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THE APPLICATION OF CIRCULAR STEEL TUBE FOR CONCRETE CORE CONFINEMENT AND ADDITIONAL AXIAL SUPPORT IN REINFORCED CONCRETE COLUMN

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ABSTRACT: Circular hoops, rectilinear hoops with crossties, and spirals are widely used in reinforced concrete columns as transverse reinforcement to prevent shear failure and provide confinement. Besides transverse reinforcement, many researchers have used square or circular steel tubes to provide confinement to concrete. This paper compares experimentally the application of circular steel tubes and spirals in providing confinement to concrete. Five types of compressive test specimens were tested under axial compression, comprising one type of column confined by rectilinear hoops, one type of column confined by a circular steel tube, two types of columns confined by a combination of circular steel tube and rectilinear hoops, and one type of column confined by a combination of spirals and rectilinear hoops. The result showed that circular steel tubes confined the concrete core well and provided additional axial support. The compressive test specimens using circular steel tubes had 40.74% higher axial load-carrying capacity, exhibited more ductile behavior, and had less damage than compressive test specimens using spirals. It proved that circular steel tubes were more effective in providing confinement to concrete than spirals. Rectilinear hoops with a spacing of one-fourth and one-half of the column cross-section increased the maximum axial load by 57.78% and 20.89%, respectively. The effect of the arching action on the concrete between the rectilinear hoops and the circular steel tubes could be neglected so that there was no ineffectively confined area, and the outer concrete was assumed to be fully effectively confined by the rectilinear hoops.

Keywords: Circular steel tube, Spirals, Confinement, Concentric axial compression, Effectively confined area

1. INTRODUCTION

The development of plastic hinges cannot be avoided at the base of reinforced concrete columns, which are connected to the foundations as part of the energy dissipation mechanism under strong earthquakes. If the columns have a high axial load level, a high quantity of transverse reinforcement must be provided for adequate confinement so that reinforced concrete columns have enough ductility. The objectives of providing a high quantity of transverse reinforcement are to confine the concrete core and to prevent the longitudinal reinforcement from buckling. Circular hoops, rectilinear hoops with crossties, and spirals are commonly used as transverse reinforcement. Besides transverse reinforcement, many researchers [1-18] have used square or circular steel tubes to provide confinement to concrete. To see the effectiveness of circular steel tubes in providing confinement to the concrete in plastic hinge regions of concrete columns, a series of compressive tests of concrete with various arrangements of transverse reinforcement, including the combination with circular steel tubes, were carried out.

It is noted that the application of circular steel tubes in reinforced concrete have been introduced, which act as a composite member named Concrete Filled Steel Tube (CFST). Circular steel tubes in the columns under axial compression could increase the axial load-carrying capacity [1–3] and showed higher ductility than square steel tubes [4]. The ratio between the diameter and thickness of circular steel tubes affected the column's axial load-carrying capacity more than the concrete core's compressive strength [5]. Other researchers strengthened the steel tube with vertical stiffeners to prevent local buckling of the steel tubes so the plastic strength could be attained and the ductility was increased [6–8].

Some researchers also inserted circular steel tubes for concrete-encased and filled steel tubes (CEFT) and concrete-filled double-skin steel tubes (CFDST) in their experiments. The inner circular steel tube in the columns subjected to axial compressive load effectively confined the concrete core so that the column could maintain its residual axial load-carrying capacity after reaching its ultimate strength [9–12]. The inner circular steel tube and concrete core contributed significantly to increasing the ductility of the columns [13–16]. The inner circular steel tube was suggested to have a diameter of at least half the cross-sectional dimension of the column [13]. The inner circular steel tube's greater diameter could increase the compressive test specimen's ultimate axial stress and strain [17]. The concrete around the circular steel tube could resist local buckling of the inner circular steel tube and protect it from the threat of corrosion [14,18].

However, the circular steel tubes from previous research were applied to the whole length of columns. There has not been any research using an inner circular steel tube to substitute crossties in the column's plastic hinge region. There was a lack of information on whether inner circular steel tubes were more effective in providing confinement than other types of transverse reinforcement, such as spirals. This research on CEFT columns was conducted to investigate the contribution of circular steel tube in providing confinement to the concrete core and supporting axial compressive loads, compared the effectiveness of circular steel tube and spirals in providing confinement to the concrete core, and determined the effectively confined concrete area between the rectilinear hoops and the circular steel tube.

2. RESEARCH SIGNIFICANCE

American Concrete Institute (ACI) regulation [19] requires that if the factored axial load is greater than 0,3 $A_g f_c'$ in columns of special moment frames and rectilinear hoops are used, then every longitudinal bar around the perimeter of the column core at the plastic hinge must have lateral support by using hoops or crossties (Fig. 1).

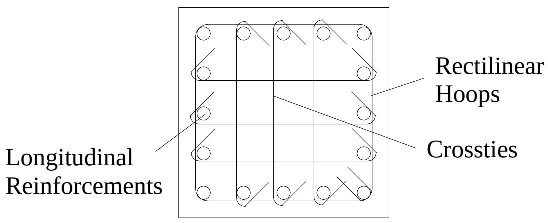


Fig. 1 Transverse reinforcement in columns

This requirement makes the need for transverse reinforcement become high, and the need to provide crossties at any longitudinal reinforcement makes the construction process hardly possible. Therefore, it is necessary to find an alternative way to replace the requirement to provide crossties at any longitudinal reinforcement in those plastic hinge regions.

This research tried to modify the ACI requirements by replacing crossties in the plastic hinge regions with circular steel tubes. This research is carried out in two stages. This paper is the result of the first stage of the study, which investigates the effectiveness of circular steel tubes and compares circular steel tubes and spirals. In the subsequent research, the circular steel tubes will be inserted only in the plastic hinge region of the columns to substitute the crossties so the construction can be simplified.

3. EXPERIMENTAL PROGRAM

3.1 Compressive Test Specimens

Five types of compressive test specimens were tested in this research, comprising one type of column confined by rectilinear hoops, one type of column confined by a circular steel tube, two types of columns confined by a combination of circular steel tube and rectilinear hoops, and one type of column confined by a combination of spirals and rectilinear hoops. All the compressive test specimens had a square cross-section of 120 mm and a height of 360 mm. The height-to-width ratio was three, so the compressive test specimens behaved as short columns when subjected to an axial compressive load [20]. The details of the compressive test specimens are summarized in Table 1 and shown in Fig. 2. The diameter-to-thickness ratio of the circular steel tube was 22.3, and the volumetric ratio of the circular steel tube was greater than the minimum requirement of 1% [21]. The circular steel tube and spirals had a height of 340 mm lower than the compressive test specimen's height, as seen in Fig. 1, so the axial compressive load did not directly act on the circular steel tube and spirals.

The specimens RH30, ST3RH30, and SP50RH30 had rectilinear hoops with a spacing of one-fourth of the column cross-section dimensions, namely 30 mm. The spacing of rectilinear hoops in specimens RH30 and SP50RH30 meet requirements in columns of special moment frames according to ACI regulation [19]: the least of one-fourth of the minimum column dimension, six times the longitudinal bar diameter, and 150 mm.

Table 1 Details of compressive test specimens

Specimen	Longitudinal Reinforcements	Rectilinear Hoops	Circular Steel Tube	Spirals
RH30	4-D10	Ø6 at 30	-	-
ST3	-	-	Ø2,5" (3 mm thick)	-
ST3RH30	4-D10	Ø6 at 30	Ø2,5" (3 mm thick)	-
ST3RH60	4-D10	Ø6 at 60	Ø2,5" (3 mm thick)	-
SP50RH30	4-D10	Ø6 at 30	-	Ø12 at 50

Note: RH30 = rectilinear hoops with 30 mm spacing, ST3 = steel tube with 3 mm thickness, ST3RH30 = steel tube with 3 mm thickness and rectilinear hoops with 30 mm spacing, ST3RH60 = steel tube with 3 mm thickness and rectilinear hoops with 60 mm spacing, SP50RH30 = spirals with 50 mm spacing and rectilinear hoops with 30 mm spacing

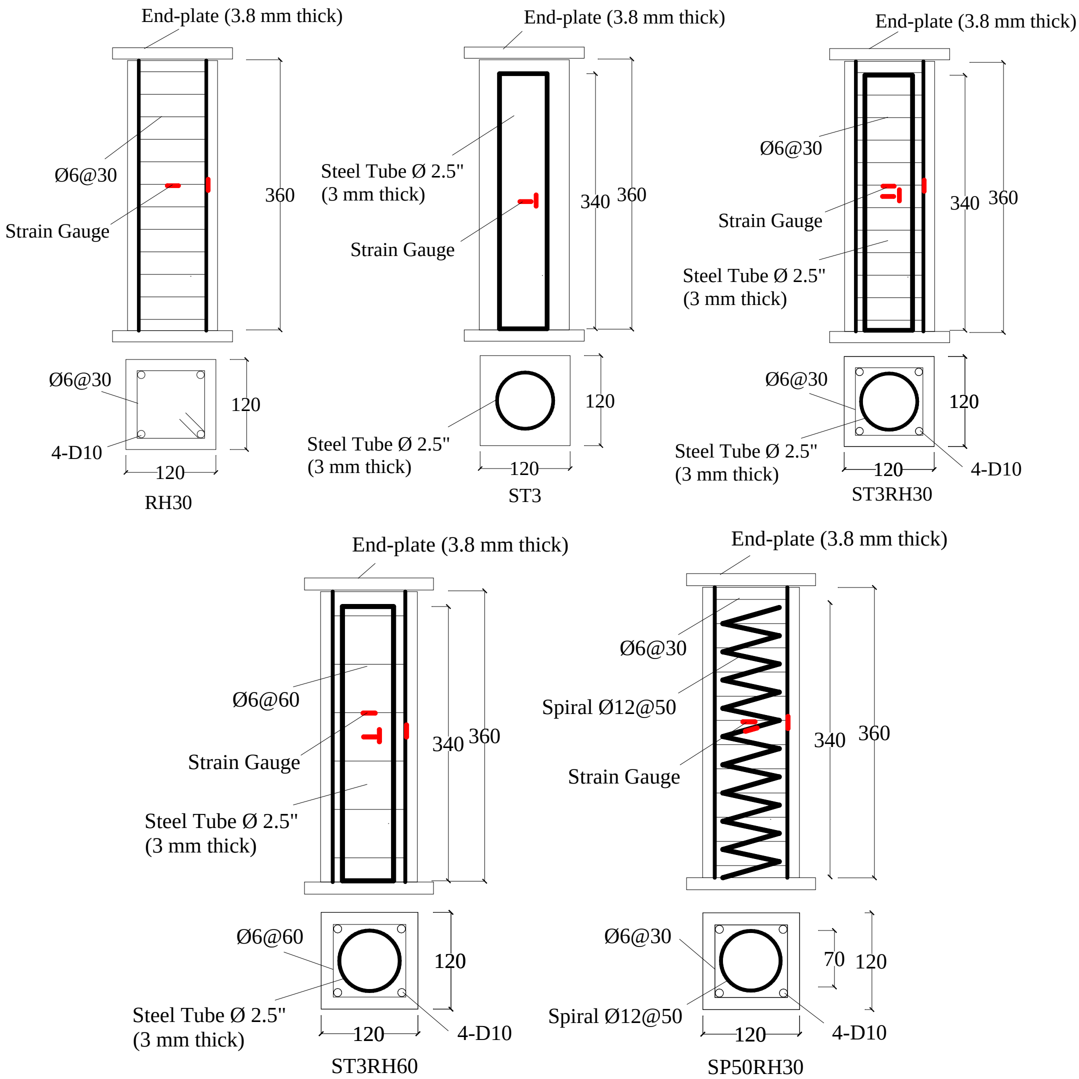


Fig. 2 Details of compressive test specimens

One-fourth of the column cross-section dimension in specimen ST3RH30 is the maximum spacing of transverse reinforcement in end-bearing splices of encased composite columns used as highly ductile members according to American Institute of Steel Construction (AISC) regulation [22].

The compressive test specimens using circular steel tubes were compared to the compressive test specimens using spirals to investigate the confinement to the concrete core. The circular steel tubes in specimens ST3, ST3RH30, and ST3RH60 had nearly the same effective lateral confining stresses as spirals in specimen SP50RH30. The arching action in the vertical direction had been included in the effective lateral confining stress calculation for spirals. The specimen ST3 was compared to the specimens ST3RH30 and ST3RH60 to investigate whether the concrete between the rectilinear hoops and the circular steel tube was entirely confined or not.

3.2 Material Properties

The compressive test specimens were made with normal concrete using a maximum coarse aggregate of 10 mm. The concrete mix proportion for 1 m^3 was 233 kg water, 416 kg cement, 832 kg sand, and 832 kg coarse aggregate. The water-cement ratio was 0.56. Three 150 x 300 mm cylinders were tested at the age of 28 days under axial compression to determine the unconfined concrete's compressive strength and modulus of elasticity. The average compressive strength and modulus of elasticity obtained from the tests were 40.74 MPa and 29,824.63 MPa, respectively. Tensile tests were conducted on steel material, and the yield strength of the longitudinal bar, rectilinear hoops, spirals, and circular steel tube were 499.10 MPa, 468.90 MPa, 470.51 MPa, and 243.35 MPa, respectively. The modulus of elasticity of longitudinal bar, rectilinear hoops, spirals, and circular steel tube were 192,000 MPa, 197,600 MPa, 195,100 MPa, and 191,500 MPa, respectively.

3.3 Test Setup and Instrumentation

Fig. 3 shows the test setup and the test specimen. A hydraulic jack with a capacity of 1000 kN was used to provide an axial compressive load on the compressive test specimen. A 2000 kN load cell measured the value of the axial compressive load. Two linear variable displacement transducers (LVDT) were used to measure the axial deformation of the 250 mm mid-height region to obtain the critical strain. The mid-height region is a critical area where most damage due to axial compressive loads occurs [23]. When the mid-height of the compressive test specimen starts to damage, the LVDT attached to that region can shift so that the data becomes inaccurate. To anticipate that one additional LVDT was used to measure the overall axial deformation.

A hinged support was used to ensure there was no moment at the support of the compressive test specimens when an unexpected eccentricity happened if the position of the hydraulic jack was not precisely concentric to the specimens. Strain gauges were attached to longitudinal reinforcement, rectilinear hoops, circular steel tubes (axial and hoop directions), and spirals at the mid-height of the compressive test specimens, as seen in Fig. 2. The strain gauges on the circular steel tubes were attached in the mid-height so the strain data obtained could be used to measure the stress of the circular steel tube [24] and avoid the end effect [25].

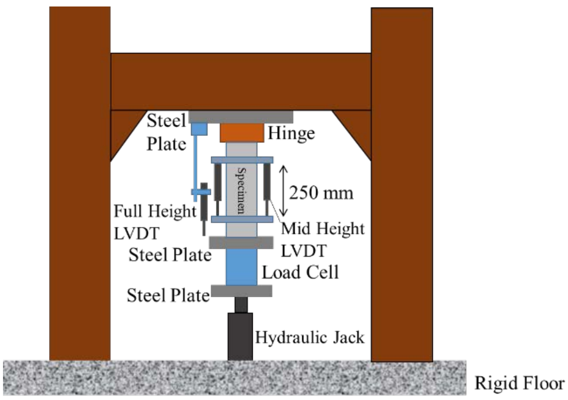
A data logger recorded all the test data, including loads measured by the load cell, displacements measured by the LVDT, and strains measured by the strain gauges. The concentric axial compressive load was applied until the compressive load supported by the concrete section was less than the axial load-carrying capacity of the confined concrete. The axial load supported by the concrete was obtained by subtracting the axial load supported by the longitudinal reinforcement from the total axial load. The axial load supported by the concrete would be used to compare the compressive test specimens' test results.

4. RESULT AND DISCUSSION

4.1 Failure Modes

Fig. 4 shows the damage and failure modes of the compressive test specimens after the test. After testing, all the compressive test specimens suffered damage near mid-height. The columns using circular steel tubes showed less damage than the columns using spirals. The concrete cover spalling occurred gradually on specimens ST3, ST3RH30, and ST3RH60, while the concrete cover spalling on specimens SP50RH30 appeared suddenly. The concrete between the rectilinear hoops and circular steel tube on specimen ST3RH30 was not damaged, while minor damage occurred at the concrete between the rectilinear hoops and spirals on specimen SP50RH30. In compressive test specimens using circular steel tubes, the outer concrete's expansion was minimal because the concrete core's expansion inside the circular steel tube had been resisted by the circular steel tube, so its damage was reduced and made the concrete cover spall gradually. The circular steel tube could prevent damage to the concrete core (Fig. 5), while the concrete core confined with spirals experienced crushing failure.

The rectilinear hoops with a spacing of one-fourth of the column cross-section (Ø6 at 30) on specimens RH30, ST3RH30, and SP50RH30 meet the requirements for transverse reinforcement in a column of the special moment frame according to ACI [19] and AISC [22], could prevent or reduce damage to the confined concrete and avoid or minimize buckling of the longitudinal reinforcement. The concrete confined by rectilinear hoops with a spacing of one-half of the column cross-section (Ø6 at 60) on specimen ST3RH60 suffered severe damage after the test, accompanied by buckling of the longitudinal reinforcement.



(a) Test setup

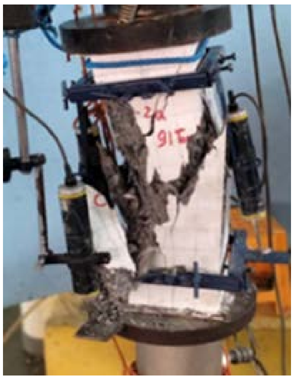
(b) Test specimen

Fig. 3 Test setup and test specimen

RH30

ST3

ST3RH30



ST3RH60

SP50RH30

Fig. 4 Failure modes of the compressive test specimens at the end of the test

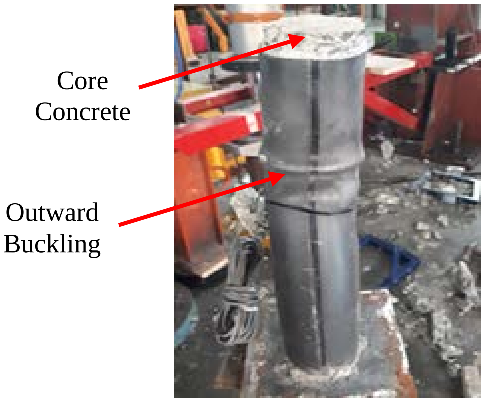


Fig. 5 The core concrete in circular steel tube

4.2 Axial Load-Axial Strain Relationships

Fig. 6 shows the relationships between axial load and axial strain of all the compressive test specimens obtained from the axial compressive tests. For compressive test specimens using circular steel tubes, the diagram shows the axial load from two conditions: the axial load supported by concrete and circular steel tube and the axial load supported by concrete only. The axial load supported by the circular steel tube was not included for the latter. The additional axial support provided by the circular steel tube can be seen in the diagram. The axial strains were calculated from the average of the two mid-height LVDT readings.

The test result comparison between specimens RH30 and ST3RH30 can be seen in Fig. 6a. The axial load-carrying capacity on specimen RH30 decreased rapidly after the strain reached 0.0045, shortly after the maximum axial load was attained due to the spalling of the concrete cover. After the strain reached 0.001, the circular steel tube confined the core concrete effectively so that specimen ST3RH30 showed greater axial stiffness and axial load-carrying capacity than RH30. The axial load-carrying capacity on specimen ST3RH30 decreased gradually after the concrete cover started to spall when the strain reached 0.002. The specimen ST3RH30, using a circular steel tube, showed a higher axial load-carrying capacity than the specimen RH30, and the axial load-carrying capacity decreased gradually after the peak axial load, although the axial load supported by the circular steel tube was not considered. The test result proved that using a circular steel tube in specimen ST3RH30 could increase axial load-carrying capacity and change the compressive test specimens' behavior from brittle to ductile.

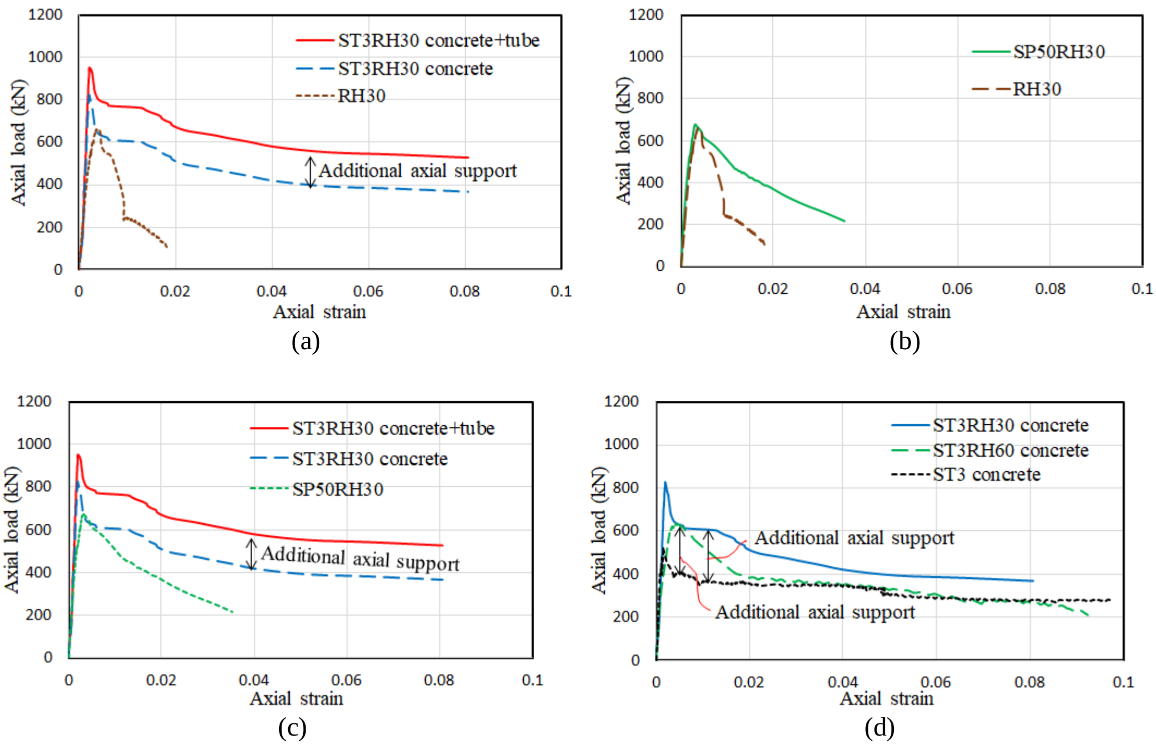


Fig. 6 Axial load-strain relationships of the compressive test specimens

Fig. 6b shows the test result comparison between specimens RH30 and SP50RH30. Before the maximum axial load was reached, the specimen SP50RH30 showed slightly greater axial stiffness than RH30, as seen in Fig. 6b. The specimen SP50RH30 showed higher axial load-carrying capacity than the specimen RH30 after the maximum axial load attained until the axial strain reached 0.035 when the concrete cover was crushed suddenly.

The test result of specimen ST3RH30 using a circular steel tube and rectilinear hoops was compared with specimen SP50RH30 using spirals and rectilinear hoops (Fig. 6c). Spirals in specimen SP50RH30 had the same effective lateral confining stress as circular steel tube in specimen ST3RH30. Specimen ST3RH30 showed greater axial stiffness and axial load-carrying capacity than SP50RH30 after the axial strain reached 0.001 because of the confinement of the circular steel tube. The axial load-carrying capacity on specimen SP50RH30 decreased after the concrete cover spalling occurred when the strain reached 0.003. The specimen ST3RH30 showed better performances and more ductile behavior until the end of the test. It had a higher axial load-carrying capacity than specimen SP50RH30, although only the axial load supported by the concrete was considered, and the axial load supported by the circular steel tubes was not considered.

After the maximum axial load was attained, the axial load-carrying capacity of the columns using circular steel tubes decreased very gradually due to the spalling of the concrete cover, followed by buckling of the circular steel tube. On the other hand, the columns using spirals had brittle behavior because the axial load-carrying capacity decreased very rapidly. The circular steel tube effectively confined the concrete core to avoid damage and contributed to additional axial support, increasing axial load-carrying capacity. The circular steel tube and the concrete core gave enough residual axial load-carrying capacity after the spalling of the concrete cover, so the column had ductile behavior. The test proved that the circular steel tube was more effective in confining the concrete core than spirals.

The test result comparison between specimens ST3RH30, ST3RH60, and ST3 can be seen in Fig. 6d. The diagram shows the axial load supported by concrete only without the axial load supported by the circular steel tube. The additional axial support provided by the outer concrete confined by the rectilinear hoops can be seen in the diagram. The axial load-carrying capacity of specimens ST3RH30 and ST3RH60 was greater than ST3 after the strain reached 0.0015 and 0.002, respectively, due to the additional axial support provided by concrete outside the circular steel tube confined by rectilinear hoops. Specimen ST3RH30 showed a higher axial load-carrying capacity than specimen ST3 until the end of the test. The concrete between rectilinear hoops and circular steel tube had not been damaged, so it still contributed to support the axial load. Specimen ST3RH60 showed a higher axial load-carrying capacity than specimen ST3 until axial strain 0.04. After that, the diagrams coincided because the concrete between rectilinear hoops and circular steel tube had been damaged.

4.3 Maximum Axial Loads

Table 2 shows the maximum axial loads of all compressive test specimens.

Table 2 Maximum axial loads

Type	N_u Experiment (kN)
RH30	663.916
ST3	683.010
ST3*	523.022
ST3RH30	952.522
ST3RH30*	825.235
ST3RH60	793.790
ST3RH60*	632.301
SP50RH30	676.838

*Note: * without the axial load supported by the circular steel tube*

For the compressive test specimens using longitudinal reinforcements, the test results were the total axial load reduced by the axial load supported by longitudinal reinforcements as follows:

$$N_u = N_{u\,total} - N_{u\,long} \tag{1}$$

$$N_{u\,long} = f_s A_s \tag{2}$$

$$f_s = E_s \varepsilon_s \quad \text{if } \varepsilon_s < \varepsilon_y \tag{3}$$

$$f_s = f_y \quad \text{if } \varepsilon_s \geq \varepsilon_y \tag{4}$$

in which: $N_{u\,total}$ is the total axial load, $N_{u\,long}$ is the axial load supported by longitudinal reinforcements, f_s is the normal stress of longitudinal reinforcement, A_s is the area of longitudinal reinforcement, E_s is modulus of elasticity of longitudinal reinforcement, ε_s is the strain of longitudinal reinforcement obtained from the strain gauge reading, ε_y is the yield strain, and f_y is the yield stress of longitudinal reinforcement. The axial load supported by the concrete would be used to compare the specimens' test results. For compressive test specimens using circular steel tubes (ST3, ST3RH30, and ST3RH60), the test results were considered in two conditions, including the axial load supported by the circular steel tube and without the axial load supported by the circular steel tube. For the latter, the test results were reduced by the axial load supported by the circular steel tubes as follows:

$$N_{u\,tube} = A_{st} \sigma_a \tag{5}$$

in which: A_{st} and σ_a are the cross-sectional area and the axial stress of the circular steel tube, respectively. The stresses of circular steel tubes were calculated by considering the interaction of hoop strain and axial strain [22]. The axial stress (σ_a) of the circular steel tube can be calculated by the following equations:

$$\sigma_a = \frac{E_s}{1 - \nu_s^2} \left(\nu_s \varepsilon_l + \varepsilon_a \right) \tag{6}$$

where E_s and ν_s are the modulus of elasticity and Poisson's ratio of the circular steel tube, ε_l and ε_a are the circular steel tube's measured hoop strain and axial strain obtained from the strain gauge reading.

When the specimens ST3RH30 and ST3RH60 reached their ultimate strength, the concrete outside the circular steel tube had reached a plastic condition, so it experienced greater expansion than the circular steel tube [9]. The interaction stress between the outer concrete and circular steel tube did not exist. At this stage, the concrete inside the circular steel tube was only confined by the circular steel tube.

Table 3 shows the increase in the maximum axial loads on columns using rectilinear hoops after circular steel tubes or spirals were added to the concrete core and the increase in the maximum axial loads on columns using circular steel tubes compared to columns using spirals. Table 3 also shows the increase in maximum axial load on columns using circular steel tubes after rectilinear hoops were added with two spacing variations, namely a spacing of one-fourth and one-half of the column cross-section.

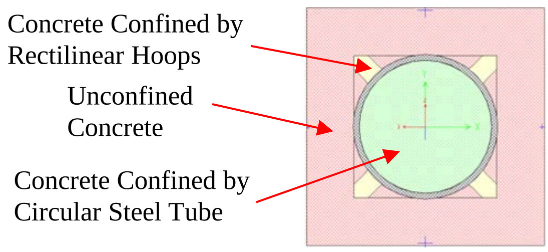
Table 3 Comparison of the maximum axial loads

Type	Deviation (%)
RH30 and ST3RH30	43.47
RH30 and ST3RH30*	24.30
RH30 and SP50RH30	1.95
SP50RH30 and ST3RH30	40.74
SP50RH30 and ST3RH30*	21.93
ST3 and ST3RH30	39.46
ST3* and ST3RH30*	57.78
ST3 and ST3RH60	16.22
ST3* and ST3RH60*	20.89

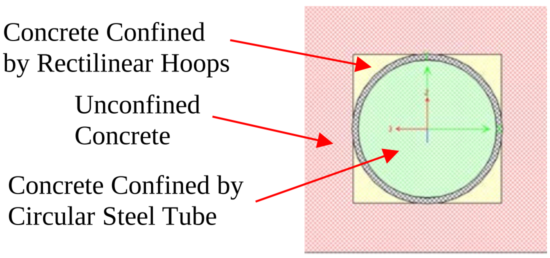
*Note: * without the axial load supported by the circular steel tube*

The addition of circular steel tubes to the concrete core of columns using rectilinear hoops (ST3RH30 compared to RH30) increased the maximum axial load higher than the addition of spirals to the concrete core of columns using rectilinear hoops (SP50RH30 compared to RH30). This test result also showed that the maximum axial loads of the column using circular steel tube (ST3RH30) was higher than that using spirals (SP50RH30), even though the axial load supported by the circular steel tubes was neglected. The compressive test specimens using spirals had low maximum axial load because the spirals had not yet yielded, and the rectilinear hoops stresses were still small when the maximum axial load was attained.

Rectilinear hoops with a spacing of one-fourth of the column cross-section (ST3RH30) increased the maximum axial load higher than rectilinear hoops with a spacing of one-half of the column cross-section (ST3RH60). If arching action occurred in the concrete between the rectilinear hoops and the circular steel tube, using a decreased spacing of the rectilinear hoops would not significantly affect the axial load-carrying capacity. The compressive test specimens using rectilinear hoops with a spacing of one-fourth and one-half of the column cross-section should have slightly different load-carrying capacities because the outer concrete was only confined to the corner of the column section (Fig. 7a). The test showed that the axial load-carrying capacity of specimen ST3RH30 was higher than that of specimen ST3RH60. This result indicated that rectilinear hoops could effectively confine the concrete outside the circular steel tube, and there was no effect of arching action (Fig. 7b).



(a) With arching action



(b) Without arching action

Fig.7 Effectively and ineffectively confined cross-section

The lateral deformation in the concrete outside the circular steel tube was minimal because the expansion of the concrete core inside the circular steel tube had been resisted by the circular steel tube. The bending deformation of the longitudinal reinforcements and rectilinear hoops was also minimal, so the effect of the arching action could be neglected.

5. CONCLUSIONS

This paper presents the experimental results of columns using rectilinear hoops, circular steel tube, two combinations of circular steel tube and rectilinear hoops, and a combination of spirals and rectilinear hoops subjected to axial compression. Based on the test result, it was found that the circular steel tube confined the concrete core well, prevented the concrete core from being damaged until the end of the test, and provided additional axial support. The circular steel tube and the concrete core provided residual axial load-carrying capacity after the maximum axial load, showing ductile behavior.

The compressive test specimens using circular steel tubes had 40.74% higher axial load-carrying capacity, exhibited more ductile behavior, and had less damage than compressive test specimens using spirals. This result proved that circular steel tubes more effectively confined the concrete core than spirals.

The test result also showed that rectilinear hoops with a spacing of one-fourth of the column cross-section increased the maximum axial load by 57.78%. In contrast, rectilinear hoops with a spacing of one-half of the column cross-section increased the maximum axial load by 20.89%. The effect of the arching action on the concrete between the rectilinear hoops and the circular steel tubes could be neglected so that the outer concrete was assumed to be fully effectively confined by the rectilinear hoops.

Future research will apply the circular steel tube to substitute crossties in the plastic hinge region of the columns subjected to quasi-static lateral load.

6. ACKNOWLEDGMENTS

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