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 paper steel jacketing with thermal post tension, as an external confinement, is proposed. In order to evaluate the efficiency of this method, theoretical is 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.

KEYWORDS: STEEL JACKETING, THERMAL POST TENSION, COLUMNS, REINFORCED CONCRETE, CONFINEMENT

1. 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 numerous researchers such as Richard in 1928, Sheikh and Uzumeri in 1982, Fafitis and Shah in 1985 and Mander et al. in 1988 [1]. The most important reasons of low ductility capacity of RC columns are:
1. Lack of lateral reinforcing particularly in plastic hinge regions.
2. Insufficient splice length in longitudinal reinforcing.
3. Using plain and smooth surface reinforced bars.
4. 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.

2. BASIC EQUATIONS:

As mentioned before, effects of confinement on the strength and ultimate strain of the concrete have been studied by numerous researchers [1]. All researchers 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 [1] is used to show the effectiveness of proposed method of confinement. Those relationships are presented in Figure 1.

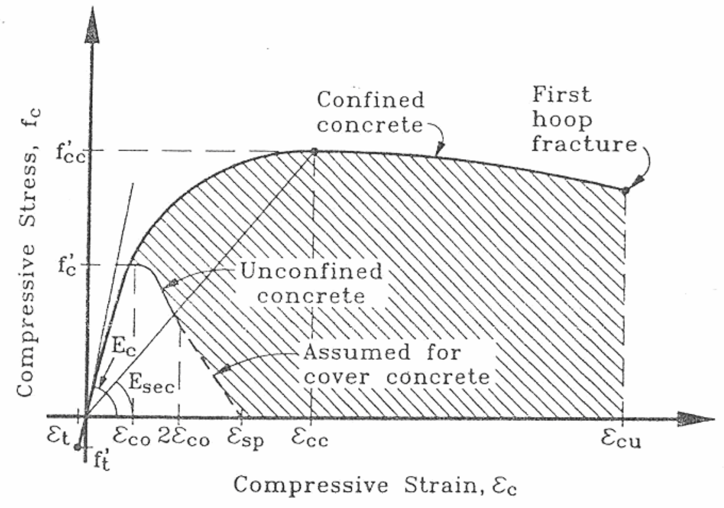


Figure 1: Stress-strain model for concrete in compression [1].

The parameters shown in figure 1 can be derived as following:

$$f_c = \frac{f_{cc}' \ xr}{r-1+x^r} \tag{2.1}$$

Where, f_c : compression stress, f_{cc}' :peak of confined compression strength

$$x = \frac{\varepsilon_c}{\varepsilon_{cc}} \tag{2.2}$$

$$\varepsilon_{cc} = \left[R\left(\frac{f'_{cc}}{f_{co}'}-1\right)+1\right]\varepsilon_{co} \tag{2.3}$$

$$r = \frac{E_C}{E_C - E_{Sec}} \tag{2.4}$$

Where, f'_c : cylindrical compression strength in 28 day, ε_{co} :strain corresponding to cylindrical compression strength in 28 day

$$E_C = 5000\sqrt{f'_c}.(Mpa) \tag{2.5}$$

$$E_{Sec} = \frac{f'_{cc}}{\varepsilon_{cc}} \tag{2.6}$$

Where, ε_{cc} :strain corresponding to peak of confined compression strength, E_C :tangent modules of elasticity, E_{sec} :sSsecant modules of elasticity.

$$f'_{cc} = f'_{co}\left(2.254\sqrt{1+\frac{7.94 f'_1}{f'_{co}}} - \frac{2 f'_1}{f'_{co}} - 1.254\right) \tag{2.7}$$

Where, f'_l :confinement pressure

$$f'_l = 1/2 K_e \rho_s \ f_{yh} \tag{2.8}$$

Where, K_e : coefficient for type of transverse hoops configuration, f_{yh} : yielding strength for transverse reinforcing.

$$K_e = \frac{1 - s^{'}/2d_s}{1 - \rho_{cc}} \tag{2.9}$$

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.

3. THEORETICAL APPROACH:
3.1) 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.

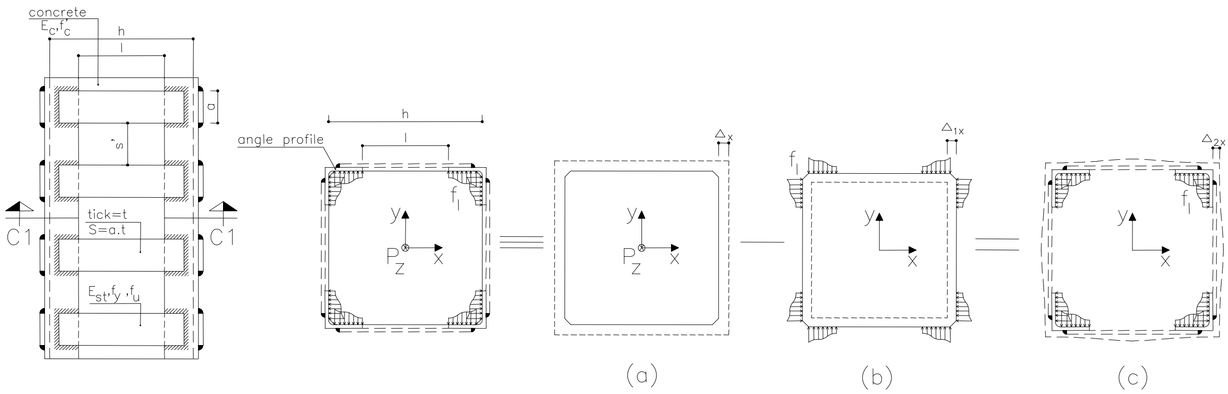


Figure 2: Compatibility relationship between steel jacketing and concrete section

$$\Delta_x - \Delta_{1x} = \Delta_{2x} \tag{3.1}$$

Where, $\Delta_x, \Delta_{1x}, \Delta_{2x}$: are introduced in Figure 2

Pressure distribution between angle profile and concrete column section via steel jacketing will be obtained as shown in Figure 3.

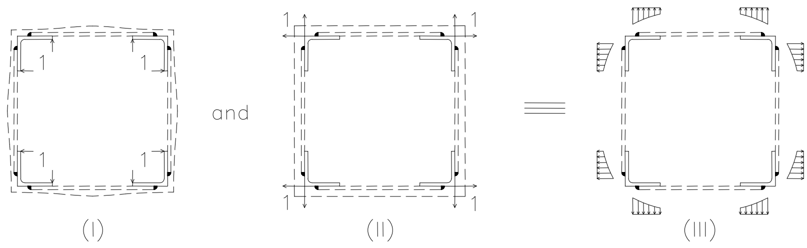


Figure 3: Pressure distribution

To simplify the equations, final pressure distribution in the form of Figure 4 is assumed.

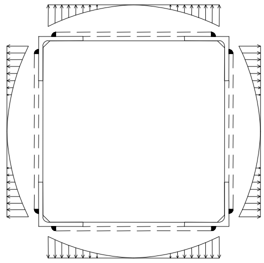


Figure 4: Assumed final pressure distribution

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

3.1.1) Airy function for uniform distribution

$$f_2(x,y) = \frac{C_{20}}{2}x^2 + \frac{C_{02}}{2}y^2 \quad (3.2)$$

$$\sigma_{x1} = \frac{\partial^2 f_2}{\partial y^2} = C_{02} \quad (3.3)$$

$$\sigma_{y1} = \frac{\partial^2 f_2}{\partial x^2} = C_{20} \quad (3.4)$$

$$\tau_{xy1} = -\frac{\partial^2 f_2}{\partial x \partial y} = 0 \quad (3.5)$$

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

Where, h is dimension of column section

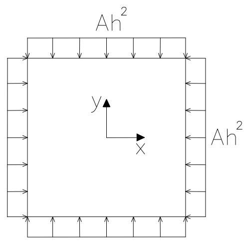


Figure 5: uniform distribution

3.1.2) Airy function for parabolic distribution

$$f_4(x,y) = \frac{C_{40}}{4\times 3}x^4 + \frac{C_{22}}{2}x^2y^2 + \frac{C_{04}}{4\times 3}y^4 \quad (3.6)$$

$$\sigma_{x2} = \frac{\partial^2 f_4}{\partial y^2} = C_{22}x^2 + C_{04}y^2 \quad (3.7)$$

$$\sigma_{y2} = \frac{\partial^2 f_4}{\partial x^2} = C_{40}x^2 + C_{22}y^2 \quad (3.8)$$

$$\tau_{xy2} = -\frac{\partial^2 f_4}{\partial x \partial y} = -2C_{22}xy \quad (3.9)$$

By applying the compatibility relationship:

$$\frac{\partial^4 f_4}{\partial x^4} + 2\frac{\partial^4 f_4}{\partial x^2 \partial y^2} + \frac{\partial^4 f_4}{\partial y^4} = 0 \tag{3.10}$$

$$2C_{22} = -(C_{40} + C_{04}) \tag{3.11}$$

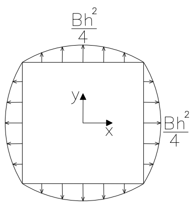
Using symmetry leads to:

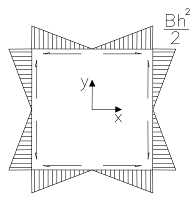
$$C_{22} = -C_{40} = -C_{04} \tag{3.12}$$

If: $C_{40} = C_{04} = -B$ and $C_{22} = B$

$$x = h/2 \rightarrow \sigma_{x2} = C_{04}(y^2 - x^2) = B(y^2 - \frac{h^2}{4}) \tag{3.13}$$

$$y = h/2 \rightarrow \sigma_{y2} = C_{40}(x^2 - y^2) = B(x^2 - \frac{h^2}{4}) \tag{3.14}$$





Normal stress distribution Shear stress distribution
Figure 6: Shear and Normal stress distributions

Combination of the two above distributions shown on figures 5, 6 leads to following distribution in figure 7.

$$\sigma_x = B(x^2 - y^2) - \frac{Ah^2}{4} \tag{3.15}$$

$$\sigma_y = B(y^2 - x^2) - \frac{Ah^2}{4} \tag{3.16}$$

If: A=B

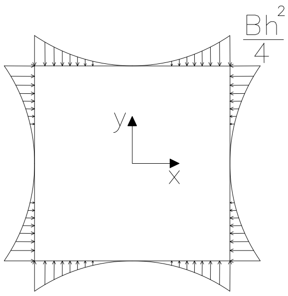


Figure 7: Combined distribution

In the plane strain case strain distribution in external edge along of x direction

$$\varepsilon_x = \frac{1}{E_c}((1-\nu_c{}^2)(B(x^2 - \frac{h^2}{4}) - \frac{Ah^2}{4}) - \nu_c(1+\nu_c)(B(\frac{h^2}{4} - x^2) - \frac{Ah^2}{4}) \tag{3.17}$$

$$\Delta'_x = \int_{-h/2}^{h/2} \varepsilon_x dx \tag{3.18}$$

$$\Delta_{1x} = \frac{\Delta'_x}{2} \rightarrow \Delta_{1x} = \frac{(1+\nu_c)(6\nu_c - 5)Bh^3}{24E_c} \quad \text{In each corner} \tag{3.19}$$

Where, Δ_{1x} : Parameter that introduced in Figure 2 and Eqn 3.1.
Steel jacketing force with above confinement pressure can be obtained in the following equations.

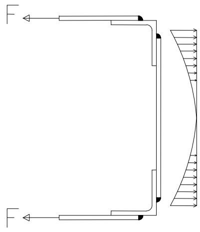


Figure 8: Steel jacketing under internal pressure

$$\Delta''_x = \frac{Fl}{ES} = \frac{Bah^3 l}{24E_{st}S} \tag{3.20}$$

$$\Delta_{2x} = \Delta''_x / 2 \rightarrow \Delta_{2x} = \frac{Bd_c h^3 l}{48E_{st}S} \tag{3.21}$$

Where, Δ_{2x} : Parameter that introduced in Figure 2 and Eqn 3.1.
When the column is under axial loading, lateral strain will be obtained by the following equation.

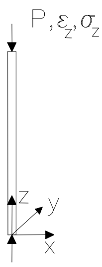


Fig 9: Column under axial loading

$$\Delta_x = \frac{\varepsilon_x .h}{2} = \frac{\nu\varepsilon_z h}{2} \tag{3.22}$$

$$\frac{\nu\varepsilon_z h}{2} - \frac{B(1+\nu_c)(6\nu_c - 5)h^3}{24E_c} = \frac{Bd_c h^3 l}{48E_{st}S} \tag{3.23}$$

At x=h/2 stress distribution will be as the following equation:
d_c : Centre to centre transverse plates distance in height

$$\sigma_x = -\frac{\nu_c \varepsilon_z}{-\frac{(1+\nu_c)(6\nu_c - 5)h^2}{12E_c} + \frac{d_c h^2 l}{24E_{st}S}} y^2 \tag{3.24}$$

Then, average confinement pressure can be calculated by the following equation.

$$f_{lp}=\frac{\nu_c\varepsilon_z}{-\frac{(1+\nu_c)(6\nu_c-5)}{E_c}+\frac{d_c l}{2E_{st}S}} \tag{3.25}$$

Where, f_{lp} : Passive confinement pressure

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

α : Thermal Expansion ratio

ΔT : Difference of environment and applied temperature

$$f_{la}=\frac{\alpha\Delta T E_{st}S}{d_c h} \tag{3.26}$$

$$f_{lt}=f_{lp}+f_{la} \tag{3.27}$$

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

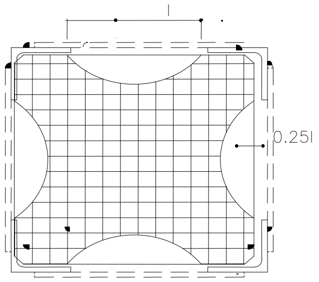


Figure 10: Effective confinement area

$$\beta_1=\frac{A_{in}}{A_g}=\frac{h^2-\frac{2}{3}l^2}{h^2} \tag{3.28}$$

$$\beta_2=\frac{a}{s'} \tag{3.29}$$

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

$$f_{lm}=\beta_1\beta_2\left(\frac{\alpha\Delta T E_{st}S}{d_c h}+\frac{\nu_c\varepsilon_z}{-\frac{(1+\nu_c)(6\nu_c-5)}{E_c}+\frac{d_c l}{2E_{st}S}}\right) \tag{3.30}$$

$$\nu_c=\nu_{co}\left(C_1\left(\frac{\varepsilon_z}{\varepsilon_{cc}}\right)+1\right)\le 0.5 \tag{3.31}$$

C_1 can be obtained by Rizcalla and Fam 2001 [2] Eqn 3.32.:

$$C_1=1.914\left(\frac{f_{lm}}{f'_{co}}\right)+0.719 \tag{3.32}$$

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 ε_z and using Eqns (2.1.) to (2.9.), relationships by Mander et al for confined concrete, the values of $f'_{cc},\varepsilon'_{cc}$ can be calculated.

In start of calculation, E_c is assumed as $15000\sqrt{f'_{co}}$ then modified with $\dfrac{\sigma_{zi}-\sigma_{zi-1}}{\varepsilon_{zi}-\varepsilon_{zi-1}}$ coefficient

until calculation convergences. By this approach nonlinearity of concrete can be considered. In this study the procedure is programmed in MATLAB software.
Theoretical relationships as presented in section 3.1 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.
For comparing theoretical and experimental results real force resisted by concrete should be calculated as following. Experimental work that is another article from these authors and is reviewing in "Journal of Applied Sciences", and theoretical results with regard to concrete stress-strain are shown in Fig 12 .

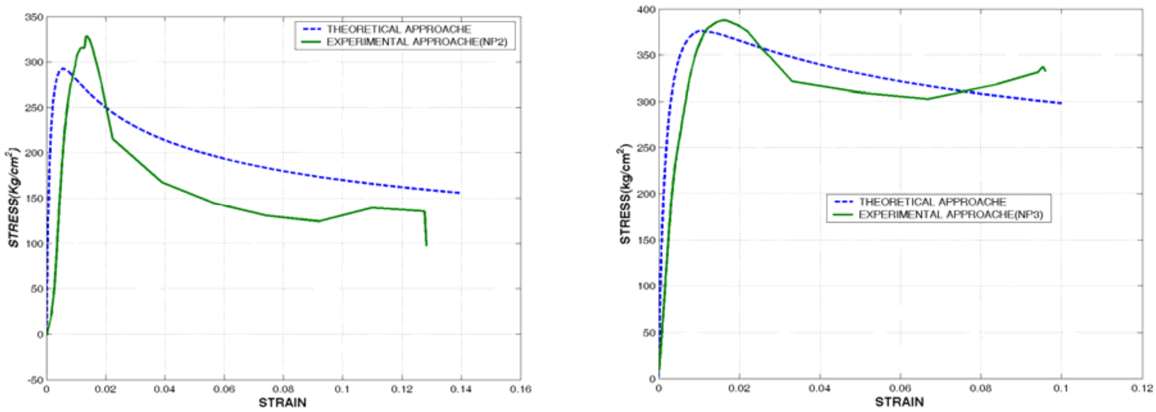


Figure 11: Experiment results compared with theoretical results

Conclusion:

1. Post tensioning has caused active confinement and further enhancement in axial stiffness and strength.
2. Existing low distance between transverse plates in height has caused slop of softening branch of curves to be diminishing.
3. The results of proposed theoretical approach for axial stress-strain and confinement pressure can be used in lateral cyclic and monotonic behavior assessment of columns.

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