# EXPERIMENTAL INVESTIGATION ON SQUARE STEEL TUBED RC COLUMNS UNDER AXIAL COMPRESSION

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## Abstract

**This paper reports an experimental study on the behaviors and modes of failure of the square steel tubed RC columns subjected to concentrically axial load, applied directly to the RC core. The main variables were the compressive strength of the concrete, the wall thickness of the steel tube and the tie spacing. All square columns were 150 mm in width and 750 mm in height. A total of 36 specimens, including 24 tubed RC columns and 12 reference RC columns, were tested. It was found that the tubed RC columns have a ductile-like with strain hardening, elastic-perfectly plastic and strain-softening behavior. The mode of failure of the columns is in progressive mode with very large axial deformability. The wall thickness of the steel tube and the compressive strength of concrete are the major factors, influencing the behaviors, axial compressive capacity and modes of failure of the columns. Since the behaviors of the column are different from those of the CFT column, the ACI 318 design equation considerably overestimates the axial compressive capacity of the column. Finally, based on the results obtained from this study, the design equation for the tubed RC column was proposed.**

**Keywords:** **Tubed RC column, concrete-filled steel tube column, axial compression, reinforced concrete column**

## Introduction

Steel member has the advantages of high strength and ductility. Concrete member has the advantages of high compressive strength and stiffness. A composite column is defined as a compression member which may either be a concrete encased steel column or a concrete filled steel tube (CFT) column. The CFT column, as an example shown in Figure 1.a, has gained acceptance for high-rise buildings as an alternative to pure reinforced concrete or pure steel column during the past decades. Traditionally, the CFT column is subjected to axial load both on the steel tube and on the concrete core and the steel tube performs as primary longitudinal main reinforcement to the concrete core. It has beneficial qualities of both materials and has the following advantages: (1) higher strength-to-weight ratio and higher rigidity than conventional reinforced concrete column, (2) high ductility and toughness for

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resisting reversal load, (3) higher load carrying capacity due to the composite action between steel and concrete and (4) saving in material and construction time (Saw and Liew, 2000).

In the past years, different design codes for the CFT column have been formulated. All codes assume full interaction between the steel tube and the concrete core, but neglecting the effect of confinement. According to ACI 318, the plastic resistance (squash load) of a composite column with axial loading is given by the sum of the resistances of the components as follows:

$$N_{ACI} = 0.85 A_c f'_{co} + A_s f_y^s + A_{tube} f_y^{tube}$$

in which $A_c$ , $A_s$ and $A_{tube}$ are cross-sectional area of concrete, steel reinforcement and steel tube, respectively; $f'_{co}$ is cylindrical compressive strengths of the concrete; $f_y^s$ = yielding strength of the main steel reinforcement; and $f_y^{tube}$ = yielding strength of the coupons cut from the steel tube. To prevent local buckling of the steel tube under axial loading, ACI 318 limits the wall thickness ($t$) for rectangular hollow section (RHS) according to the equation:

$$B / t \leq \sqrt{3E_s / f_y^{tube}}$$

where $B$ is the greater width of the steel tube wall and $E_s$ = modulus of elasticity of the steel. However, this limitation is not a necessary requirement for the CFT column (Shanmugam *et al*., 2001).

Xiao *et al.* (2005) proposed a new CFT column system, referred to as confined CFT (CCFT) column system. In this column system, additional transverse reinforcement is designed for the potential plastic hinge region to achieve improved seismic performance in order to provide more efficient confinement effect to the concrete. The concept was investigated by seismic testing model CFT and CCFT column. It was found that the proposed CCFT column system can provide excellent seismic performance.

In recent years, a new type of the composite column called "Tubed column", as an example shown in Figure 1(b), has been increasingly used in the construction of buildings (Tomii *et al*., 1985; Xiao *et al.*, 2005; Han *et al.*, 2008). The term "Tubed column" refers to the function of the steel tube as primarily transverse reinforcement for concrete

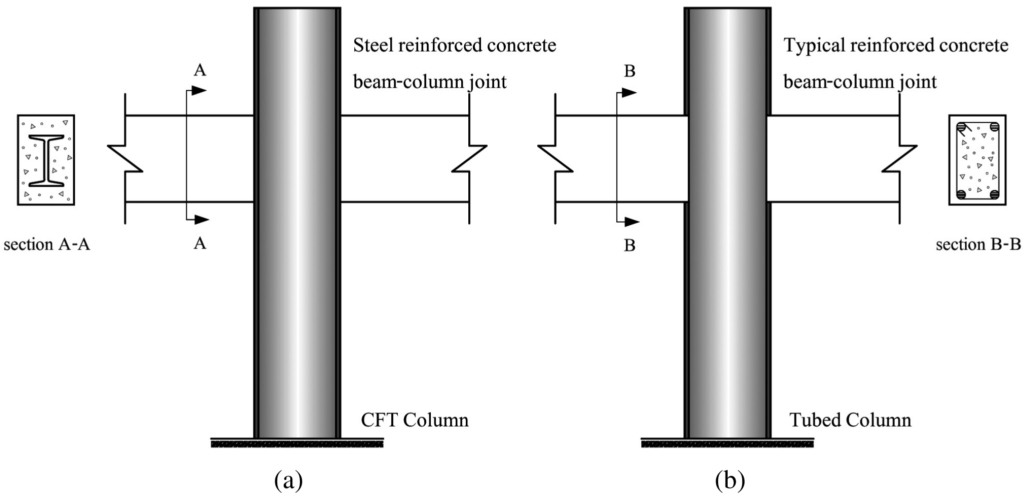



**Figure 1. Two different composite columns: (a) Concrete filled steel tube column with steel reinforced concrete beam-column joint and (b) Tubed column with typical reinforced concrete beam-column joint**

core. It is practically subjected to axially compressive load on the concrete core only. The composite action between the steel tube and concrete core is occurred only in the transverse direction. The beam-column joint of the tubed RC column must be properly detailed in order to minimize the direct transfer of the axial stresses into the tube. This can be done by building gaps between the tube and the beam or the floor or the footing at the ends of the column by following the well-known reinforced concrete beam-column joint (Han *et al.,* 2008), making it easier to construct than the conventional CFT column. Seangatith *et al.* (2008) reported the structural behaviors and mode of failure of square tubed concrete columns. A total of 33 specimens were tested under concentrically axial load applied directly to the concrete core. It was found that the tubed concrete columns have ductile-like behavior. They were failed in progressive mode of failure, which can be considered as localized failure, with a high axial ductility, compared to the reference columns. With the increasing of the ultimate compressive strength of the concrete and the wall thickness of the steel tube, the axial compressive strength of the columns increases. In addition, the E.I.T. 1008-38(4314) specification for composite column was inadequate to predict the strength of the tubed concrete column.

In the past few years, some studies were carried out on the tubed RC columns. Tomii *et al.* (1985) investigated the tubed RC column concept as a method to prevent shear failure and to improve the ductility of short columns in RC frame structures. The investigation was performed by testing model columns under constant axial load and cyclic shear in double curvature condition. The experimental results indicate that the tubed RC column concept can provide excellent improve ductility. Priestley *et al.* (1994) studied on steel jacketing concept used to retrofit existing deficient square RC bridge columns for enhancing shear strength. This concept can be considered as the application of the tubed RC column concept, in which the steel jacket is used to provide additional transverse reinforcement, in order to increase the capacity and ductility of an existing column. The jacket was built by welding steel shells to encase the column to form a tubed RC column. According to the study, the steel jacketing concept can significantly enhance the shear strength of the column.

Although it was found from the literature reviews that the tubed RC column has a potential to be used in structural engineering applications, the applications are still limited due to the lack of information and reliable design criteria. This paper is intended to provide a portion of that need. The main objectives of this experimental study are twofold: first, to report the behaviors and the modes of failure of the square steel tubed RC columns subjected to concentrically axial load applied directly to the RC core and, second, to compare the obtained axial compressive capacity with that of the reference RC columns and the values predicted by ACI 318 design equation and, if necessary, to propose the appropriate design equation.

## Test Specimens and Test Setup

A total of 36 specimens, including 24 tubed RC columns and 12 reference RC columns, were tested under concentrically axial load, applied directly to the RC core. The main variables in this test program were: $f'_{co}$ = 18, 25 and 32 MPa; $t$ = 3.2 and 4.5 mm; and tie spacing, $s$ = 75 mm and 150 mm. A summary of the specimens is presented in Table 1, where $L$ = height of the specimen and is chosen to be 5 times of the width of steel tube to avoid the effect of end conditions, $A_s$ = gross cross cross-sectional area of the specimen, and $\rho = ( A_{tube} + A_s ) / A_g$ = ratio of the cross-sectional area of steel to the gross area of the column.

From Table 1, the test specimens were classified into 3 groups: Group 1 is the reference RC column and Group 2 and 3 are the tubed RC column with $t$ = 3.2 and 4.5 mm, respectively. The RC columns were designed according to the ACI 318 and were tested as reference for comparison purpose. The specimen numbers were designated in the form of C(S)-$f'_{co}$-$t$–$s$, where “C” or “S” represents the reference RC column and the tubed RC column, respectively. For example, the specimen number S-18-3.2-75 is the tubed RC column, having $f'_{co}$ = 18MPa, $t$ = 3.2 mm, and $s$ = 75 mm. Two specimens were tested for each specimen number. Figure 2 shows the details of the column specimens.

The concrete was the ready-mixed concrete produced by Concrete Products and Aggregate Co., Ltd. (CPAC) and was designed for $f'_{co}$ at 28 days of 18, 25, and 32 MPa. Concrete was placed in five layers and each layer was compacted by using a vibrator. The averaged compressive strengths of each type of concrete, tested according to ASTM C39, were found to be 19.6, 26.3, and 32.6 MPa, respectively.

In this study, all square steel tubes, having the width $B$ = 150 mm, were typical cold-formed carbon steel and seam welded by using welding machine. Three coupons were randomly cut from each type of the steel tubes and were tested according to ASTM E8. The $f_y^{tube}$ of the steel tubes with $t$ = 3.2 and 4.5 mm was found to be 312.1 and 391.5 MPa, respectively. Also, three specimens were randomly cut from each type of the steel reinforcements and were tested according to ASTM E8. It was found that the $f_y^s$ of the main steel reinforcement DB12 and the steel tie RB6 was 368.3 and 255.3 MPa, respectively.

Figure 3 shows a schematic view and the picture of the test setup. Specimens were placed in a 2,000 kN SHIMADZU Universal Testing Machine. The axial compressive load was applied pass the top and bottom steel bearing plates, directly to the RC core as shown in Figure 4(a), which is different from that of the CFT columns as shown in Figure 4(b), in which the concrete core and the steel tube were loaded simultaneously. The bearing plates have the dimension of 140 mm by 140 mm wide by 50 mm thick. Two linear variable differential transducers (LVDT) were used to monitor

**Table 1. Summary of the details of the column specimens used in this study**

| Group | Specimen No. | B/t ratio | L/B ratio | $\rho$ (%) | Concrete $A_s$ (mm$^2$) | Concrete $f'_{co}$ (MPa) | Steel tube $A_{tube}$ (mm$^2$) | Steel tube $f_y^{tube}$ (MPa) | RebarDB12 $A_s$ (mm$^2$) | RebarDB12 $f_y^s$ (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | C-18-0-75 | - | - | 2.0 | 22,047 | 19.6 | - | - | 113.1 | 368.3 |
| | C-25-0-75 | - | - | 2.0 | 22,047 | 26.3 | - | - | 113.1 | 368.3 |
| | C-32-0-75 | - | - | 2.0 | 22,047 | 32.6 | - | - | 113.1 | 368.3 |
| | C-18-0-150 | - | - | 2.0 | 22,047 | 19.6 | - | - | 113.1 | 368.3 |
| | C-25-0-150 | - | - | 2.0 | 22,047 | 26.3 | - | - | 113.1 | 368.3 |
| | C-32-0-150 | - | - | 2.0 | 22,047 | 32.6 | - | - | 113.1 | 368.3 |
| 2 | S-18-3.2-75 | 46.9 | 5.0 | 10.2 | 20,145 | 19.6 | 1,833 | 312.1 | 113.1 | 368.3 |
| | S-25-3.2-75 | 46.9 | 5.0 | 10.2 | 20,145 | 26.3 | 1,833 | 312.1 | 113.1 | 368.3 |
| | S-32-3.2-75 | 46.9 | 5.0 | 10.2 | 20,145 | 32.6 | 1,833 | 312.1 | 113.1 | 368.3 |
| | S-18-3.2-150 | 46.9 | 5.0 | 10.2 | 20,145 | 19.6 | 1,833 | 312.1 | 113.1 | 368.3 |
| | S-25-3.2-150 | 46.9 | 5.0 | 10.2 | 20,145 | 26.3 | 1,833 | 312.1 | 113.1 | 368.3 |
| | S-32-3.2-150 | 46.9 | 5.0 | 10.2 | 20,145 | 32.6 | 1,833 | 312.1 | 113.1 | 368.3 |
| 3 | S-18-4.5-75 | 33.3 | 5.0 | 13.5 | 19,312 | 19.6 | 2,567 | 391.5 | 113.1 | 368.3 |
| | S-25-4.5-75 | 33.3 | 5.0 | 13.5 | 19,312 | 26.3 | 2,567 | 391.5 | 113.1 | 368.3 |
| | S-32-4.5-75 | 33.3 | 5.0 | 13.5 | 19,312 | 32.6 | 2,567 | 391.5 | 113.1 | 368.3 |
| | S-18-4.5-150 | 33.3 | 5.0 | 13.5 | 19,312 | 19.6 | 2,567 | 391.5 | 113.1 | 368.3 |
| | S-25-4.5-150 | 33.3 | 5.0 | 13.5 | 19,312 | 26.3 | 2,567 | 391.5 | 113.1 | 368.3 |
| | S-32-4.5-150 | 33.3 | 5.0 | 13.5 | 19,312 | 32.6 | 2,567 | 391.5 | 113.1 | 368.3 |

overall axial shortening of the RC core and to ensure that a uniform compression was imposed on the test specimens. Two strain gages were installed on the exterior wall of the steel tube at the mid-height, as shown in Figure 5, to measure the vertical deformations and perimeter expansion of the steel tube wall and to indirectly monitor the transferring of the axial load from the RC core to the steel tube. Before the beginning of the test, a preload of

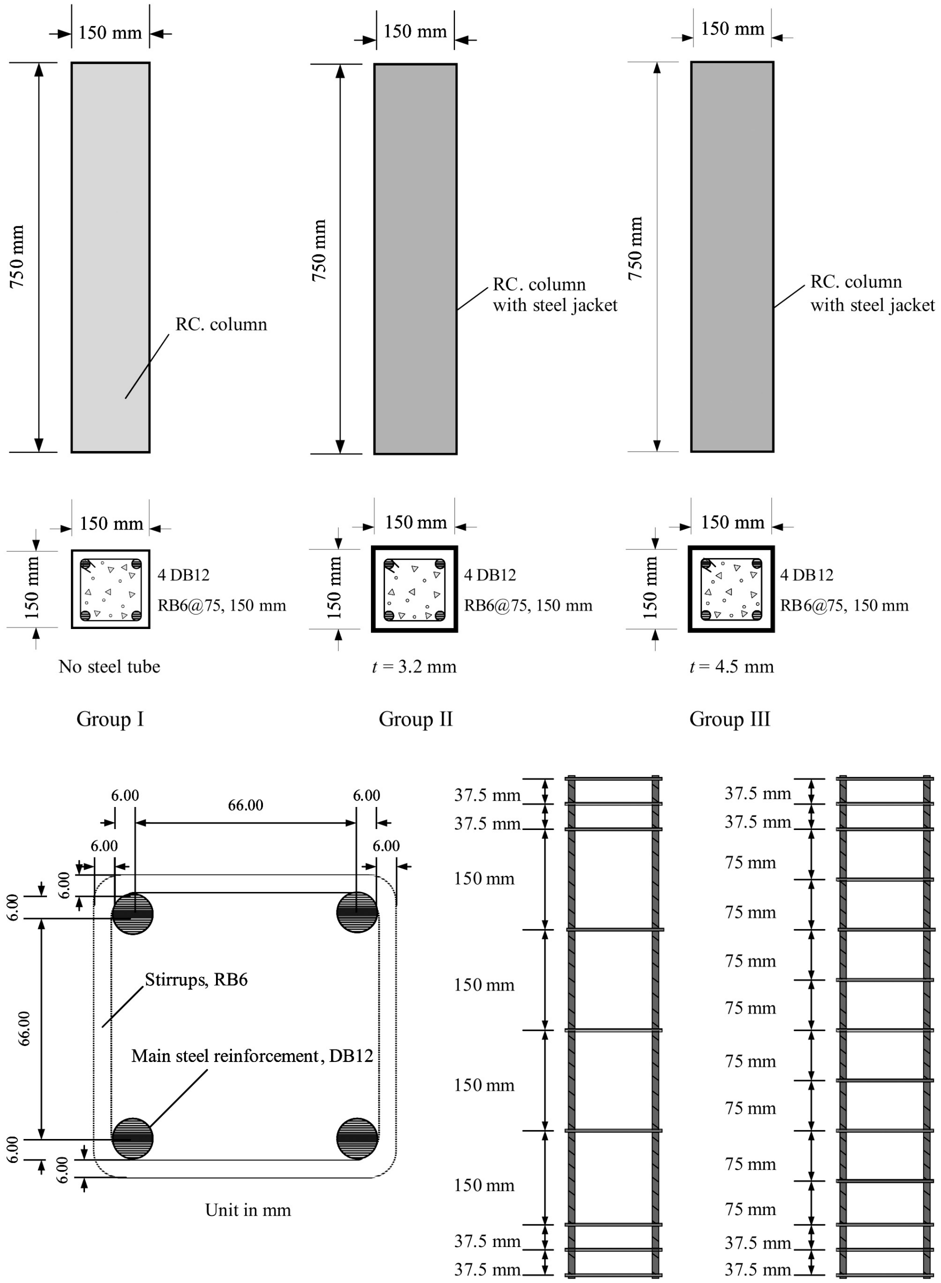
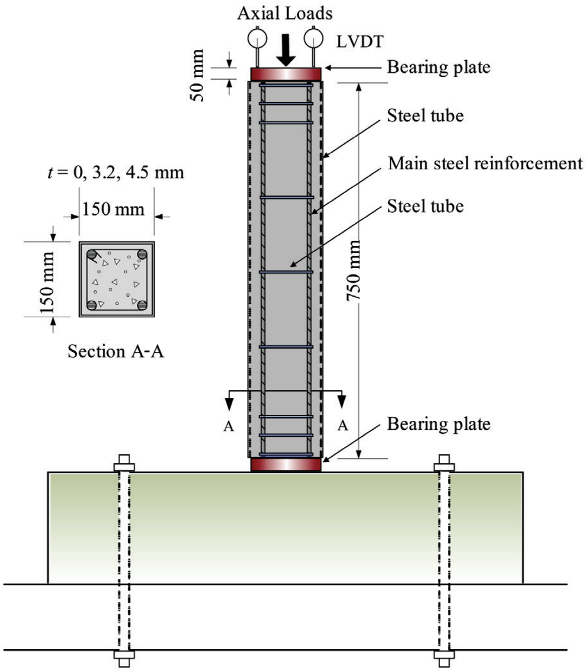
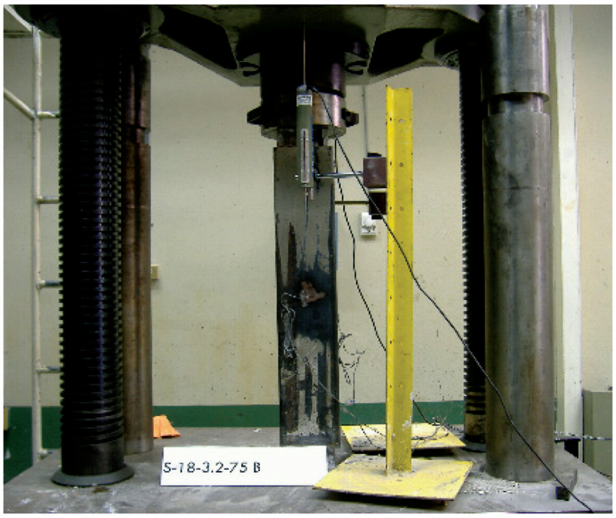



**Figure 2. A schematic view of the details of the test specimens**




(a)




(b)

**Figure 3. Test setup (a) a schematic view and (b) a photograph**

approximately 20% of the predicted axial compressive capacity of the specimens was applied in order to reduce the friction between the steel bearing plates and the specimens, and to balance the uneven bed surfaces. Then, the specimen was unloaded to about 5 kN to seat it

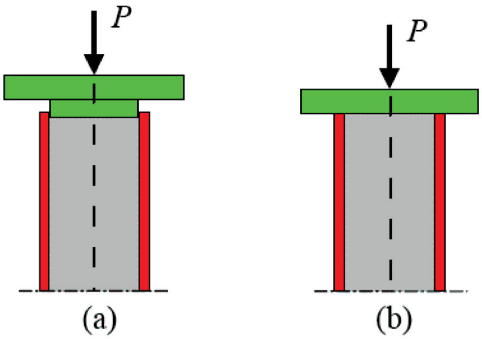



**Figure 4. A schematic view of the application of the axial load for (a) tubed RC column and (b) typical CFT column**

**Figure 5. Strain gage installation at the mid-height of a tubed RC column specimen**

to the testing position. Finally, the specimens were loaded at such a slow rate that the outward local protrusion of the steel tube wall could be carefully observed. A data acquisition system was used to collect the axial load, axial shortening of the RC core and the axial strain and lateral strain of the steel tube wall. Finally, at the end of the test, the modes of failure were recorded.

## Experimental Results and Discussions

### Specimen Behaviors

It should be noted that all of the tests were stopped at about 100 mm axial shortening, without a complete failure, since the maximum depth of the bearing steel plate was reached. Such a large axial deformation, which is about

40 times larger than the ultimate compressive strain of the concrete ($\varepsilon_{c,ult}$), may be very useful in a building subjected to seismic load. However, for the practical purpose, the maximum axial shortening considered here was limited to 20 mm, which is equivalent to the averaged axial strain of the RC core of 0.0267 mm/mm and about 10 times larger than the $\varepsilon_{c,ult}$. Also, the "axial compressive capacity" or $N_{c,\exp}$ of the columns is defined as the maximum axial load occurred within 20 mm of the axial shortening.

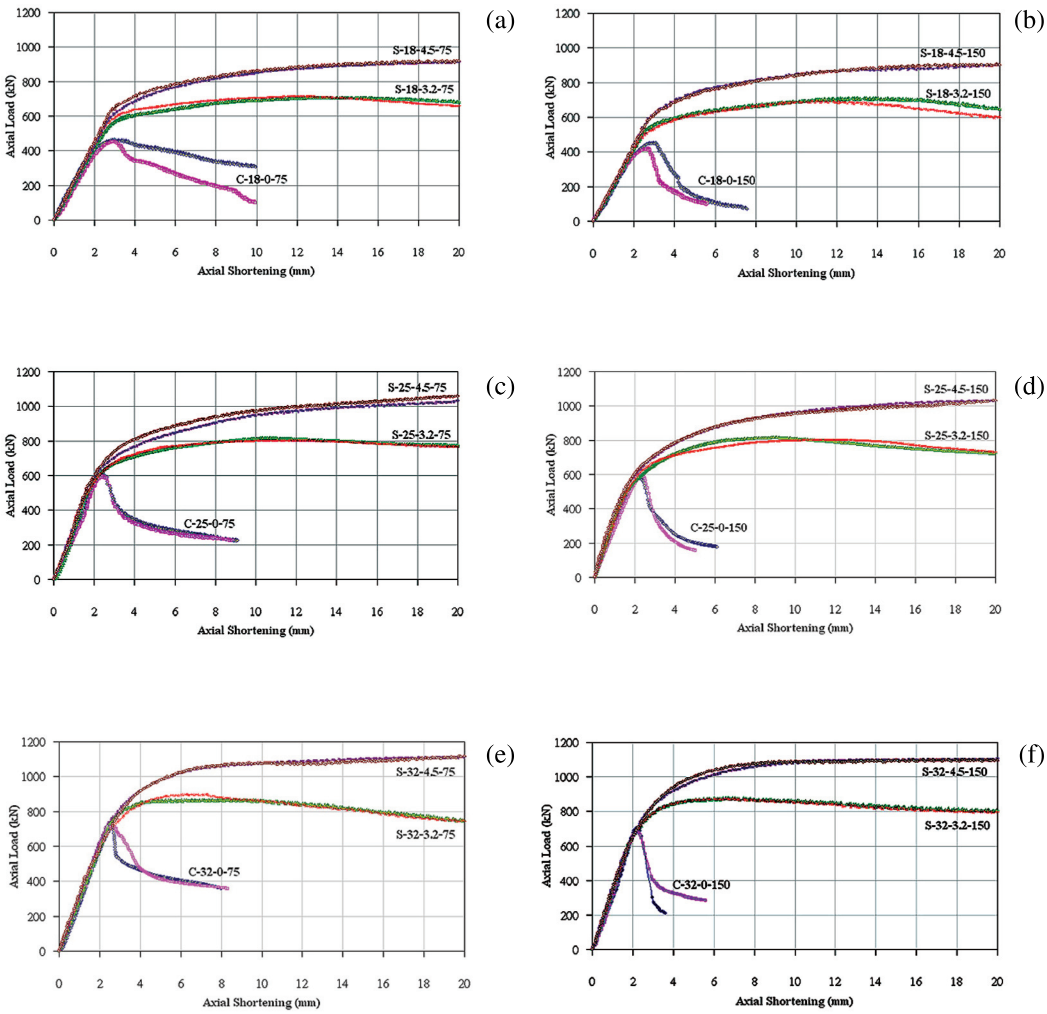



**Figure 6. Axial load versus axial shortening of the RC and tubed RC columns**

**(a) $f'_{co}$ = 18 MPa, $s$ = 75 mm.** **(b) $f'_{co}$ = 18 MPa, $s$ = 150 mm.**

**(c) $f'_{co}$ = 25 MPa, $s$ = 75 mm.** **(d) $f'_{co}$ = 25 MPa, $s$ = 150 mm.**

**(e) $f'_{co}$ = 32 MPa, $s$ = 75 mm.** **(f) $f'_{co}$ = 32 MPa, $s$ = 150 mm.**

Figure 6 shows the axial load versus axial shortening for the RC and the tubed RC columns. The tubed RC columns have linear elastic behavior up to the ultimate compressive strength of the RC column ($N_{u,RC}$) or about 60-70% of their $N_{c,exp}$ loads. This initial part of the curves is nearly identical to that of the RC columns, indicating that the stiffness of the columns is nearly equal. This is due to the fact that, in this early stage, the lateral expansion of the RC core due to the Poisson's effect is small and the steel tube has little restraining effect on the RC core as shown in Figures 7(a) and 7(b). It can also be checked by using the unconfined modulus of elasticity of a composite made with a soft material (RC core) in a rigid tube (steel tube), determined from the method of mechanics of materials, in the form of

$$E_{tubed} = \frac{1-\nu}{(1-2\nu)(1+\nu)} E_{RC} \cdot .$$

If the Poisson's ratio of the RC core is assumed to be 0.1, $E_{tubed} = 1.023E_{RC}$, which agrees well with the obtained test results.

After that, the curves are gradually becoming nonlinear due to the start of the yielding of the main steel reinforcements and the cracking of the concrete underneath the applied load, causing the value of the Poisson's ratio of the concrete approaching 0.5. Thus, the lateral expansion of the RC core begins to increase rapidly and significantly greater than that of the steel tube. This produces the increasing of the lateral pressure at the steel tube wall-concrete interface as a schematic view shown in Figure 7(c), leading to the restraint of the RC core provided by the outer steel tube (Figure 10). Further increasing the axial load results in a noticeable increase of the outward local protrusion of the steel tube wall in the areas near the top and bottom end of the columns (Figures 9(b) and 9(c)), and then, the $N_{c,exp}$ was reached.

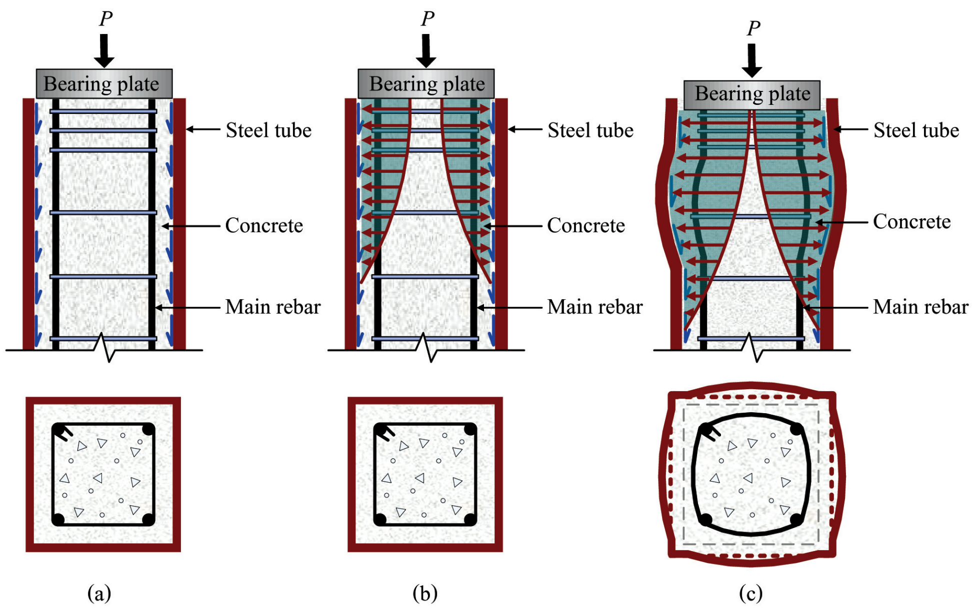



**Figure 7. A schematic view of transferring mechanism of the applied load near the top end of the tubed RC column (a) at the early stage, (b) during linear elastic behavior and c.) during nonlinear behavior**

The tubed RC column exhibited various types of nonlinear behavior, depending mainly on the wall thickness of the steel tube. The columns with 4.5 mm wall thickness tend to exhibit the strain hardening or elastic-perfectly plastic behavior, and those with 3.2 mm tend to exhibit the strain-softening behavior. This is because the steel tube section with thicker wall thickness has larger stiffness to prevent the local protrusion of the steel tube wall due to the lateral expansion of the RC core. The strain hardening behavior was observed in the specimen S-18-4.5-75, S-18-4.5-150, S-25-4.5-75 and S-25-4.5-150 and the elastic-perfectly plastic behavior was observed in the specimen S-32-4.5-75 and S-32-4.5-150. The strain-softening behavior was observed in the specimen S-18-3.2-75, S-18-3.2-150, S-25-3.2-75, S-25-3.2-150, S-32-3.2-75 and S-32-3.2-150.

## Load Transferring Mechanism in the Tubed RC Column

Figure 8 shows an example of the axial load versus the axial strain and the lateral strain on the mid-height of the steel tube of the specimen S-32-4.5. The axial strain has a negative value and the lateral strain has a positive value. The axial load versus axial strain curves can be classified into two parts. In the first part, they have a linear relationship up to 50-60% of the axial compressive capacity, corresponding to the observed linear behavior of the tubed RC columns in Figures 6(e) and 6(f). This indicates that a portion of the axial load linearly transfers to the middle part of the tubed RC columns, through the interfacial shear stress between the steel tube walls and the RC core as a schematic sketch shown in Figure 7 (Han *et al.* 2008). Then, the curves are nonlinear and start to rise gradually and become flatter until the axial load reaches the $N_{c,exp}$ with the axial strains considerably less than the yielding strain of the steel, varying from 740 to 1390 $\mu\varepsilon$ as shown in Table 2, indicating that the full interaction between the steel tube and the RC core does not develop.

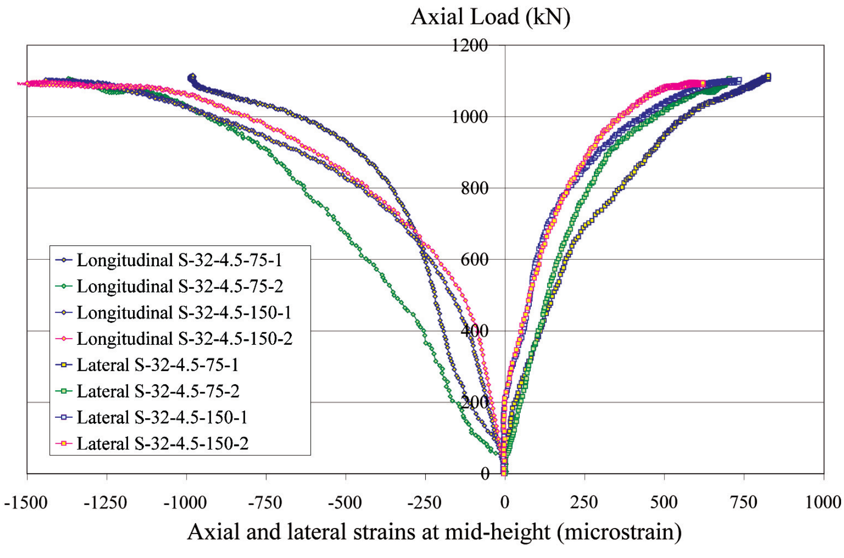



**Figure 8. Axial load versus axial and lateral strains at the mid-height of the tubed RC column specimen S-32-4.5**

**Modes of Failure**

Figure 9(a) shows a typical failure mode of the reference RC columns. The failure of the RC columns starts with the crack and the spall off of the concrete shell outside the ties. Then, the concrete core crushes and the longitudinal steel reinforcement buckle outward between ties at the ultimate compressive strength. Figures 9(b) and 9(c) show the failure mode of the tubed RC columns with $t = 3.2$ and 4.5 mm, respectively. At failure, the steel tubes had a significant outward local protrusion of the steel tube walls in the area near the top and bottom ends. However, as shown in Figure 8, they give partial restraints to the lateral expansion of


**Figure 9. Typical modes of failure of the test specimens (a) RC column, (b) and (c) tubed RC columns with $t$ = 3.2 and 4.5 mm, respectively**

the RC core and promote the transferring of the axial load from the RC core to the other parts of the column, in turn, provide the column with large axial deformability.

Figure 10 shows the failure mode at the top end of the tubed RC columns. Due to the square section, the corner can maintain the right angle when the middle portion of the wall of the steel tube protrude or move outward, indicating that the steel tube primarily provides the restraint to the RC core from the corners.

**Axial Compressive Capacity and the Corresponding Strain**

Table 2 shows the comparisons of the obtained axial compressive capacity ($N_{c,exp}$) and the corresponding strain ($\varepsilon_{c,exp}$) of the reference RC and tubed RC columns. It can be seen from the ratio of the axial compressive capacity of the tubed RC column to the ultimate compressive strength of the RC column ($N_{c,RC}$) or $N_{c,exp} / N_{c,RC}$ ratio that the tubed RC columns

(a)

(b)

**Figure 10. Failure mode of the RC core at the top of the tubed RC columns (a) $t$ = 4.5 mm, (b) $t$ = 3.2 mm**

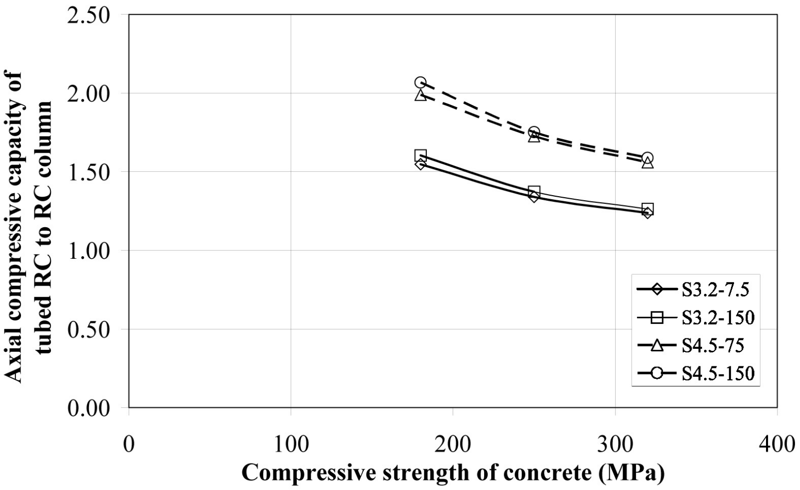



**Figure 11. $N_{c,exp} / N_{u,RC}$ ratio versus compressive strengths of the concrete**

**Table 2. Comparison of the axial compressive capacity and their corresponding strain of the RC and tubed RC columns and their behaviors**

| Group | Specimen No. | $N_{c,exp}$ (kN) | $N_{c,exp}/N_{u,RC}$ | $\varepsilon_{c,exp}$/ (% strain) | $\varepsilon_{c,exp}/\varepsilon_{u,RC}$ | $\varepsilon$ at mid-height of steel tube at $N_{c,exp}$ load (% strain) | $f_{cal}^{tube}$, calculated axial stress at mid-height of steel tube at $N_{c,exp}$ (MPa) | $f_{cal}^{tube}/f_y^{tube}$ | Ratio of axial in steel tube over ($f_y^{tube}A_{tube}$) | Behavior of the tubed RC columns |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | C-18-0-75 | 459.9 | - | 0.396 | - | - | - | - | - | - |
| | C-25-0-75 | 605.3 | - | 0.329 | - | - | - | - | - | - |
| | C-32-0-75 | 713.6 | - | 0.351 | - | - | - | - | - | - |
| | C-18-0-150 | 437.4 | - | 0.373 | - | - | - | - | - | - |
| | C-25-0-150 | 590.3 | - | 0.305 | - | - | - | - | - | - |
| | C-32-0-150 | 693.9 | - | 0.298 | - | - | - | - | - | - |
| 2 | S-18-3.2-75 | 711.8 | 1.55 | 1.726 | 4.36 | 0.107 | 214 | 0.69 | 0.44 | strain-softening |
| | S-25-3.2-75 | 811.2 | 1.34 | 1.459 | 4.44 | 0.091 | 182 | 0.58 | 0.36 | strain-softening |
| | S-32-3.2-75 | 883.7 | 1.24 | 0.969 | 2.76 | 0.074 | 148 | 0.47 | 0.30 | strain-softening |
| | S-18-3.2-150 | 701.4 | 1.60 | 1.607 | 4.30 | 0.102 | 204 | 0.65 | 0.46 | strain-softening |
| | S-25-3.2-150 | 810.5 | 1.37 | 1.383 | 4.54 | 0.077 | 154 | 0.49 | 0.38 | strain-softening |
| | S-32-3.2-150 | 876.1 | 1.26 | 0.893 | 3.00 | 0.085 | 170 | 0.54 | 0.32 | strain-softening |
| 3 | S-18-4.5-75 | 914.9 | 1.99 | 2.667 | 6.73 | 0.139 | 279 | 0.71 | 0.45 | strain hardening |
| | S-25-4.5-75 | 1,044.5 | 1.73 | 2.667 | 8.11 | 0.113 | 226 | 0.58 | 0.44 | strain hardening |
| | S-32-4.5-75 | 1,113.2 | 1.56 | 2.667 | 7.60 | 0.099 | 198 | 0.51 | 0.40 | elastic-perfectly plastic |
| | S-18-4.5-150 | 904.0 | 2.07 | 2.667 | 7.14 | 0.135 | 270 | 0.69 | 0.46 | strain hardening |
| | S-25-4.5-150 | 1,033.6 | 1.75 | 2.667 | 8.75 | 0.093 | 186 | 0.48 | 0.44 | strain hardening |
| | S-32-4.5-150 | 1,101.9 | 1.59 | 2.667 | 8.95 | - | - | - | 0.41 | elastic-perfectly plastic |

with $t$ = 3.2 mm and 4.5 mm have larger $N_{c,exp}$ than the $N_{u,RC}$ of the RC column by 1.24 to 1.60 times and 1.56 to 2.07 times, respectively, and have larger corresponding strain by 2.8 to 4.5 times and 6.7 to 9.0 times, respectively. With the increasing in the wall thickness, the axial compressive capacity and the corresponding strain increase. However, for a given ultimate compressive strength of the concrete and the wall thickness of the steel tube with different tie spacing such as the specimen S-18-3.2-75 and S-18-3.2-150 in group 2, the $N_{c,exp}$ / $N_{u,RC}$ ratio is approximately identical. This indicates that the tie spacing has no influence on the axial compressive capacity of the columns. In addition, for a given steel tube wall thickness and tie spacing with increasing in the ultimate compressive strength of concrete from 18 to 32 MPa, such as the specimen S-18-3.2-75, S-25-3.2-75 and S-32-3.2-75 in group 2, the $N_{c,exp}$ / $N_{u,RC}$ ratio decreases as shown in Figure 11, indicating that the effectiveness of the restraint effect of the steel tube to the RC core reduces.

## Comparison with ACI 318

It should be noted that the tubed RC column is subjected to the axial load applied directly to the RC core as shown in Figure 4(a), which is different from the typical CFT column as shown in Figure 4(b). Also, no local wall buckling of the steel tube due to the axial compressive load was observed from all the tests. Thus, the limiting $B/t$ ratios set by the ACI 318 design codes are not applicable to the columns used in this study. In addition, the ACI 318 design equation may not be applicable to the tubed RC columns since only partial interaction between the steel tube and RC core is developed in the column. Hence, the major objective of the following comparison is to check whether the design equation can be used to predict the $N_{c,exp}$ of the tubed RC column.

Table 3 shows the comparison of the obtained test results with those computed by

**Table 3. Comparison of the test results with those computed by using the ACI 318 and the proposed design equation**

| Group | Specimen No. | $N_{c,exp}$ (kN) | $N_{ACI}$ (kN) | $N_{c,exp}$ / $N_{ACI}$ | $N_{c,exp}^{tube}$ (kN) | $N_{c,exp}^{tube}$ / $A_s f_y^{tube}$ | $N_{ACI}^{proposed}$ (kN) | $N_{c,exp}$ / $N_{ACI}^{proposed}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | C-18-0-75 | 459.9 | 413.86 | 1.11 | | | - | - |
| | C-25-0-75 | 605.3 | 542.88 | 1.11 | | | - | - |
| | C-32-0-75 | 713.6 | 661.04 | 1.08 | | | - | - |
| | C-18-0-150 | 437.4 | 413.86 | 1.06 | | | - | - |
| | C-25-0-150 | 590.3 | 542.88 | 1.09 | | | - | - |
| | C-32-0-150 | 693.9 | 661.04 | 1.05 | | | - | - |
| 2 | S-18-3.2-75 | 711.8 | 954.31 | 0.66 | 252.0 | 0.44 | 553.9 | 1.29 |
| | S-25-3.2-75 | 811.2 | 1072.36 | 0.68 | 205.9 | 0.36 | 671.9 | 1.21 |
| | S-32-3.2-75 | 883.7 | 1180.49 | 0.73 | 170.1 | 0.30 | 780.0 | 1.13 |
| | S-18-3.2-150 | 701.4 | 954.31 | 0.63 | 264.0 | 0.46 | 553.9 | 1.27 |
| | S-25-3.2-150 | 810.5 | 1072.36 | 0.66 | 220.3 | 0.38 | 671.9 | 1.21 |
| | S-32-3.2-150 | 876.1 | 1180.49 | 0.71 | 182.2 | 0.32 | 780.0 | 1.12 |
| 3 | S-18-4.5-75 | 914.9 | 1374.11 | 0.54 | 455.1 | 0.45 | 670.6 | 1.36 |
| | S-25-4.5-75 | 1044.5 | 1487.62 | 0.53 | 439.2 | 0.44 | 784.1 | 1.33 |
| | S-32-4.5-75 | 1113.2 | 1591.58 | 0.60 | 399.6 | 0.40 | 888.1 | 1.25 |
| | S-18-4.5-150 | 904.0 | 1374.11 | 0.53 | 466.7 | 0.46 | 670.6 | 1.35 |
| | S-25-4.5-150 | 1033.6 | 1487.62 | 0.49 | 443.3 | 0.44 | 784.1 | 1.32 |
| | S-32-4.5-150 | 1101.9 | 1591.58 | 0.59 | 408.1 | 0.41 | 888.1 | 1.24 |

using the ACI 318 design equations. The $N_{c,exp}$/ $N_{ACI}$ ratio of the reference RC column shows the values slightly larger than unity, indicating that the test results are in good agreement with the design equation. But, the $N_{c,exp}$/ $N_{ACI}$ ratio of the tubed RC columns, which are in the range of 0.49 to 0.73, are considerably lower than the predicted results and the thicker the wall thickness of the steel tube, the lower the values of the ratios. Based on the scope of this study, it is proposed that the ACI 318 design equation should be modified by adjusting the contribution of the yielding strength of the steel tube on the axial compressive capacity of the tubed RC column. By subtracting the obtained $N_{u,RC}$ of the RC column from the obtained $N_{c,exp}$ of the column with the same variable, and then, dividing the results by the theoretical yielding strength of the steel tube ($f_y^{tube}$ $A_{tube}$), it was found that the ratio is in the range of 0.30 to 0.46 as shown in Table 3. Thus, to make the design equation conservative due to a limit in the number of tested column, it is proposed that the lowest of the ratios should be used and the design equation is in the form of

$$N_{ACI}^{proposed} = 0.85A_c f'_{co} + A_s f_y^s + 0.30A_{tube} f_y^{tube}$$

Comparing of the test results with those computed from the proposed design equation, the values of the $N_{c,\exp}/N_{ACI}^{proposed}$ ratio are larger than unity in the range of 1.12 to 1.36, indicating that the proposed design equation is conservative and underestimate the axial compressive capacity of the column by 12% to 36%.

## Conclusions

An experimental investigation on the behaviors and modes of failure of the square steel tubed RC columns subjected to concentrically axial load and applied directly to the RC core has been presented in this paper. Since the concept of tubed RC column is different from the typical CFT columns, the comparison between the axial compressive capacity of the column with that calculated from the ACI 318 design equation was also performed to check its adequacy. Based upon the results of this study, the following conclusions can be drawn:

1. The tubed RC columns have a linear elastic behavior up to approximately 60-70% of their axial compressive capacity. Then, the behavior of the columns is gradually becoming nonlinear and can be classified into three types: strain hardening, elastic-perfectly plastic and strain-softening, depending mainly on the wall thickness of the steel tube and the compressive strength of the concrete. The columns with thicker wall thickness and with lower concrete compressive strength have higher restraining effect on the lateral outward protrusion of the crushed concrete core underneath the axial load by the steel tube wall than those with thinner wall thickness and higher concrete compressive strength. The tie spacing of the RC core, specified in accordance with the ACI 318, has no influence on the axial compressive capacity of the tubed RC columns. The typical failure mode of the columns is progressive mode with a very high axial deformability.

2. The tubed RC column concept can be used to provide additional transverse reinforcement in order to enhance the axial compressive capacity and significantly improve the axial deformability (ductility) of the RC columns. However, by comparing the obtained axial compressive capacity with that predicted by the ACI 318 design equations, it was found that the design equations considerably overestimate the axial compressive capacity of the tubed RC column. This is because of the difference between the application of the axial load on the tubed RC column and the CFT column. Thus, only partial interaction between the steel tube and the RC core is developed in the tubed RC column.

3. Based on the results obtained from this study, the modified design equation based on the ACI 318 design equations is proposed by introducing the strength reduction factor of 0.30 to the yielding strength of the steel tube and keeping the contribution of the concrete and the main reinforcement the same. Hence, it is in the form of $N_{ACI}^{proposed} = 0.85A_c f'_{co} + A_s f_y^s + 0.30A_{tube} f_y^{tube}$.

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