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Experimental and Theoretical Study of Reinforced Concrete Columns with Poor Confinement Retrofitted by Thermal Post Tension Steel Jacketing

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Abstract: An effective enhancement of the reinforced concrete columns with low ductility can be accomplished thru increasing its confinement. Confinement generally is provided by lateral reinforcing in columns sections. If lateral reinforcing is insufficient, use of external devices such as FRP, steel or reinforced concrete jacketing is effective for columns retrofitting. In this study, steel jacketing with thermal post tension, as an external confinement, is proposed. In order to evaluate the efficiency of this method, theoretical and experimental approaches are used. The theoretical approach is based on solving the plane strain equation of a section considering nonlinear behavior of concrete. Confinement pressure will be obtained by solving the equation at each step of applying axial load at the top of the column. To enter confinement pressure term in stress-strain relationship, approach proposed by Mander is used. Modified stress-strain relationship of retrofitted section by the proposed method is also capable of modeling cyclic behavior. A comparison of experimental and theoretical approaches leads to promising results for the proposed approach.

Key words: Steel jacketing, thermal post tension, columns, reinforced concrete, confinement

INTRODUCTION

Columns are among the most important elements of structures as their collapse or severe damage can lead to collapse of building during seismic events. These elements can be part of building or bridges. One of the basic approaches in retrofitting of reinforced concrete structures is ductility enhancement of columns by increasing their confinement. Effects of confinement on the strength and ultimate strain of the concrete have been studied by Mander *et al*. (1988). The most important reasons of low ductility capacity of RC columns are:

- Lack of lateral reinforcing particularly in plastic hinge regions
- Insufficient splice length in longitudinal reinforcing
- Using plain and smooth surface reinforced bars
- Lack of sufficient concrete strength and usage of high strength steel reinforcing

In this study, thermal post tension steel jacketing for external confinement of RC square section are used for ductility and stiffness improvement. Only square section RC columns with uniformly distributed transverse and longitudinal reinforcing are considered. Both theoretical and experimental approaches are used to assess stress-strain relationships for RC columns confined by the proposed method.

Results of this assessment can lead to modification of the stress-strain curves for concrete confined by post tensioned steel jacketing. These stress-strain curves are the basic tools for studying lateral monotonic and cyclic behavior of RC columns retrofitted by this method.

BASIC EQUATIONS

As mentioned earlier, effects of confinement on the strength and ultimate strain of the concrete have been studied in numerous researches. All researches confirmed that lateral pressure by transverse reinforcing caused improvement in the strength and ultimate strain of RC columns. In this study, relationship proposed by Mander *et al*. (1988) is used to show the effectiveness of proposed method of confinement. Those relationships are shown in Fig. 1.

The parameters shown in Fig. 1 can be derived as following:

$$f_c = \frac{f'_{cc} x r}{r - 1 + x^r} \qquad (1)$$

Where:

f_c = Compression stress
f'_{cc} = Peak of confined compression strength

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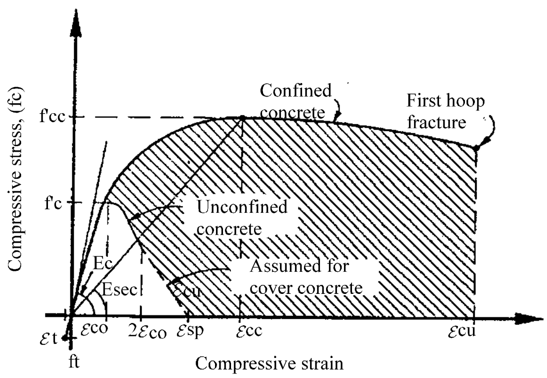

Fig. 1: Stress-strain model for concrete in compression Mander *et al*. (1988)

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}} \tag{2}$$

$$\varepsilon_{cc} = \left[R\left(\frac{f'_{cc}}{f'_{co}} - 1\right) + 1\right]\varepsilon_{co} \tag{3}$$

$$r = \frac{E_C}{E_C - E_{Sec}} \tag{4}$$

Where:

f'_c = Cylindrical compression strength in 28 day

ε_{co} = Strain corresponding to cylindrical compression strength in 28 day

$$E_C = 5000\sqrt{f'_c}.(\text{Mpa}) \tag{5}$$

$$E_{Sec} = \frac{f'_{cc}}{\varepsilon_{cc}} \tag{6}$$

Where:

ε_{cc} = Strain corresponding to peak confined compression strength

E_c = Tangent modules of elasticity

E_{sec} = Secant modules of elasticity

$$f'_{cc} = f'_{co}\left(2.254\sqrt{1 + \frac{7.94 f'_l}{f'_{co}}} - \frac{2f'_l}{f'_{co}} - 1.254\right) \tag{7}$$

Where:

f'_l = Confinement pressure

$$f'_l = 1/2 K_e \rho_s f_{yh} \tag{8}$$

Where:

K_e = Coefficient for type of transverse hoops configuration

f_{yh} = Yielding strength for transverse reinforcing

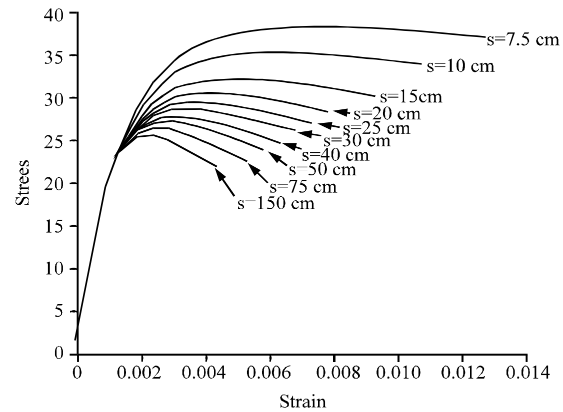

Fig. 2: Stress-strain curves for confined concrete with difference lateral reinforcing distances

$$K_e = \frac{1 - s'/2d_s}{1 - \rho_{cc}} \tag{9}$$

Where:

ρ_{cc} = Longitudinal reinforcing area to confined concrete area ratio

ρ_s = Transverse reinforcing volume to confined concrete volume ratio

s' = Distance between hoops in height of column

d_s = Transverse hoops diameter

Mander *et al*. (1988) relationships for confined concrete by 10 mm diameter transverse reinforcing at difference distances is shown in Fig. 2.

THEORETICAL APPROACH

Plain strain elasticity equation: In this approach deformations of column due to increase in axial load is considered. Using steel angle profiles will guarantee deformation compatibility between steel jacketing and concrete column section thru confinement pressure between them as following.

$$\Delta_x - \Delta_{1x} = \Delta_{2x} \tag{10}$$

Where:

Δ_x, Δ_{1x}, Δ_{2x} are introduced in Fig. 3.

Pressure distribution between angle profile and concrete column section via steel jacketing will be obtained as shown in Fig. 4.

To simplify the equations, final pressure distribution in the form of Fig. 5 is assumed.

For the column section subjected to above distribution a combination of uniform and parabolic distributions for Airy functions are considered.

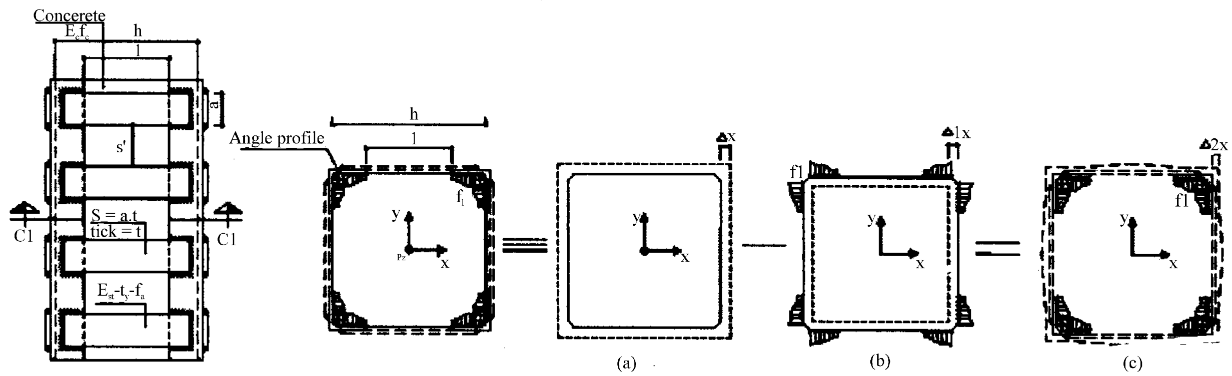

Fig. 3: Compatibility relationship between steel jacketing and concrete section

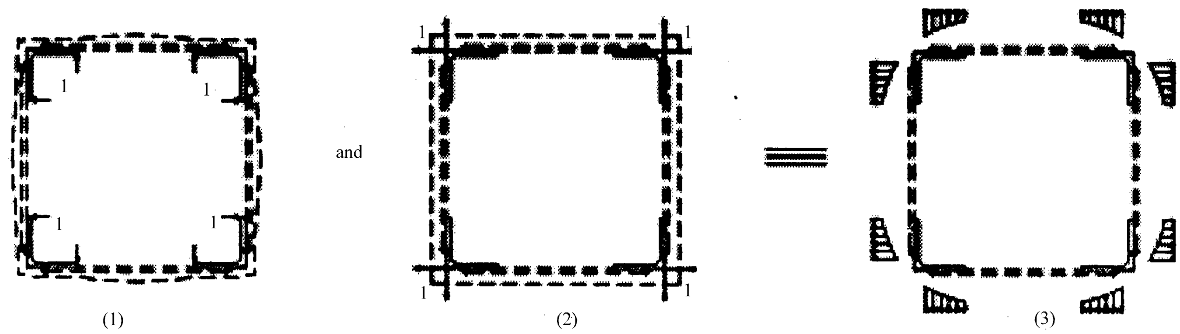

Fig. 4: Pressure distribution

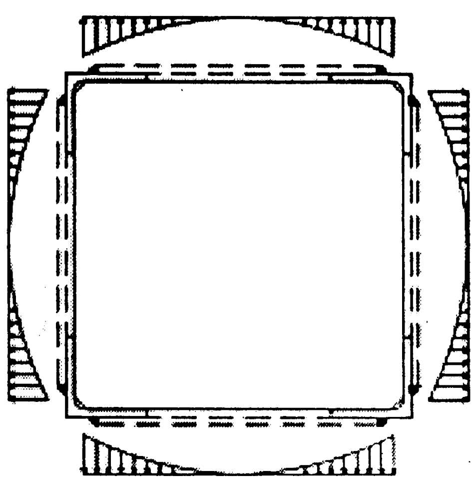

Fig. 5: Assumed final pressure distribution

Airy function for uniform distribution:

$$f_2(x,y) = \frac{C_{20}}{2}x^2 + \frac{C_{02}}{2}y^2 \tag{11}$$

$$\sigma_{x1} = \frac{\partial^2 f_2}{\partial y^2} = C_{02} \tag{12}$$

$$\sigma_{y1} = \frac{\partial^2 f_2}{\partial x^2} = C_{20} \tag{13}$$

$$\tau_{xy1} = -\frac{\partial^2 f_2}{\partial x \partial y} = 0 \tag{14}$$

If: $C_{20} = C_{02} = -Ah^2$

Where:
h: Dimension of column section

Airy function for parabolic distribution:

$$f_4(x,y) = \frac{C_{40}}{4\times 3}x^4 + \frac{C_{22}}{2}x^2y^2 + \frac{C_{04}}{4\times 3}y^4 \tag{15}$$

$$\sigma_{x2} = \frac{\partial^2 f_4}{\partial y^2} = C_{22}x^2 + C_{04}y^2 \tag{16}$$

$$\sigma_{y2} = \frac{\partial^2 f_4}{\partial x^2} = C_{40}x^2 + C_{22}y^2 \tag{17}$$

$$\tau_{xy2} = -\frac{\partial^2 f_4}{\partial x \partial y} = -2C_{22}xy \tag{18}$$

By applying the compatibility relationship:

$$\frac{\partial^4 f_4}{\partial x^4} + 2\frac{\partial^4 f_4}{\partial x^2 \partial y^2} + \frac{\partial^4 f_4}{\partial y^4} = 0 \quad (19)$$

$$2C_{22} = -(C_{40} + C_{04}) \quad (20)$$

Using symmetry leads to:

$$C_{22} = -C_{40} = -C_{04} \quad (21)$$

If: $C_{40} = C_{40}$ = -B and C_{22} = B

$$\sigma_{x2} = C_{04}(-x^2 + y^2) \quad (22)$$

$$\sigma_{y2} = C_{40}(x^2 - y^2) \quad (23)$$

$$x = h/2 \rightarrow \sigma_{x2} = C_{04}(y^2 - x^2) = B(y^2 - \frac{h^2}{4}) \quad (24)$$

$$y = h/2 \rightarrow \sigma_{y2} = C_{40}(x^2 - y^2) = B(x^2 - \frac{h^2}{4}) \quad (25)$$

$$\tau_{xy2} = 2Bxy \quad (26)$$

Shear stress is not effective in enlarging or reducing the size of the section.

Combination of the two above distributions shown on Fig. 6, 7 leads to following distribution in Fig. 8.

$$\sigma_x = B(x^2 - y^2) - \frac{Ah^2}{4} \quad (27)$$

$$\sigma_y = B(y^2 - x^2) - \frac{Ah^2}{4} \quad (28)$$

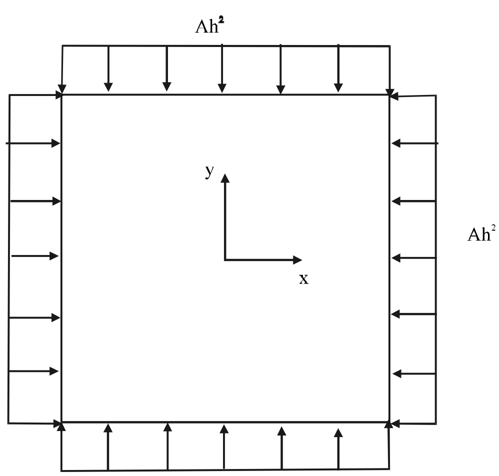

Fig. 6: Uniform distribution

If: A=B
In the plane strain case:

$$\varepsilon_x = \frac{1}{E}((1-\nu^2)\sigma_x - \nu(1+\nu)\sigma_y) \quad (29)$$

$$\varepsilon_y = \frac{1}{E}((1-\nu^2)\sigma_y - \nu(1+\nu)\sigma_x) \quad (30)$$

Strain distribution in external edge along of x direction

$$\varepsilon_x = \frac{1}{E_c}((1-\nu_c{}^2)(B(x^2 - \frac{h^2}{4}) - \frac{Ah^2}{4}) - \nu_c(1+\nu_c)(B(\frac{h^2}{4} - x^2) - \frac{Ah^2}{4}) \quad (31)$$

$$\Delta'_x = \int_{-h/2}^{h/2} \varepsilon_x dx \quad (32)$$

$$\Delta_{1x} = \frac{\Delta'_x}{2} \rightarrow \Delta_{1x} = \frac{(1+\nu_c)(6\nu_c - 5)Bh^3}{24E_c} \text{ In each corner} \quad (33)$$

Where:
Δ_{1x} = Parameter that introduced in Fig. 3 and Eq. 10

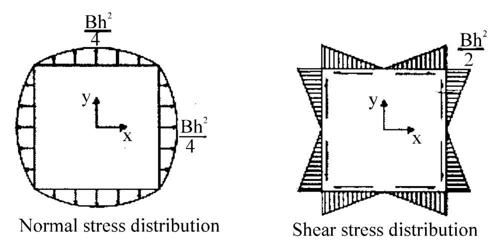

Fig. 7: Shear and Normal stress distributions

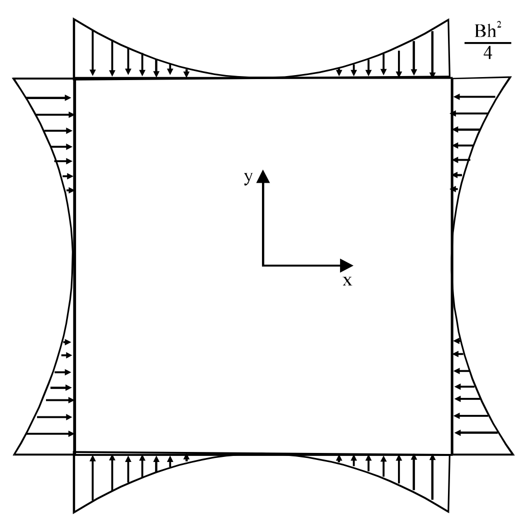

Fig. 8: Combined distribution

Steel jacketing force with above confinement pressure (Fig. 9) can be obtained in the following equations

$$2F = \int_{-h/2}^{h/2} -\sigma_x . d_c . dy \rightarrow F = -\frac{ah^3}{24}(3(B-A)-B) \tag{34}$$

$$\Delta''_x = \frac{Fl}{ES} = \frac{Bah^3 l}{24E_{st}S} \tag{35}$$

$$\Delta_{2x} = \Delta''_x / 2 \rightarrow \Delta_{2x} = \frac{Bd_c h^3 l}{48E_{st}S} \tag{36}$$

Where:

Δ_{2x}: Parameter that introduced in Fig. 3 and Eq 10

When, the column is under axial loading, (Fig. 10) lateral strain will be obtained by the following equation.

$$\Delta_x = \frac{\varepsilon_x . h}{2} = \frac{\nu \varepsilon_z h}{2} \tag{37}$$

$$\frac{\nu \varepsilon_z h}{2} - \frac{B(1+\nu_c)(6\nu_c - 5)h^3}{24E_c} = \frac{Bd_c h^3 l}{48E_{st}S} \tag{38}$$

$$B = \frac{\nu_c \varepsilon_z}{\frac{(1+\nu_c)(6\nu_c-5)h^2}{12E_c} + \frac{d_c h^2 l}{24E_{st}S}} \tag{39}$$

$$\sigma_x = \frac{\nu_c \varepsilon_z}{-\frac{(1+\nu_c)(6\nu_c-5)h^2}{12E_c} + \frac{d_c h^2 l}{24E_{st}S}}\left((x^2 - y^2) - \frac{h^2}{4}\right) \tag{40}$$

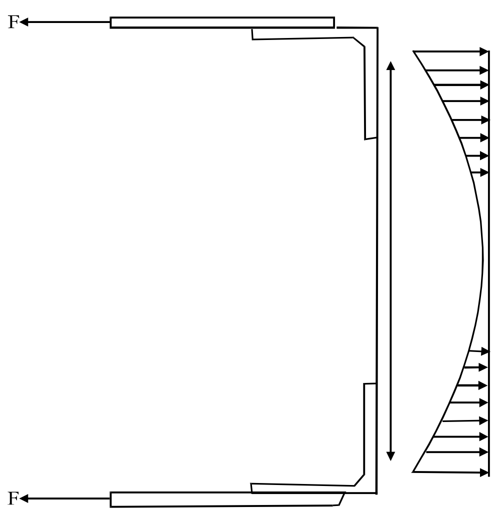

Fig. 9: Steel jacketing under internal pressure

At x=h/2 = Stress distribution will be as the following equation:

d_c = Centre to centre transverse plates distance in height

$$\sigma_x = -\frac{\nu_c \varepsilon_z}{-\frac{(1+\nu_c)(6\nu_c-5)h^2}{12E_c} + \frac{d_c h^2 l}{24E_{st}S}} y^2 \tag{41}$$

Then, average confinement pressure (Fig. 11) can be calculated by the following equation.

$$f_{lp} = \frac{1}{ah}\int \sigma_x dA \tag{42}$$

$$f_{lp} = \frac{\nu_c \varepsilon_z}{-\frac{(1+\nu_c)(6\nu_c-5)}{E_c} + \frac{d_c l}{2E_{st}S}} \tag{43}$$

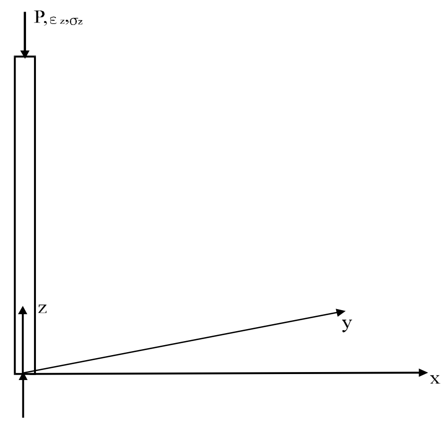

Fig. 10: Column under axial loading

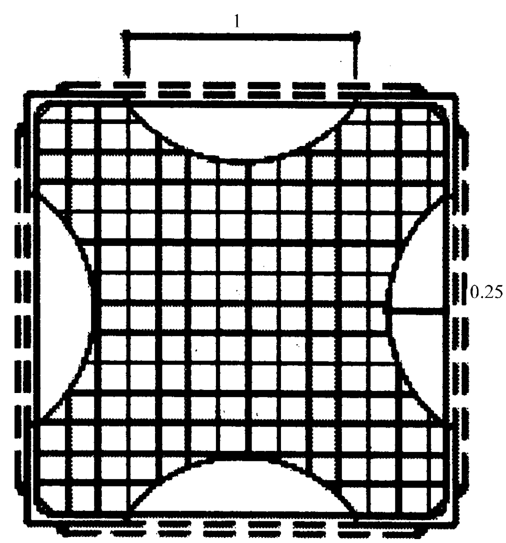

Fig. 11: Effective confinement area

Where:
f_{lp} = Passive confinement pressure

Thermal post tensioning will created an active confinement in the column section.

$$\varepsilon_t = \alpha \Delta T \tag{44}$$

Where:
α = Thermal Expansion ratio
ΔT = Difference of environment and applied temperature

$$f_{la} = \frac{\alpha \Delta T E_{st} S}{d_c h} \tag{45}$$

$$f_{lt} = f_{lp} + f_{la} \tag{46}$$

$$f_{lt} = \frac{\alpha \Delta T E_{st} S}{d_c h} + \frac{\nu_c \varepsilon_z}{-\frac{(1+\nu_c)(6\nu_c - 5)}{E_c} + \frac{d_c l}{2E_{st} S}} \tag{47}$$

In order to modify f_{lt} due to the effective confinement area one should consider the following modifications.

$$\beta_1 = \frac{A_{in}}{A_g} = \frac{h^2 - \frac{2}{3} l^2}{h^2} \tag{48}$$

$$\beta_2 = \frac{a}{s'} \tag{49}$$

And finally: $f_{lm} = \beta_1 . \beta_2 . f_{lt}$

$$f_{lm} = \beta_1 \beta_2 \left(\frac{\alpha \Delta T E_{st} S}{d_c h} + \frac{\nu_c \varepsilon_z}{-\frac{(1+\nu_c)(6\nu_c - 5)}{E_c} + \frac{d_c l}{2E_{st} S}}\right) \tag{50}$$

$$\nu_c = \nu_{co}\left(C_1\left(\frac{\varepsilon_z}{\varepsilon_{cc}}\right) + 1\right) \le 0.5 \tag{51}$$

C_1 = Can be obtained by Fam and Rizcalla (2001) Eq. (52):

$$C_1 = 1.914\left(\frac{f_{lm}}{f'_{co}}\right) + 0.719 \tag{52}$$

Where:
ν_{co} = Original poison ratio
ε'_z = Strain corresponding to maximum confined stress
f'_{co} = Unconfined strength of concrete

To apply the proposed approach, after calculation of f_{lm}in each step of and using Eq. 1-9, relationships by Mander *et al.* (1998) for confined concrete, the values of f'_{cc} ε'_{cc} can be calculated.

In start of calculation, E_c is assumed as $15000\sqrt{f'_{co}}$ then modified with $\frac{\sigma_{zi} - \sigma_{zi-1}}{\varepsilon_{zi} - \varepsilon_{zi-1}}$ coefficient until calculation convergences. By this approach nonlinearity of concrete can be considered. In this study, the procedure is programmed in MATLAB software.

Experimental approach: This approach has been used for verification of theoretical approach of this study. Four short concrete column specimens are constructed then retrofitted by steel jacketing technique without any internal reinforcing.

Properties of specimens: Concrete compression testing machine used for axial testing. As the top and bottom compressor plates of this machine at most can be opened about 330 mm and its bearing capacity was 3000 kN thus dimensions of specimens are selected as 150×150×330 mm.

Steel jacketing is applied after 28 day curing. Three standard cylinder specimens are provided from concrete for compression strength measuring. Results of compression strength have been shown in Table 1.

Average of compression strength for three specimens is 25.5 MPa. Four steel specimens have been provided from angle and plate elements and corresponding to ASTM standard have been tested under tension as shown in Fig. 12 and 13.

Four short concrete column specimens are named as the following.

NP2 : Non post tensioning and two transverse plates in height
NP3 : Non post tensioning and three transverse plates in height

Table 1: Compression strength of specimens

No. of specimen	Compression strength (MPa)
C1	26.2
C2	25.7
C3	24.8

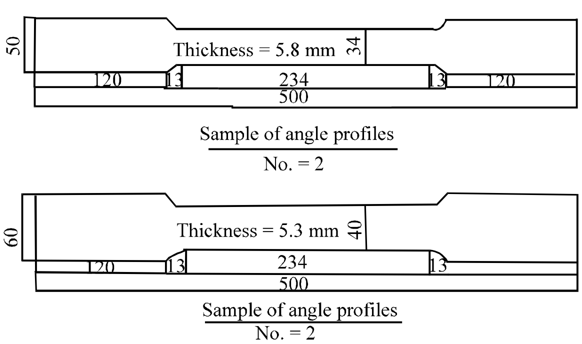

Fig. 12: Sample of steel elements for tension testing

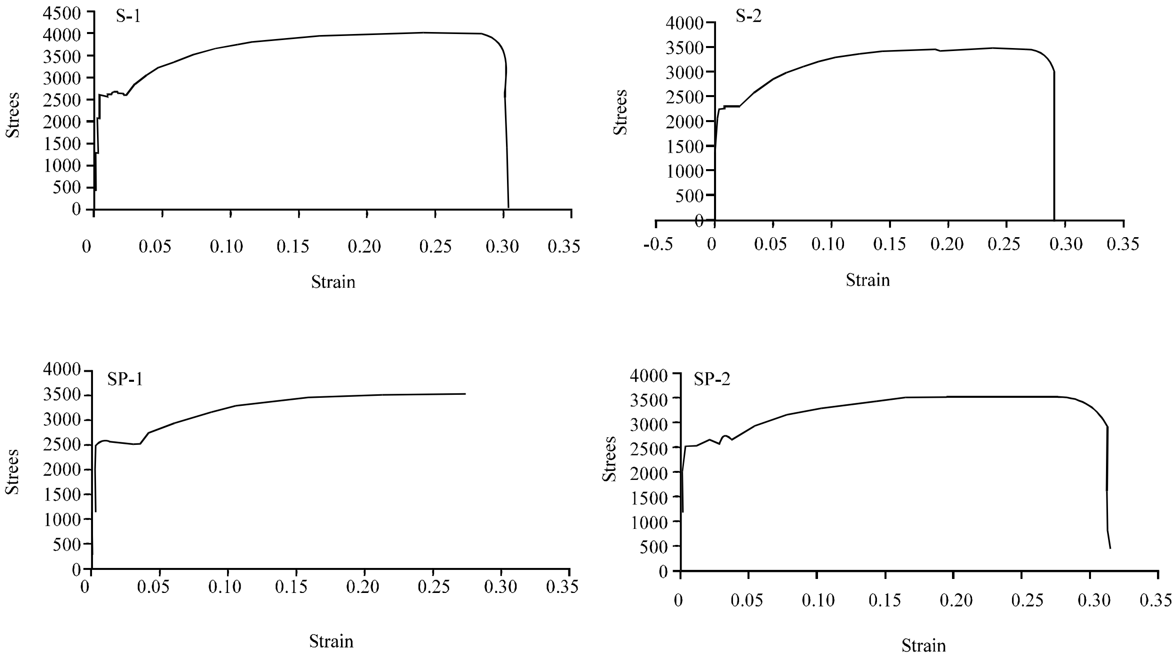

Fig. 13: Stress-strain diagram for angle profile (S-1, 2) and steel plate (Sp-1, 2) steel samples

Fig. 14: Post tensioning and gauges installation

P3-200 : Post tensioning with 200°C (ΔT) and three transverse plates in height

P2-200 : Post tensioning with 200°C (ΔT) and two transverse plates in height

Post tensioning is conducted by welding one side of plate to angle and increasing temperature to ΔT = 200°C with fire device and then welding another side of plate to angle. After 3 days strain gauges and LVDT s are installed as shown in Fig. 14.

Test machine has tuned to 1 kN/SEC rate of loading to the specimens.

COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESULTS

Strain-stress diagrams obtained from tests for four specimens are shown in Fig. 15.

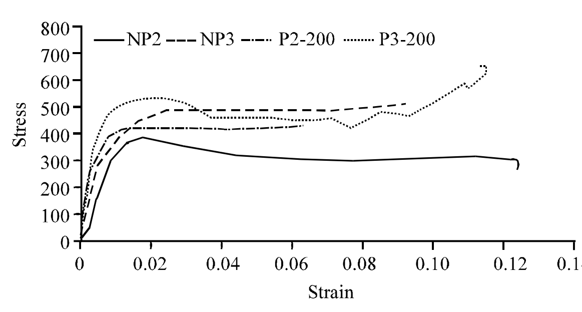

Fig. 15: Stress-strain diagrams for four specimens

Theoretical relationships as have considered only confinement effects on stress and strain enhancement. Surface friction between concrete and angles has caused some of axial force to be transferred to steel angles and increases axial capacity.

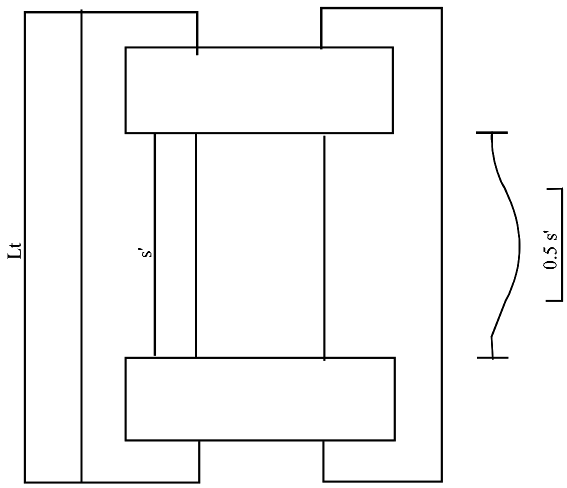

Fig. 16: Steel angle P_s modification factor

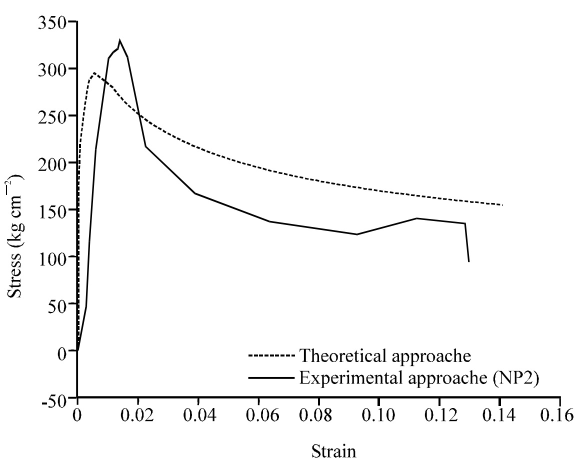

Fig. 17: NP2 specimen experiment compare with theoretical results

For comparing theoretical and experimental results real force resisted by concrete should be calculated as following.

$$P_c = P_t - P_s \tag{53}$$

Where:
P_s: Steel angle force
P_t: Total force
P_c: Concrete force

Steel force P_s has been obtained by strain recorded during axial loading by strain gauges installed on angle profile by considering a modification factor as shown in Fig. 16.

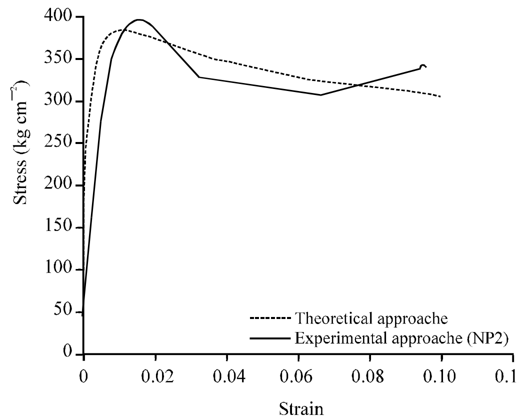

Fig. 18: NP3 specimen experiment compare with theoretical results

$$\beta_3 = \frac{L_t - 0.5s'}{L_t}$$

Experimental and theoretical results with regard to concrete stress-strain are shown in Fig. 17 and 18.

CONCLUSION

- Steel jacketing caused increase in stiffness, ductility and strength of axial strain-stress behavior of concrete
- Steel jacketing retrofitting will prevent brittle crushing mode of failure in column
- Post tensioning has caused active confinement and further enhancement in axial stiffness and strength
- Existing low distance between transverse plates in height has caused slop of softening branch of curves to diminish
- The results of experimental and theoretical approaches for axial stress-strain and confinement pressure can be used in lateral cyclic and monotonic behavior assessment of columns

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