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Main framework of rehabilitation and strengthening of RC columns subjected to combined bending

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Abstract:-- **The aims of this paper is to focus on the current methods in strengthening columns, which are exposed to axial load and bending moment (or exposed to un-axial loads), by means of steel angles, and to invest these methods in numerical practical examples according to ultimate strength method. Then suggesting useful method & equations to strengthen RC column subjected to axial and bending moment. Afterward, a comparative study has been conducted to figure out the governing parameters of behavior of steel angles and strips that strengthen RC columns. It has been started by outlining general framework for rehabilitation & strengthening of RC columns via steel angles and strips exposed to a combined bending, which will be studied in detail. It shows the current experimental proposed equations to strengthen axially loaded columns.**

Index Terms— axial, bending, RC columns, rehabilitation, strengthening, steel angles

INTRODUCTION

Most of the theoretical and experimental studies related to the rehabilitation and strengthening of reinforced concrete RC columns concern with columns exposed to axial loads. Rarely you see research on columns exposed to axial loads and bending moment, the latter being the goal of this research. Concrete columns in all types of installations (bridges, buildings, halls, places of worship, etc.) are exposed to structural defects in load capacity for many reasons: poor implementation, emergency loads, earthquakes, damage, cracking, etc. This requires careful study of the situation of each column separately and to identify the causes of the imbalance and to develop the solutions necessary to restore its structural ability. The main deficiency found in literature is insufficient studies on the steel angles and strips strengthened RC columns subjected to bending and axial load domain. So, further studies are required on the behavior under axial load and flexure to establish a complete guideline to design or to check the adequacy of steel angles and strips strengthened RC columns.

The rehabilitation and strengthening process includes these items:

1- Maintenance procedure:

Related to a phase after damage (or damage) in order to restore the column to its former status in terms of performance and durability (and perhaps to a higher level).

2- Restoration work:

The aim is to improve the unaffected column to increase existing structural endurance.

3- Strengthening work:

Aims to improve the structural performance and durability of the column without causing damage to this element.

4- Rehabilitation work:

Aims to return the column to its previous structural state. It includes four main groups and a fifth secondary:

- Maintenance works on loaded column (Post-damage).
- Maintenance works on column un-loaded column (Post-damage)
- Strengthening works on loaded column (No-damage)
- Strengthening works on un-loaded column (No-damage)
- Different unpretentious works (measurements or changes in structural function)

5- Assessment

It aims at assessing the current state of the column or building in relation to past and present data and future requirements (Re-design).

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II. CURRENT USED STRENGTHENING METHODS (FIG. 1 AND 2)

A. Current methods

There are many ways to increase the axial load capacity and available ductility of concrete columns. The most important methods currently used globally are:

- Reinforced concrete jacketing: cast in place or pre-cast. Adding new concrete jacket with additional reinforcement

- Strengthening via steel elements: steel jacketing. Using external steel angles and horizontal strips,

- Fiber reinforced polymer FRP: ordinary or pre-stressed. Wrapping the original column section with Fiber-Reinforced Polymers, FRP

- Strengthening via pre-stressed concrete tendons. May be fixed outside the structural element.

However, Strengthening of RC columns using steel angles connected by horizontal strips is one of the cheapest and fairly easiest available techniques so far.

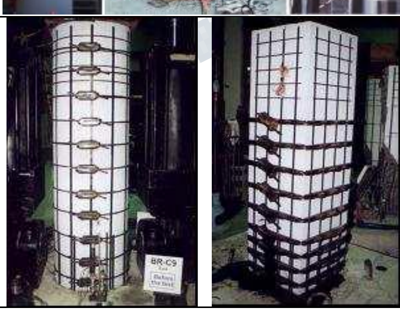
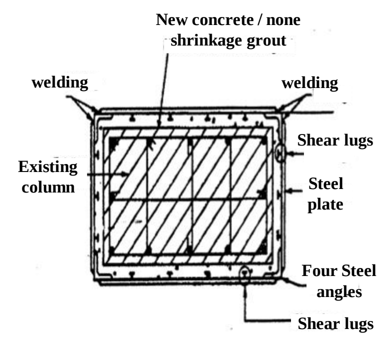
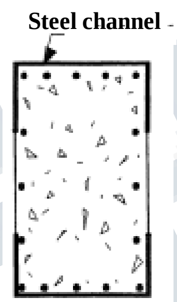
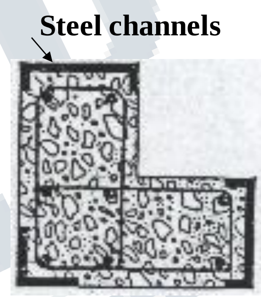
	**Precast Concrete Jacketing**
	**FRP**
	**External Pre-stressing**

Fig. 1 Current used methods of strengthening columns

	Steel jacketing refers to encasing the column with steel plates and filling the gap with concrete or nonshrink grout.
	

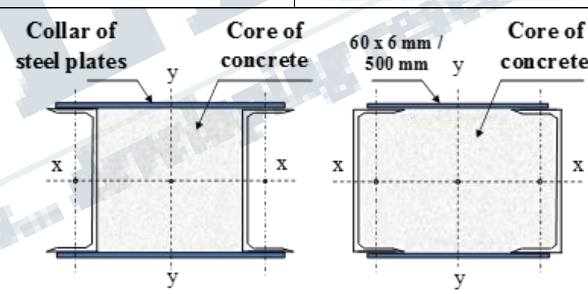


Fig. 2 Strengthening of RC Columns with Steel Jacketing

III. COMPOSITE SECTION OF CONCRETE STEEL

Fig. 3 shows steel - RC column sections after strengthening (composite situation) by steel elements. American specification ACI-10.14. 5 gave the following equations to calculate of radius gyration, in order to find slenderness of a composite column of concrete and steel:

$$r = \sqrt{\frac{0.20\, E_c I_g + E_s I_s}{0.20\ E_c A_g + E_s A_s}} = \sqrt{\frac{0.20\, I_g + n\, I_s}{0.20\, A_g + n\, A_s}} \quad (1)$$

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Where:

E_c = Modulus of elasticity of concrete

$E_c = \gamma_c^{1.5}\,(0.043)\sqrt{f_c'} \approx 4729.77\sqrt{f_c'}$ MPa

γ_c = Density of concrete (kg/m^3)

f_c' = Compressive strength of concrete (MPa)

I_g = Gross moment of inertia of the whole section about center of gravity CG (ignoring steel inside section)

I_s = Moment of inertia of steel sections about CG of composite section

A_g = Total area of gross composite section (without deducting any of steel sections or vertical reinforcing steel)

A_s = Steel sections area in strengthened RC section (composite section)

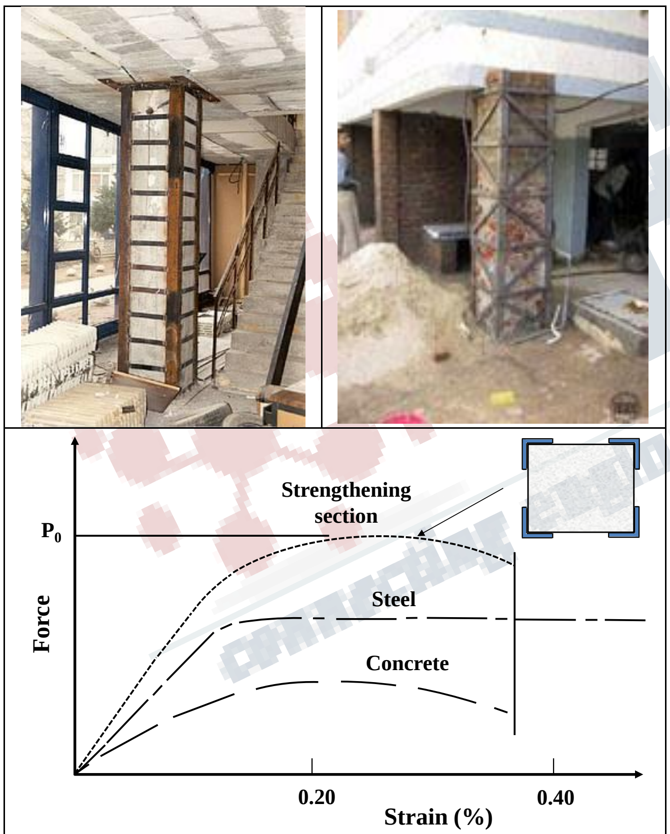

Fig. 3 Strengthening of RC columns with Steel Jacketing

IV. PREVIOUS MODELS (AXIAL FORCE)

First model

According to Euro-code No. 4 [1], the ultimate load of composite columns can be expressed by the following equation (Fig. 4):

$$P_u = f_{cd}\, b^2 \left[1 + 2.02 \left\{ w_s \left[1 - \frac{2}{3}\frac{(b-2l_{ang})^2}{b^2}\right]\left[1 - \frac{s}{2b}\right]^2 \right\}^{0.87}\right] \quad (2)$$

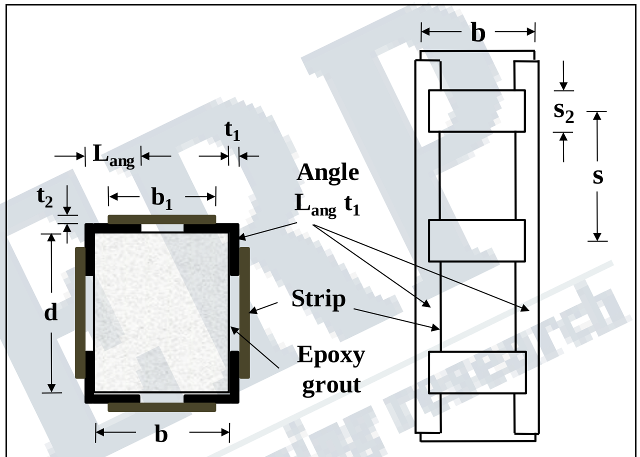

Fig. 4 Component of steel jacketing

Where:

$$w_s = \rho_s \frac{F_{y,strip}}{f_{cd}}$$

f_{cd} = Compressive strength of unconfined concrete

b = Side dimension of RC column

ρ_s = Ratio of steel battens in the area of: b s

s = Spacing of steel strips

L_{ang} = Side of (Length) of a steel angle

$F_{y,strip}$ = Yield stress of strip

Second model

Calderon et al. [6] proposed a design equation for determining the ultimate load that is carried by a RC column strengthened with steel angles and battens. The formula is founded on the analysis of failure mechanisms observed in experimental and numerical approaches performed on full-scale specimens. Finally, the proposal was verified by comparing the results obtained from application of proposed formula, laboratory specimens test and FE models test. However, the proposed design formula is expressed by this Eq.

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$$P_u = 0.85\, b\, d\, f_c' + A_{sr} f_{yr} + 2.5 f_1 b d + N_L \quad (3)$$

Where:
b, d = Side dimension of RC column
f_c' = Compressive strength of concrete
A_{sr} , f_{yr} = Area of longitudinal steel and its yield stress
f_1 = Confinement pressure
N_L = Axial force carried by angles = $N_0 [1 - e^{-m s_2}]$
N_0 = Load carried by concrete

$$m = \frac{4 \mu \upsilon_c}{b\left[1 - \upsilon_c + \frac{bE_c}{2t_2 E_s}\right]}$$

The parameters f_1 and N_L are calculated by considering two possible types of failure modes: failure by yielding of angles or failure due to yielding of strips of the strengthened column. The following section deals with the earlier two cases:
Failure caused by yielding of angles. Failure by yielding of angles is one of the criteria in which angles are buckled in the middle portion of two strips. When it happens it is obvious that the angles are no longer able to confine the concrete.

$$f_1 = \frac{q_h \sqrt{2}}{b} \quad \text{or} \quad q_h = \frac{16}{L_{ang}^2} M_p$$

μ = the friction co-efficient ≈ 0.50
b = the side of column
υ_c = Poisson's ratio of concrete ≈ 0.20
s_2 = width of strip; t_2 = thickness of strip
E_s and E_c = elastic modulus of caging steel and concrete respectively.

Experimental axially loaded model:

Figure (5) shows a section of an experimental RC column model [2] after strengthening (composite situation) via four steel angles.
Data:
$L_x = L_y = 100$ cm , b = d = 150 mm , $s_2 = 50$ mm
s = 170 mm
$f_c' = 37$ MPa , $F_y = 485$ MPa , $f_{yr} = 400$ MPa

Required: failure load ?

One angle: L 30 x 30 x 3 $W_t = 0.12$ KN/m
$A_s = 174\ mm^2$, $I_x = I_y = 1.4\ cm^4$
$r_x = r_y = 9.0$ mm

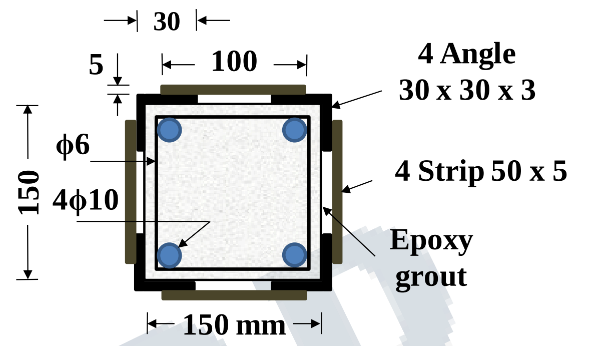

Fig. (5)

Equation (2):

$$P_u = f_{cd}\, b^2 \left[1 + 2.02 \left\{ w_s \left[1 - \frac{2}{3}\frac{(b - 2l_{ang})^2}{b^2}\right] \left[1 - \frac{s}{2b}\right]^2 \right\}^{0.87}\right]$$

$$w_s = \rho_s \frac{F_{y,strip}}{f_{cd}} = \frac{2(L_{ang})}{b}\frac{F_{y,strip}}{f_{cd}} = \frac{2(30)}{150}\frac{485}{37} = 5.24$$

$$P_u = 37\,(0.15)^2 \left[1 + 2.02 \left\{5.24 \left[1 - \frac{2}{3}\frac{(150 - 60)^2}{(150)^2}\right] \left[1 - \frac{170}{2(150)}\right]^2 \right\}^{0.87}\right]$$

= 2138 KN versus 2190 KN (exp.)

V. SUGGESTED METHOD, ULTIMATE STRENGTH METHOD OF STRENGTHENING (AXIAL FORCE & BENDING)

No buckling case

The following equations are used to compute structural capacity of column subjected to combined axle load and bending moment. It applied on short column ($L_e / r_{min} \le 40$ or $L_e / b \le 12$):

$$\left(\frac{P_u}{P_o}\right)^2 + \left(\frac{M_u}{M_o}\right) \le 1 \qquad (3)$$

Where:

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L_e = Effective length of column
b = Column dimension in the direction of buckling
P_o = Axial force (no bending):

$$P_o = 0.85\, f_c'\, A_c + A_s F_y + A_{sr} f_{yr}$$

A_s , A_c = Areas of steel and concrete sections
A_{sr} , f_{yr} = Area and yield stress of steel reinforcement
M_o = Plastic moment of steel section (no axial):

$$M_o \approx F_y Z_y$$

Z_y = Plastic Section Modulus (about week-axis of section)
P_u , M_u = Applied factored axial force and bending moment

Buckling case (Fig. 6)

The following equations are used to compute structural capacity of column subjected to combined axle load and bending moment that applied on long column ($L_e / r_{min} > 40$ or $L_e / b > 12$):

$$\left(\frac{P_u}{P_{cr}}\right)^2 + \frac{\delta M_u}{M_o} \le 1 \qquad (4)$$

P_{cr} = Critical axial load is computed from one of these equations:

$$\left.\begin{aligned} KL < KL_c &\Rightarrow P_{cr} = P_o\left[1 - 0.5\left(\frac{KL}{KL_c}\right)^2\right] \\ KL \ge KL_c &\Rightarrow P_{cr} = \pi^2 EI / (KL)^2 \end{aligned}\right\} \qquad (5)$$

KL = Effective length of column

$$KL_c = \pi\sqrt{\frac{EI}{0.5P_o}}$$ = Maximum effective length

Where:
$EI = E_s I_s + 0.5 E_c I_c$
E_s = 200000 MPa
γ_c = Unit weight of Concrete (Kg / m^3)
δ = Constant

$$\delta = \frac{0.6 + 0.4\alpha}{1 - (P_u / P_c)} \ge 1$$

α = The ratio between bending moments at the ends of the slender column, the signal is negative if the moments at the ends of the column are opposite in the direction.

α = – 0.5 , According to AISC 1970 , ACI 318 - 71
For thin columns in frame structures exposed to lateral displacement:

$$\alpha = 1$$

P_c = Axial load that causes buckling or:

$$P_c = \pi^2 E I / (k L)^2$$

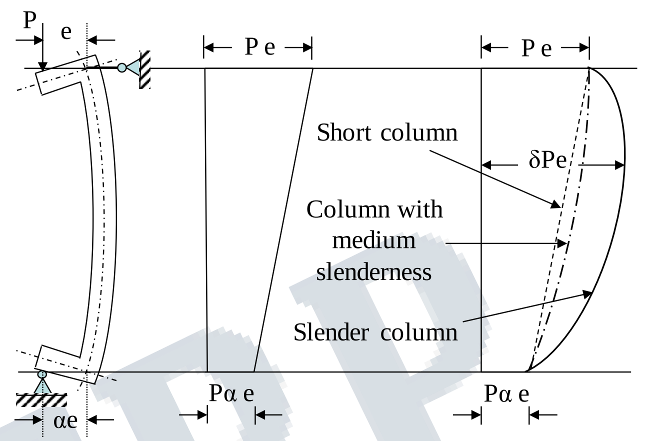

Fig. 6 Behavior of short, medium and short columns

Numerical example:

Figure (7) shows a section of a RC column after strengthening (composite situation) via four steel angles consisting.

L_x = 7 m , L_y = 5 m

Exposed to factored axial force and bending moments about x-axis:

P_u = 3500 kN , M_u = 300 kN.m.

Other data:

One angle: L 102 x 102 x 7.9 , W_t = 0.12 KN/m

A_s = 15.48 cm^2 , $I_x = I_y$ = 154.4 cm^4 , $r_x = r_y$ = 31.5 mm

f_c' = 20 MPa , F_y = 250 MPa , f_{yr} = 400 MPa

Required: Is the column sufficient or not after the strengthening?

Solution:

Check the RC column capacity without strengthening:

$$P_n = \frac{bhf_c'}{[3he/d^2] + 1.18} + \frac{A_s' f_y}{[e/(d-d')] + 0.5} \qquad (6)$$

$$P_u = \varphi P_n \,, \quad \varphi = 0.90$$

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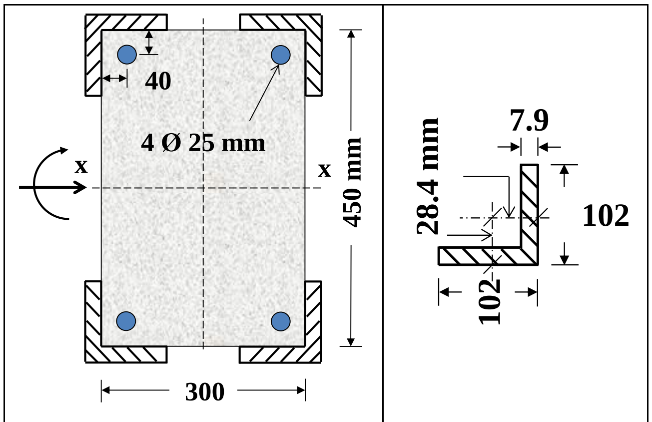

Fig. 7

$$A_s = A_s' = 4\ Ø\ 25 = 19.63\ cm^2$$

$$e = 300 / 3500 = 0.0857\ m = 8.57\ cm$$

$$P_n = \frac{0.30(0.45)(20)}{[3(0.45)(0.0857)/0.41^2]+1.18} + \frac{9.82(10)^{-4}(400)}{[0.0857/(0.41-0.04)]+0.5}$$

$$= 1982.09\ KN$$

1982.09 (0.90) << 3500 KN

Section needs strengthening

Check buckling of RC column:

About x axis: $L_x / h = 700 / 450 = 1.56 < 12$

About y axis: $L_y / b = 500 / 300 = 1.67 < 12$

No buckling

$$A_s = A_s' = 4\ Ø\ 25 = 19.63\ cm^2$$

e = 300 / 3500 = 0.0857 m e = 8.57 cm

$$P_n = \frac{0.30(0.45)(20)}{[3(0.45)(0.0857)/0.41^2]+1.18} + \frac{9.82(10)^{-4}(400)}{[0.0857/(0.41-0.04)]+0.5} = 1982.09\ KN$$

1982.09 (0.90) << 3500 KN

Section needs strengthening

Strengthening study

Local buckling requirement for one angle:

$$\frac{b}{t} \le \sqrt{\frac{3E_s}{F_y}}\ ,\quad \frac{102}{7.9} \le \sqrt{\frac{3(200000)}{250}}$$

2.91 < 48.99 o.k.

$$E_c = 4729.77\sqrt{f_c'} = 4729.77\sqrt{20} = 21\ 152.17\ MPa$$

$$EI = E_s I_s + 0.5 E_c I_c$$

$A_s = 4\ [15.48] = 61.92\ cm^2$, $A_{sr} = 1\ Ø\ 25 = 4.91\ cm^2$

$61.92 + 19.63 = 81.55\ cm^2$

$A_c = 30\ (45) – 19.63 = 1330.37\ cm^2$

$$P_0 = 0.85\ f_c'\ A_c + A_s F_y + A_{sr} f_{yr}$$

$P_0 = [0.85\ (20)\ (1330.37) + 61.92\ (250) + 19.63\ (400)]\ (10)^{-4}\ (10)^3 = 4594.83\ KN$

$$M_0 = F_y Z_x + f_{yr} Z_{xr}$$

$M_0 = 4\ [250\ (15.48)\ (20.45) + 400\ (4.91)\ (18.50)]\ (10)^{-6}\ (10)^3 = 461.90\ KN.m.$

About x-x

$$I_{sx} = 4\ [154.4 + 15.48\ (18.50)^2 + 4.91\ (20.45)^2]$$

$$= 30\ 023.22\ cm^4$$

$$I_{cx} = \frac{30(45)^3}{12} – 4\ (4.91)\ (18.50)^2$$

$$= 221\ 090.71\ cm^4$$

$$(EI)_x = 200000\ (30\ 023.22)\ (10)^{-8} + 0.5\ (21\ 152.17)\ (221\ 090.71)\ (10)^{-8}$$

$$= 83.43\ MN.m^2$$

$$(KL)_x = 7.0\ m\ <\ KL_c = \pi\sqrt{\frac{EI}{0.5P_0}}$$

$$KL_c = \pi\sqrt{\frac{83.43}{0.5(4.59483)}} = 18.93\ m$$

$$P_{cr} = P_0\left\{1 – 0.5\left(\frac{KL}{KL_c}\right)^2\right\}$$

$$P_{cr} = 4594.83\left\{1 – 0.5\left(\frac{7.0}{18.93}\right)^2\right\}$$

$$= 4280.68\ KN$$

About y-y

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$$I_{sy} = 4\,[154.4 + 15.48\,(12.95)^2 + 4.91\,(11)^2]$$
$$= 13\,378.18\ \text{cm}^4$$
$$I_{cy} = \frac{45(30)^3}{12} - 4\,(4.91)\,(11)^2$$
$$= 98\,873.56\ \text{cm}^4$$
$$(EI)_y = 200000\,(13\,378.18)\,(10)^{-8} + 0.5\,(21\,152.17)\,(98\,873.56)\,(10)^{-8}$$
$$= 37.21\ \text{MN.m}^2$$

$$(KL)_y = 5.0\ \text{m} \quad < \quad KL_c = \pi\sqrt{\frac{EI}{0.5P_0}}$$
$$KL_c = \pi\sqrt{\frac{37.21}{0.5(4.59483)}} = 12.64\ \text{m}$$
$$P_{cr} = P_0\left\{1 - 0.5\left(\frac{KL}{KL_c}\right)^2\right\}$$
$$P_{cr} = 4594.83\left\{1 - 0.5\left(\frac{5.0}{12.64}\right)^2\right\}$$
$$= 4235.34\ \text{KN}$$

4280.68 KN > 4235.34 KN
Critical about Y-Y

About x-x

$$P_c = \pi^2\frac{EI}{(KL)^2} = \pi^2\frac{83.43(10)^3}{(7.0)^2}$$
$$= 16\,804.51\ \text{KN}$$
$$P_u = 3500\ \text{KN}\ ,\ M_u = 300\ \text{KN.m.}$$
$$\alpha = 1.0\ ,\quad \delta = \frac{0.5 + 0.4\alpha}{1 - (P_u/P_c)}$$
$$\delta = \frac{0.6 + 0.4(-0.5)}{1 - (3500/16804.51)} = \frac{0.40}{1 - (0.2083)} = 0.5052$$

About y-y

$$P_c = \pi^2\frac{EI}{(KL)^2} = \pi^2\frac{37.21(10)^3}{(5.0)^2}$$
$$= 14\,689.92\ \text{KN}$$
$$P_u = 3500\ \text{KN}\ ,\ M_u = 300\ \text{KN.m.}$$

$$\alpha = 1.0\ ,\quad \delta = \frac{0.5 + 0.4\alpha}{1 - (P_u/P_c)}$$
$$\delta = \frac{0.6 + 0.4(-0.5)}{1 - (3500/14689.92)} = \frac{0.40}{1 - (0.2383)} = 0.5251$$

0.5251 > 0.5052 Critical about Y-Y

$$\left(\frac{P_u}{P_{cr}}\right)^2 + \frac{\delta\,M_u}{M_0} \le 1.0$$
$$\left(\frac{3500}{4235.34}\right)^2 + \frac{0.5251(300)}{(461.90)} = 0.68 + 0.34$$
$$= 1.02 \approx 1\ \text{o.k.}$$

CONCLUSION

- Column strengthening is a quick solution to mitigate the deficiency of load carrying capacity of RC columns. Strengthening by steel angles is the easiest and also an effective method among all other methods
- The research has been concentrated on strengthening of RC columns exposed to axial load and bending moment by packing with steel angles. This research has been systematically accommodating to both the student engineer and the scientific researcher. The packaging here is to encircle RC column with steel elements and then fill the gap between steel elements and column with a non-shrinkage concrete grout.
- The research showed how to use steel angles in the strengthening and rehabilitation of RC columns in order to improve the level of structural performance and durability without further damage to these columns.
- The research has detailed the most convenient equations currently used in the calculations of the strengthening and rehabilitation of RC columns according to ultimate strength methods, in the presence of buckling and the absence of buckling, in a clear scientific and professional manner.
- Steel sections with a thickness of less than 3 mm should not be used in the strengthening process so as not to be subject to local deformities.

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