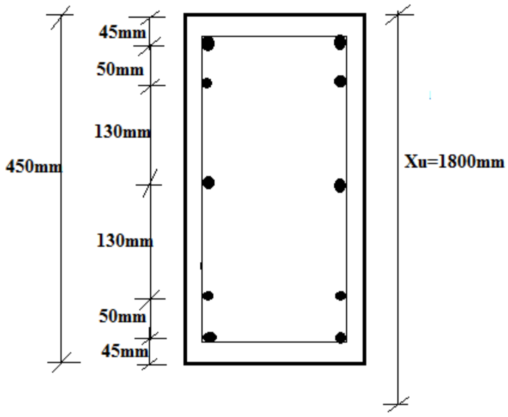
Ultimate load Pu= 1335.99 kN
Ultimate Moment Mu= 10.644kN-m

When neutral axis Xu @ level of 1350mm



Ultimate load Pu= 1374.34 kN
Ultimate Moment Mu= 4.253kN-m

When neutral axis Xu @ level of 1800mm



Ultimate load Pu= 1383.47 kN
Ultimate Moment Mu= 2.210kN-m

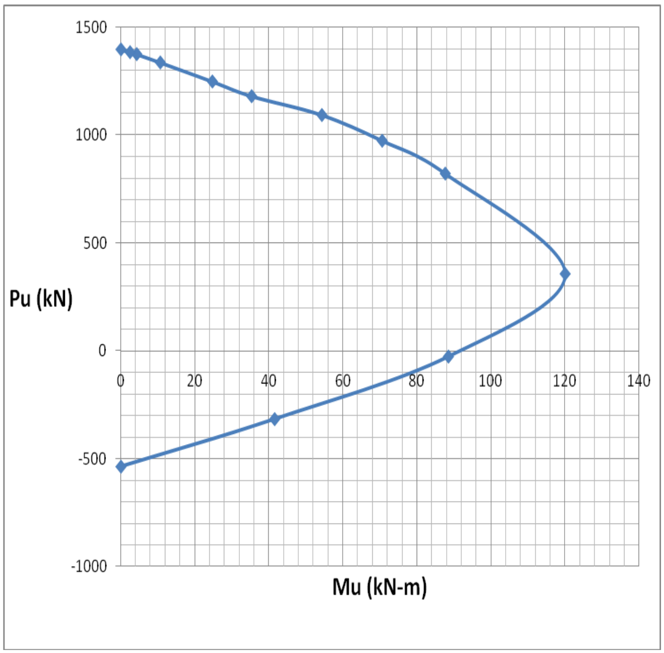
When neutral axis Xu @ a distance that Mu=0

Pu = (0.446 x f_{ck} x b x D) + ((0.79 x f_y) x (0.446 x f_{ck})) x Total area of the steel
= (0.446 x 20 x 230 x 450) + ((0.79 x 415) x (0.446 x 20) x 1482.83
Pu = 1396.14 kN

The following table shows calculated results Pu along y axis and Mu along x axis for different rows of reinforcements

Y-axis	X-axis	Xu Distance (mm)
Pu (kN)	Mu (kN-m)	
-535.37	0	0
-315.46	41.54806224	45
-25.675	88.52613749	95
357.1	120.0877434	225
821.468	87.67387132	355
973.417	70.62743549	405
1092.52	54.32366394	450
1179.71	35.33686276	540
1247.88	24.70898221	630
1336	10.64423146	900
1374.35	4.253799566	1350
1383.47	2.450064541	1800
1396.14	0	Infinity

Table 2: Values of Pu & Mu for unequally spaced longitudinal reinforcements



Graph 2: Interaction curve for the section with unequally spaced reinforcements

VI. Conclusions

The research involves obtaining results for column with unequally spaced steel reinforcements. The results obtained in the research leads to the following conclusions.

a) The column with unequally spaced longitudinal reinforcement gives more resisting moment compared to the column with equally spaced longitudinal reinforcement for neutral axis laying both at inside & outside the section. In this study the spacing of longitudinal steel reinforcement in column are done in such a way that the maximum resisting moment is obtained at particular point. In interaction curve of unequally spaced longitudinal reinforcement we can observe the gradual increase in resisting moments at different points of column starting from pure bending point (Mo) of the curve till the pure axial compression point (Po) as compared to the column section with equally spaced longitudinal reinforcement, especially in balanced failure zone and compression failure zone including axial compression zone.

b) Preliminarily we can understand the behavior of the column by stress and strain parameters. These parameters help to obtain ultimate load and ultimate moment carrying capacity of column. Unequally spaced column gives higher stress & strain values at every row of reinforcements compared to the conventional column with equal reinforcement.

c) The conventional column can be replaced by column with lesser characteristic strength of steel & concrete. This will give same or higher resisting moment at much lower weight of steel and concrete, which also reduces the self weight of the structure.

d) The longitudinal bars with lesser diameter can be introduced for column sections with higher dimensions. Thus the economy is achieved in construction of column.

e) The column is designed for values of ultimate loads & resisting moments for the regions of compression failure or balanced failure. Because compression failure region gives under reinforced section in which the steel fails first and cracks are developed in the concrete which will give enough indications of failure of the column. The columns are never designed for the Pu & Mu values of tension failure region because it gives over reinforced section where concrete will fail first.

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