



# Axial compressive behavior of square composite columns confined by multiple spirals



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## ARTICLE INFO

### Article history:

Received 11 March 2014

Accepted 5 September 2014

Available online 3 October 2014

### Keywords:

Composite column

Multiple spirals

Confinement

Axial load-carrying capacity

## ABSTRACT

This study elucidates experimentally and analytically the axial compressive load-carrying capacity and behavior of square composite steel and concrete columns confined by multiple interlocking spirals. The variables of the specimens included type of the lateral reinforcement (rectilinear hoops and multiple spirals), spacing of the lateral reinforcement, and shape of the structural steel section (cruciform and box-shaped). Specimens were tested under monotonically increased axial load. The test results demonstrated that the composite columns with multiple spirals achieved great axial load-carrying capacity and deformability because of the excellent concrete confinement attributed to the multiple interlocking spirals and the structural steel section. Smaller spacing of the spirals and larger area of the highly confined concrete in the composite columns resulted in the better strength and ductility of the columns. An analytical model was proposed to calculate the load–displacement relations of the specimens, and the model predicted well the behavior of the specimens. The effectiveness of the multiple interlocking spirals in the square composite columns was evident via this study.

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## 1. Introduction

The use of composite steel and concrete structures in medium- and high-rise buildings has been increased significantly in recent decades [1,2]. The composite column is one of the major composite structural members. Two types of composite columns are frequently used in practice. One is the concrete filled rectangular or circular steel tube. The other is the concrete encased steel section. The concrete encased steel composite columns comprise concrete, structural steel, longitudinal bars, and lateral reinforcement. Owing to the nature of concrete encased steel, the composite columns possess advantages such as high axial load-carrying capacity, high lateral stiffness compared to bare steel column, delaying the local buckling of steel elements, and great fire resistance.

Generally used in a circular cross section, spirally reinforced concrete columns can develop great axial load-carrying capacity and deformability [3–6]. The strength and deformability are attributed to the lateral confining stress generated by the spiral confinement [7–10]. Moreover, because of the characteristic of a continuously wound bar, the spirals used in a circular cross-sectional column are

time-saving and cost-effective in both fabrication and construction. However, the spirals are seldom employed in a square or a rectangular column in practical engineering since four corners of the square or rectangular cross section cannot be confined by the spirals. An innovative multi-spiral confinement was recently developed by Yin et al. [11] to enlarge the confined area for a rectangular reinforced concrete column. Fig. 1 shows one of the confinement details, using five interlocking spirals in which a large spiral is located at the center of the cross section and four small spirals are located at the corners. Yin et al. found experimentally that the interlocking multi-spiral confinement design exhibited greater strength and ductility capacities than a rectilinear hoop confinement design. The use of the five spirals in a square column is to take its superiority in concrete confinement and efficiency in automatic production in pre-fabricated columns. Automatic production of the spiral cages is common in today's precast construction industry. Production of the continuous spirals and assembly of the cages can be carried out effectively in the factory because of the cost effectiveness and lower demand of skilled labor. Fig. 2 shows the assembly sequence of the five-spiral reinforcement cage. Four small spirals at the corners successfully increase the confinement area. Furthermore, in practice, longitudinal bars and four small spirals are located at the corners to allow the continuation of the orthogonal beam reinforcement at beam-column joints.

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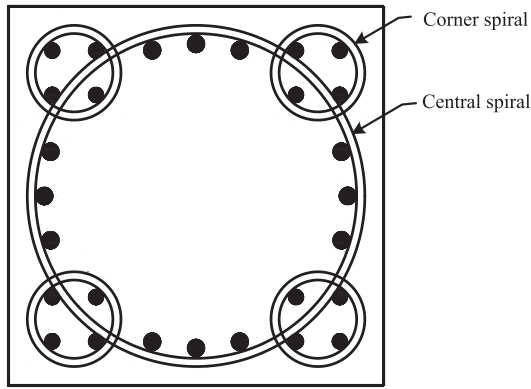


Fig. 1. Five interlocking spirals used in a square reinforced concrete column.

In this study, five-spiral confinement technique was applied to composite columns [12]. Nine columns were designed, including six spirally reinforced composite columns, two rectilinearly tied composite columns, and a reinforced concrete column. Specimens were tested under monotonically increased axial load to study the effects of multiple spirals on the strength and deformability of the composite columns. Moreover, an analytical model was proposed to predict the behavior of the specimens. However, this study emphasized the specimens subjected to concentric axial load.

Further research is needed to explore the behavior of the specimens when subjected to both axial and bending loads.

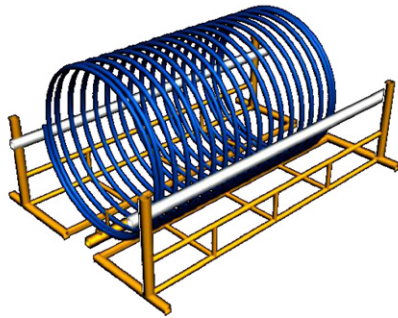
## 2. Experimental program

### 2.1. Design of the specimens

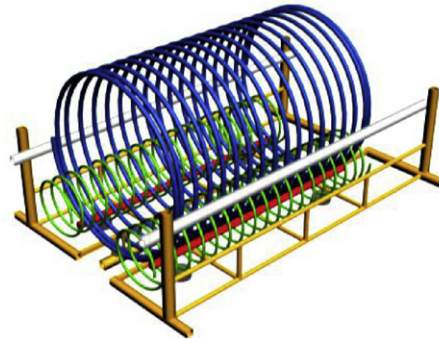
All the specimens were 600 mm square in cross section and 1200 mm in height. Fig. 3 presents the cross sections of the composite columns. Table 1 tabulates the details of the specimens. Each specimen has an individual designation to reflect its variables. The first two characters of the specimen designation denotes column types, where RC represents a reinforced concrete column; DH represents a composite column with a double H-shaped steel section; and BX stands for a composite column with a box-shaped steel section. The second group of characters denotes lateral reinforcement types, where SP indicates the spiral reinforcement; and TI represents the rectilinear hoop reinforcement. The last number denotes the pitch of the lateral reinforcement.

Two types of the structural steel section were used in the composite columns. The DH series of specimens consisted of a cruciform steel section formed by two H-shaped steel sections, H350 × 175 × 6 × 9 (dimensions in mm for depth, width, web thickness, and flange thickness, respectively). The BX series of specimens comprised a built-up box steel section, 275 × 275 × 10 × 10 (275 mm square and 10 mm thickness), welded by four steel plates. Both steel sections are frequently used in composite buildings. Moreover, these two steel sections were designed to attain almost identical cross-sectional area,

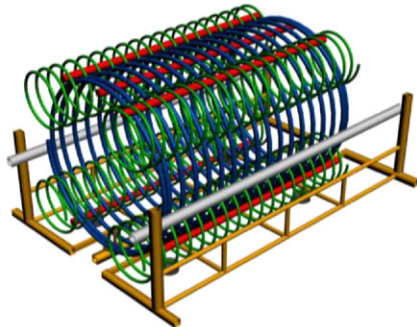
(a) Place and adjust spacing of a central large spiral



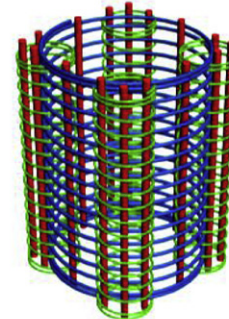
(b) Insert two corner small spirals at the bottom and adjust spacing



(c) Insert two corner small spirals at the top and adjust spacing



(d) Insert longitudinal bars and complete reinforcement cage



(Structural steel not shown for clarity)

Fig. 2. Assembly sequence of the five-spiral reinforcement cage.

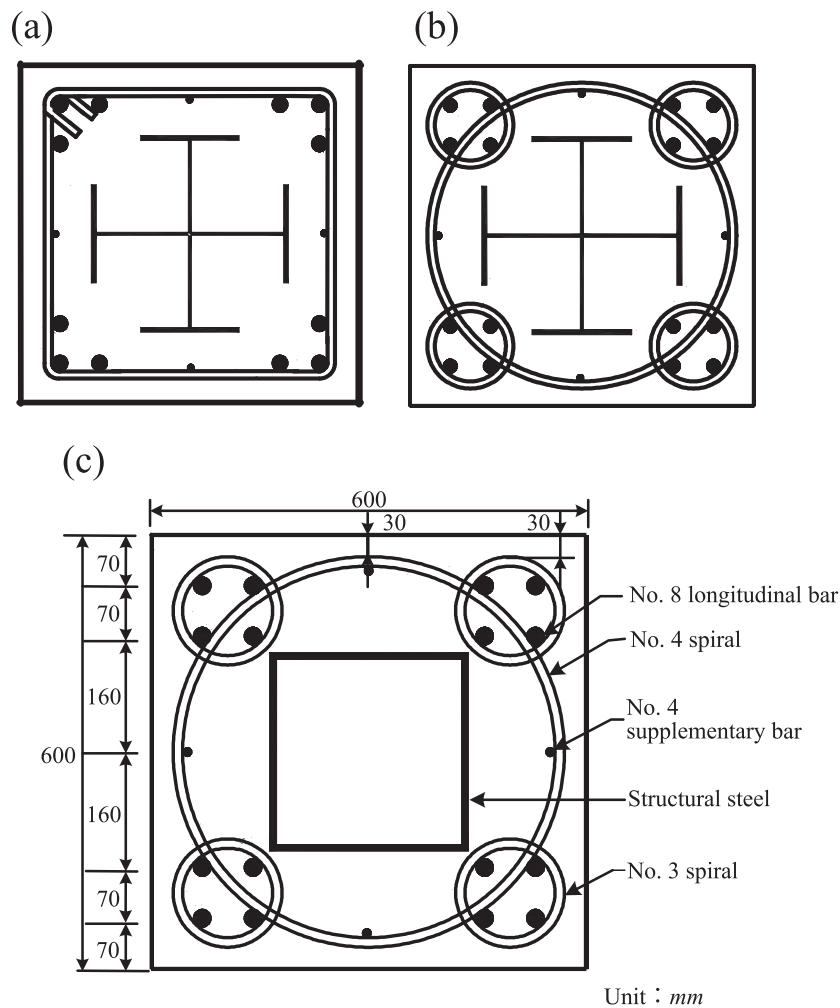


Fig. 3. Configurations of the cross sections: (a) rectilinearly tied reinforcement; (b) five-spiral reinforcement; (c) details of the BX-SP series of specimens.

**Table 1**  
Details of the specimens.

| Specimen designation | Structural steel section | Ratio of structural steel section (%) | Longitudinal bar     | Ratio of longitudinal bar (%) | Transverse reinforcement |               |                  |              |                      |                                      | Cross section configuration |
|----------------------|--------------------------|---------------------------------------|----------------------|-------------------------------|--------------------------|---------------|------------------|--------------|----------------------|--------------------------------------|-----------------------------|
|                      |                          |                                       |                      |                               | Central spiral           | Corner spiral | Rectilinear hoop | Spacing (mm) | Volumetric ratio (%) | Weight per unit length of column (N) |                             |
| RC-SP-75             | –                        | –                                     | 16 No. 8<br>12 No. 9 | 4.41                          | No. 4                    | No. 3         | –                | 75           | 1.25                 | 360                                  |                             |
| DH-TI-75             | 2-H350 × 175 × 6 × 9     | 2.87                                  | 12 No. 9             | 2.16                          | –                        | –             | No. 4            | 75           | 1.34                 | 298                                  |                             |
| DH-TI-90             | 2-H350 × 175 × 6 × 9     | 2.87                                  | 12 No. 9             | 2.16                          | –                        | –             | No. 4            | 90           | 1.11                 | 248                                  |                             |
| DH-SP-60             | 2-H350 × 175 × 6 × 9     | 2.87                                  | 16 No. 8             | 2.25                          | No. 4                    | No. 3         | –                | 60           | 1.56                 | 449                                  |                             |
| DH-SP-75             | 2-H350 × 175 × 6 × 9     | 2.87                                  | 16 No. 8             | 2.25                          | No. 4                    | No. 3         | –                | 75           | 1.25                 | 360                                  |                             |
| DH-SP-95             | 2-H350 × 175 × 6 × 9     | 2.87                                  | 16 No. 8             | 2.25                          | No. 4                    | No. 3         | –                | 95           | 0.99                 | 283                                  |                             |
| DH-SP-115            | 2-H350 × 175 × 6 × 9     | 2.87                                  | 16 No. 8             | 2.25                          | No. 4                    | No. 3         | –                | 115          | 0.81                 | 235                                  |                             |
| BX-SP-95             | □275 × 275 × 10 × 10     | 2.94                                  | 16 No. 8             | 2.25                          | No. 4                    | No. 3         | –                | 95           | 0.99                 | 283                                  |                             |
| BX-SP-110            | □275 × 275 × 10 × 10     | 2.94                                  | 16 No. 8             | 2.25                          | No. 4                    | No. 3         | –                | 110          | 0.85                 | 245                                  |                             |

Note: Reinforcing bar designation: No. 9 = D29, No. 8 = D25, No. 4 = D13, and No. 3 = D10.

**Table 2**

Yield and ultimate strengths of the structural steel and reinforcing bars.

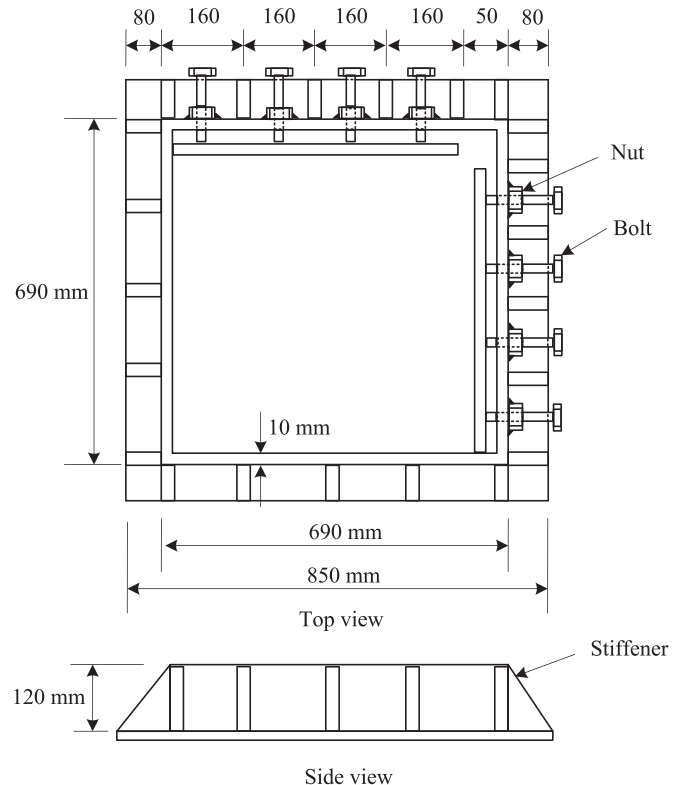
| Strength                | Steel plate thickness (mm) |     |     | Reinforcing bar |             |             |             |
|-------------------------|----------------------------|-----|-----|-----------------|-------------|-------------|-------------|
|                         | 6                          | 9   | 10  | No. 3 (D10)     | No. 4 (D13) | No. 8 (D25) | No. 9 (D29) |
| Yield strength (MPa)    | 437                        | 454 | 419 | 494             | 472         | 451         | 439         |
| Ultimate strength (MPa) | 546                        | 574 | 524 | 737             | 750         | 698         | 687         |

**Fig. 4.** Loading equipment and test setup.

and the ratios of the cross-sectional area of the structural steel section to the gross cross section are shown in Table 1.

The longitudinal bars used for the composite columns were located at the corners to prevent interference from steel beams. Twelve No. 9 (D29) longitudinal bars were used in the rectilinear hoop composite columns in which three bars were located at each corner of the column. However, 16 No. 8 (D25) bars were adopted for multi-spiral composite columns in which four bars were located at each corner. Furthermore, the cross-sectional area of 12 No. 9 (D29) bars is quite the same as that of 16 No. 8 (D25) bars, and the ratios of the cross-sectional area of the longitudinal bars to the gross cross section are tabulated in Table 1. The arrangement of the longitudinal bars is also shown in Fig. 3. Four No. 4 (D13) supplementary longitudinal bars were used to enhance the confinement. Most importantly, these bars had little effect on axial compressive strength because their lengths were 50 mm shorter than the column at both ends.

The TI series of specimens used traditional rectilinear hoop reinforcement. The SP series of specimens reinforced with multiple interlocking spirals, comprising a central large spiral and four corner small spirals. Fig. 3(c) shows details of the cross section of the BX-SP series of specimens. No. 4 (D13) bar was designed for the central spiral while No. 3 (D10) bar was used for corner spirals, considering the efficiency of the confinement. It has been recognized that the axial load-carrying capacity and deformability of a reinforced concrete column depend highly on the confinement attributed to the confined concrete core. Generally, the confined concrete core is defined as the cross-sectional area measured to the outside edges of the lateral reinforcement. The five interlocking spirals can obtain the same cross-sectional area of the confined concrete core as the rectilinear hoop arrangement. Nevertheless, the area becomes only 89% if a single central spiral is used in the column. The confinement due to lateral reinforcement can be further investigated while the specimens had the same area of the structural steel section and longitudinal

**Fig. 5.** End capping device used in the test.

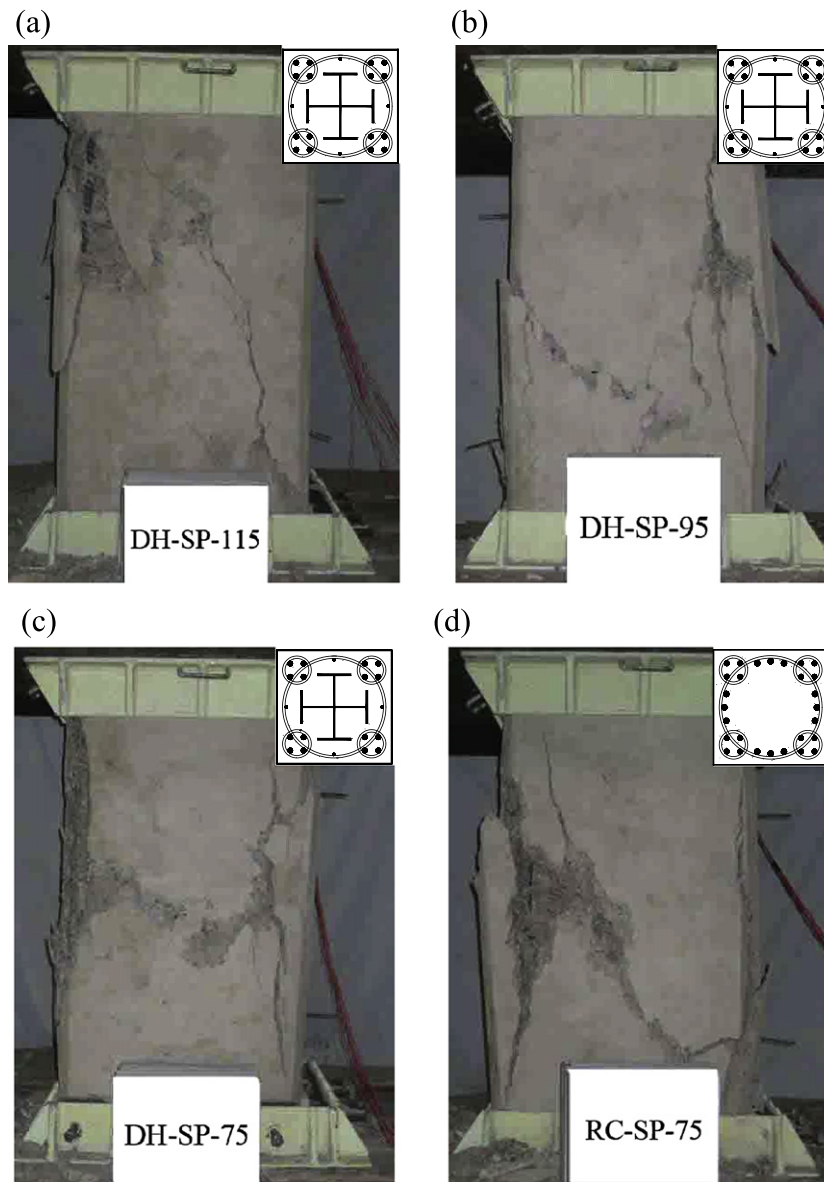


Fig. 6. Failure appearance of the specimens at peak load: (a) DH-SP-115; (b) DH-SP-95; (c) DH-SP-75; (d) RC-SP-75.

bars. The spacing of the lateral reinforcement ranged from 60 to 115 mm. Table 1 also lists the volumetric ratios of the lateral reinforcement and their weights per unit length of the column. The volumetric ratios varied from 0.81% to 1.56%, corresponding to the weight used of 235 to 449 N per unit length of the column.

## 2.2. Material properties

The specimens used ready-mix normal weight concrete. Standard concrete cylinders of 150 mm  $\times$  300 mm were cast to determine concrete compressive strength in accordance with ASTM test procedure [13]. Although the concrete compressive strength obtained from the cylinders under water-curing period of 28 days was 41.4 MPa, the average compressive strength of concrete cylinders cured in the same condition as the specimens was 34.6 MPa.

Coupons were cut from the flange and web of the rolled steel shape H350  $\times$  175  $\times$  6  $\times$  9 and steel plate used for box steel section. The structural steel was ASTM A572 Gr. 50 steel. The longitudinal bars

and spirals were ASTM A615 [14] Gr. 60 deformed bar. ASTM A370 [15] test procedure was followed to obtain the yield and ultimate strengths of the structural steel plates and deformed bars. Table 2 tabulates the average strengths of the steel plates and deformed bars.

## 2.3. Test apparatus and procedure

Fig. 4 shows the loading equipment and compression test setup for short columns. The loading equipment was a hydraulic jack with a capacity of 58,800 kN. An axial compressive force was applied to the specimens at a constant strain rate of 25  $\mu\epsilon/s$  in a monotonic manner. To ensure a uniform load distribution on the cross section of the column, both ends of the column were mounted by an end capping device and capped with high-strength gypsum. Fig. 5 shows the details of the end capping device which was made of steel plates. Through the use of the bolts and steel plates, the end capping device also exerted clamping forces to confine the column ends. During the test, linear variable differential transducers (LVDTs) were installed on the column sides to measure

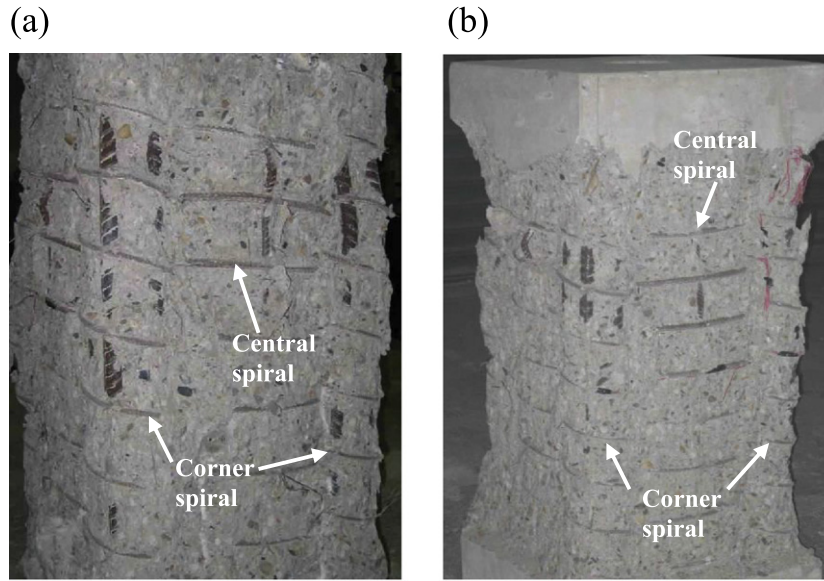


Fig. 7. Concrete core confined by five spirals: (a) specimen DH-SP-95; (b) specimen BX-SP-110.

the axial deformations. A high-speed data acquisition system was utilized to collect readings from LVDTs and axial load transducer. The test was terminated when the specimen reached collapse mode of failure or the axial load-carrying capacity dropped significantly.

### 3. Experimental results and discussions

#### 3.1. Observed behavior and failure mode

Similar behavior was observed for specimens reinforced with multiple spirals. Vertical minor cracks were first developed on the concrete, and, subsequently, these cracks were enlarged and resulted in crushing and spalling of the concrete cover. Fig. 6 presents the failure appearance of the specimens at the peak load. After the specimens reached their peak loads, the corner spirals fractured due to the lateral expansion of the concrete loaded in compression and the thrust by the buckled longitudinal bars. Consequently, the axial load-carrying capacity gradually decreased. Fig. 7 shows the appearance of the concrete core confined

by the multiple spirals. Both central and corner spirals confined the concrete well. At the end of the test, the central spiral fractured and caused rapid decrease of the load-carrying capacity of the specimens, as shown in Fig. 8.

For the TI series of specimens reinforced with rectilinear hoops, the failure was the fracture of the 135° bends of the rectilinear hoops, accompanied with the buckled longitudinal bars, after the specimens reached their peak loads. At the conclusion of the test, the failure included the severely buckled longitudinal bars, fractured rectilinear hoops, and seriously crushed confined concrete core, with significant drop of the load-carrying capacity. Fig. 9 shows the fracture of the rectilinear hoop and buckled longitudinal bars in the specimen DH-TI-90.

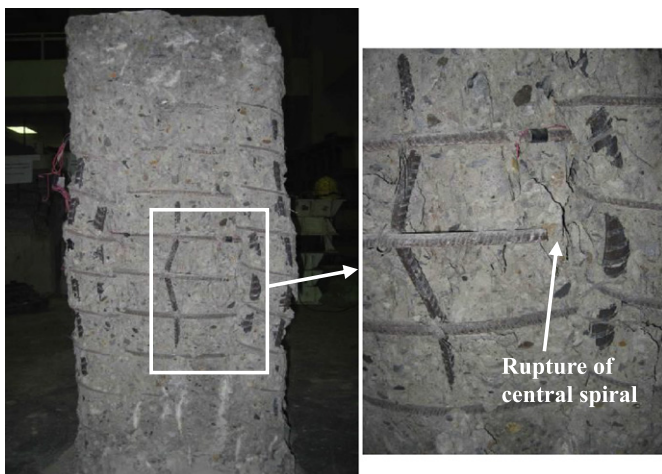


Fig. 8. Fracture of the central spiral in the specimen BX-SP-110.



Fig. 9. Fractured rectilinear hoop and buckled longitudinal bars in the specimen DH-TI-90.

**Table 3**  
Test results.

| Specimen  | Test peak load $P_{\text{test}}$ (kN) | Squash load $P_{\text{squash}}$ (kN) | Column strength ratio $\frac{P_{\text{test}}}{P_{\text{squash}}}$ | Confined concrete compressive strength $f'_{cc}$ (MPa) | Concrete compressive strength ratio $\frac{f'_{cc}}{f'_c}$ | Axial displacement at peak load $\delta_{p_u}$ | Post-peak axial displacement at 70% $P_u$ $\delta_{0.7P_u}$ | Ductility ratio $\frac{\delta_{0.7P_u}}{\delta_{p_u}}$ |
|-----------|---------------------------------------|--------------------------------------|-------------------------------------------------------------------|--------------------------------------------------------|------------------------------------------------------------|------------------------------------------------|-------------------------------------------------------------|--------------------------------------------------------|
| RC-SP-75  | 18,109                                | 17,075                               | 1.06                                                              | 38.51                                                  | 1.11                                                       | 5.28                                           | 24.84                                                       | 4.7                                                    |
| DH-TI-75  | 18,188                                | 17,428                               | 1.04                                                              | 36.65                                                  | 1.06                                                       | 3.84                                           | 24.96                                                       | 6.5                                                    |
| DH-TI-90  | 17,952                                | 17,428                               | 1.03                                                              | 35.55                                                  | 1.03                                                       | 4.32                                           | 31.80                                                       | 7.4                                                    |
| DH-SP-60  | 23,097                                | 17,577                               | 1.31                                                              | 58.83                                                  | 1.70                                                       | 5.04                                           | 50.76                                                       | 10.1                                                   |
| DH-SP-75  | 21,342                                | 17,577                               | 1.21                                                              | 50.62                                                  | 1.46                                                       | 6.48                                           | 62.40                                                       | 9.6                                                    |
| DH-SP-95  | 20,207                                | 17,577                               | 1.15                                                              | 45.31                                                  | 1.31                                                       | 6.48                                           | 53.16                                                       | 8.2                                                    |
| DH-SP-115 | 20,629                                | 17,577                               | 1.17                                                              | 47.29                                                  | 1.37                                                       | 5.28                                           | 23.76                                                       | 4.5                                                    |
| BX-SP-95  | 20,211                                | 17,701                               | 1.14                                                              | 44.78                                                  | 1.29                                                       | 3.84                                           | 26.76                                                       | 7.0                                                    |
| BX-SP-110 | 19,232                                | 17,701                               | 1.09                                                              | 40.20                                                  | 1.16                                                       | 3.72                                           | 21.96                                                       | 5.9                                                    |

### 3.2. Load–displacement behavior

Table 3 shows a summary of the test results. In order to evaluate the load-carrying capacity for different types of the columns, a squash load of the column,  $P_{\text{squash}}$ , was defined as follows:

$$P_{\text{squash}} = 0.85f'_c A_c + f_{ys} A_s + f_{yr} A_r \quad (1)$$

where  $f'_c$  is the concrete compressive strength;  $A_c$  is the concrete area;  $f_{ys}$  is the yield strength of the structural steel;  $A_s$  is the cross-sectional area of the structural steel;  $f_{yr}$  is the yield strength of the longitudinal bar; and  $A_r$  is the cross-sectional area of the longitudinal bar. Moreover,  $P_{\text{squash}}$  was calculated using the measured material strengths given in Table 2.

The squash load represents an axial compressive strength of the column by assuming the concrete crushing, and the structural steel and longitudinal bars yielding. Fig. 10 shows the normalized load–displacement curves for all the specimens. The axial loads were normalized to the squash load of the column for comparison purpose.

The spacing of the rectilinear hoop had little effects on the axial behavior as shown from DH-TI series of specimens, in Fig. 10(a). However, the closer spacing of the spirals enhanced axial load-carrying capacity and deformability of the columns as shown in Fig. 10(b) and (c) (DH-SP and BX-SP series of specimens). Compared to specimen RC-SP-75, specimen DH-SP-75 had better performance, as shown in Fig. 10(d), due to the presence of the structural steel. The structural steel section provided extra confining stress, and the highly confined concrete core surrounded by the structural steel section developed great concrete compressive strength and strain [16,17]. Moreover, the comparison of the load–displacement curves between specimens DH-SP-95 and BX-SP-95, in Fig. 10(e), demonstrated that specimen DH-SP-95 resulted in significantly greater deformability than specimen BX-SP-95 because the former had larger area of the highly confined concrete core than the latter.

### 3.3. Column strengths and confined concrete compressive strengths

As presented in Table 3, a column strength ratio was defined as  $P_{\text{test}}/P_{\text{squash}}$  which indicated the axial compressive strength enhancement of the column. The column strength ratios of DH-SP series of specimens with multiple spirals ranged from 1.15 to 1.31 which were considerably greater than those (1.03 and 1.04) of DH-TI series of specimens with rectilinear hoops. Furthermore, BX-SP series of specimens had the column strength ratios of 1.09 and 1.14. The strength enhancement by the multiple spirals was evident because the spirals could provide more even and higher lateral confining stress than rectilinear hoops. In addition, smaller spacing of the spirals resulted in higher column strength ratio that demonstrated in all DH-TI, DH-SP and BX-SP series of specimens.

The amount used of the transverse reinforcement of each specimen is shown in Table 1. With less transverse reinforcement, specimen DH-

SP-115 having multiple spirals reached higher axial load-carrying capacity as compared to specimen DH-TI-75 with rectilinear hoops. The use of the multiple spirals resulted in not only the greater load-carrying capacity but also the less cost than the use of the rectilinear hoops. The cost–benefit usage of the multiple spirals resulted also from the fabrication.

A confined concrete compressive strength  $f'_{cc}$  was derived to evaluate the concrete confinement effect due to the lateral reinforcement and the structural steel section. Considering the ultimate strength of the concrete and yielding of the structural steel and longitudinal bars at test peak load, the confined concrete compressive strength  $f'_{cc}$  can be determined from:

$$f'_{cc} = \frac{P_{\text{test}} - 0.85f'_c A_{c,\text{cover}} - f_{ys} A_s - f_{yr} A_r}{0.85A_{ch}} \quad (2)$$

where  $A_{c,\text{cover}}$  is the area of the concrete cover; and  $A_{ch}$  is the area of the confined concrete core which is defined as the cross-sectional area measured to the outside edges of the lateral reinforcement. A concrete compressive strength ratio was defined as  $f'_{cc}/f'_c$  where  $f'_c$  is the unconfined concrete compressive strength. Table 3 also lists  $f'_{cc}$  and concrete compressive strength ratios. For all the specimens, the concrete compressive strength ratios were all greater than unity. The concrete compressive strength ratios of the DH-SP series of specimens with multiple spirals ranged from 1.31 to 1.70 which were much higher than those (1.03 and 1.06) of the DH-TI series of specimens with rectilinear hoops. The multiple spirals can significantly enhance concrete confinement and, consequently, the confined concrete compressive strength.

### 3.4. Deformability and ductility

To evaluate the deformability of the columns, a ductility ratio  $\mu$  is defined as follows:

$$\mu = \frac{\delta_{0.7P_u}}{\delta_{p_u}} \quad (3)$$

where  $\delta_{p_u}$  is the axial displacement corresponding to the peak load; and  $\delta_{0.7P_u}$  is the post-peak axial displacement corresponding to 70% of the peak load. Fig. 11 shows the determination of the ductility ratio. The slope of the descending branch of the load–displacement curve had a substantial effect on the ductility ratio. Table 3 also presents the axial displacement of  $\delta_{p_u}$  and  $\delta_{0.7P_u}$ , and ductility ratios. Except for specimen DH-SP-115, all the composite columns had greater ductility ratios ( $\mu = 5.9$ –10.1) than the reinforced concrete column, specimen RC-SP-75 ( $\mu = 4.7$ ). Clearly it is because the structural steel provided not only the axial compressive strength but also the concrete confinement.

DH-SP series of specimens evidently indicated that decreasing the spacing of the spiral resulted in an increase of the ductility ratio. As the smaller spacing of the spirals was used, the lateral confining stress

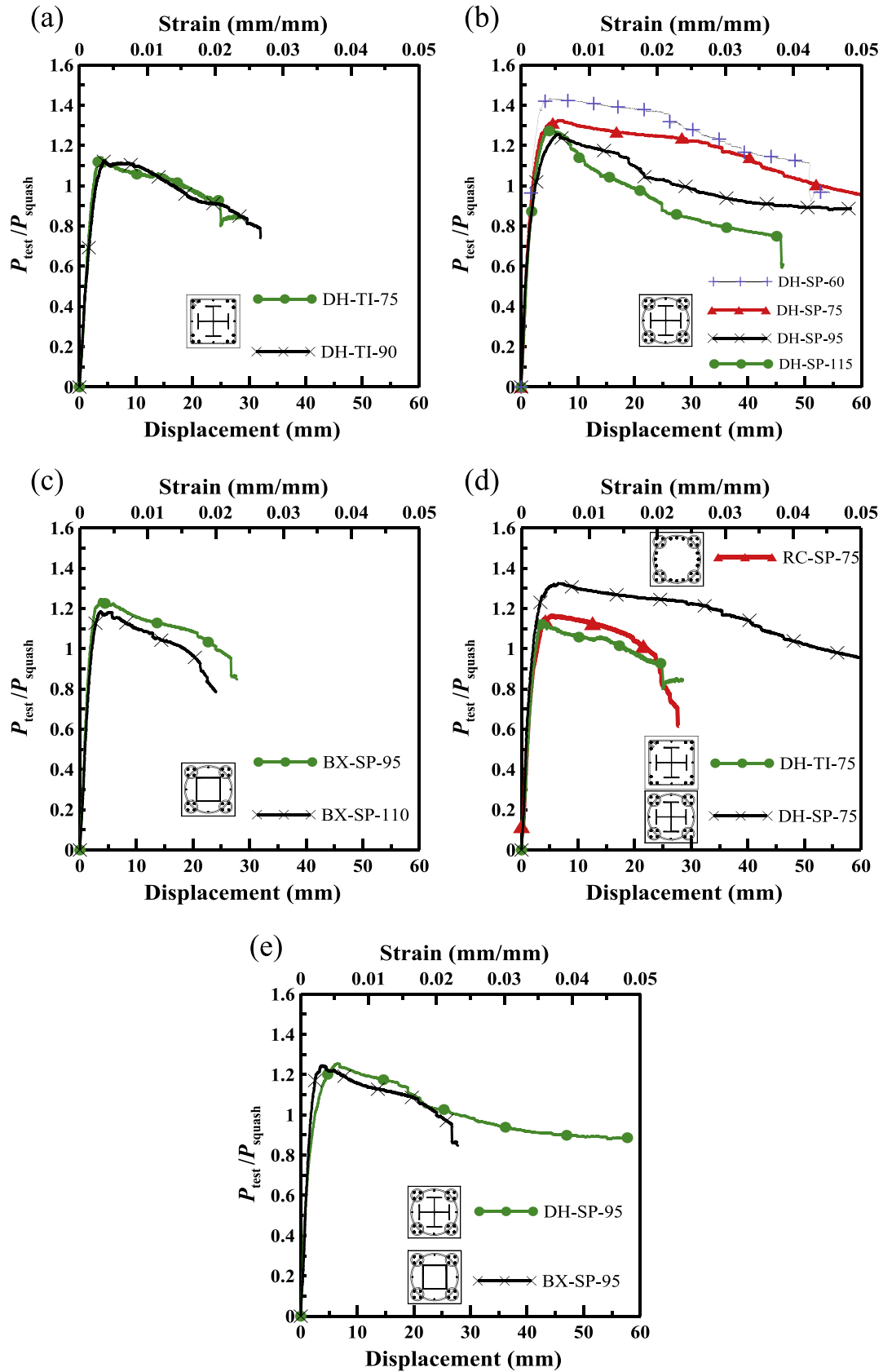


Fig. 10. Normalized load-displacement curves of the specimens.

contributed to the concrete confinement became large [7]. As a result, the concrete core was well confined and developed great compressive strength and deformability. As compared to specimen DH-TI-75

( $\mu = 6.5$ ), specimen DH-SP-75 reached higher ductility ratio ( $\mu = 9.6$ ) that demonstrated the multiple spirals provided better confinement than the rectilinear hoops. The ductility ratio of specimen DH-SP-95

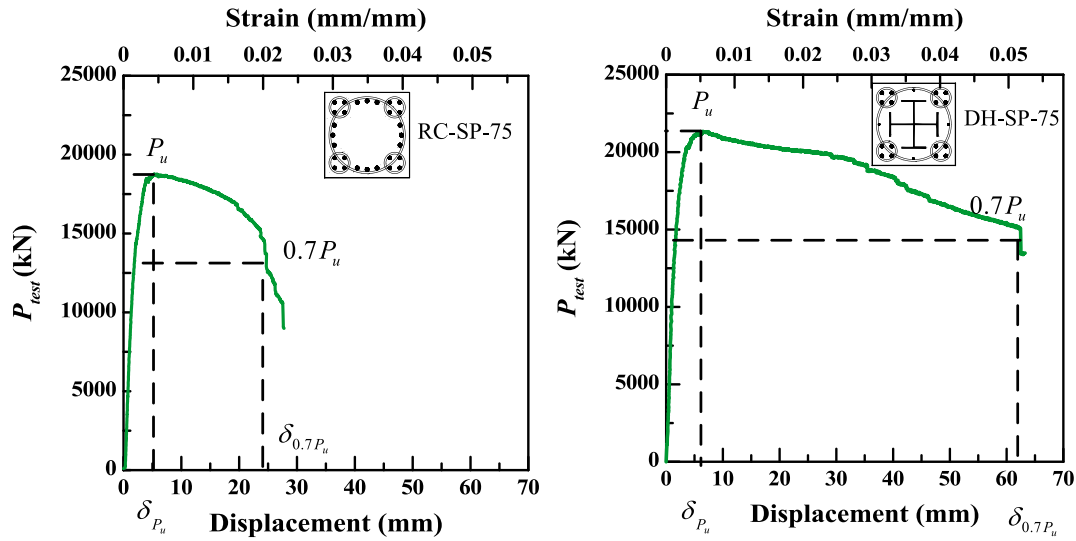


Fig. 11. Determination of ductility ratio.

( $\mu = 8.2$ ) was greater than that of specimen BX-SP-95 ( $\mu = 7.0$ ) because the former had larger area of the highly confined concrete core than the latter as mentioned earlier.

#### 4. Modeling the behavior of specimens

##### 4.1. Analytical modeling

An analytical model was proposed to calculate the axial compressive strength and load–displacement relations of the specimens. The axial compressive strength of the column is contributed from the strength of each structural material. In order to obtain the load–displacement relations of the column, the constitutive models of the materials are specified as follows.

Considering the confinement effects contributed from the transverse reinforcement and structural steel, the concrete in the cross section of the column is categorized into three types: unconfined concrete, partially confined concrete, and highly confined concrete, as shown in Fig. 12 [16, 17]. The unconfined concrete is the concrete outside the spirals. The partially confined concrete is the concrete confined by the spirals. The

highly confined concrete is the concrete enclosed by the structural steel, confining by both spiral and structural steel. Stress–strain relations for the confined concrete proposed by Mander et al. [7] were used. A compressive stress–strain curve ( $f_c$  versus  $\epsilon_c$ ) for confined concrete can be calculated based on  $f'_{cc}$  and  $\epsilon_{cc}$ , where  $f'_{cc}$  is the maximum compressive stress of the confined concrete; and  $\epsilon_{cc}$  is the corresponding strain. Based on the tests, the  $f'_{cc}$  and  $\epsilon_{cc}$  can be calculated by taking into account the confinement effect due to the lateral confining stress.

$$f'_{cc} = K f'_{co} \quad (4)$$

$$K = -1.254 + 2.254 \sqrt{1 + \frac{7.94 f'_l}{f'_{co}} - 2 \frac{f'_l}{f'_{co}}} \quad (5)$$

$$\epsilon_{cc} = \epsilon_{co} \left[ 1 + 5 \left( \frac{f'_{cc}}{f'_{co}} - 1 \right) \right] \quad (6)$$

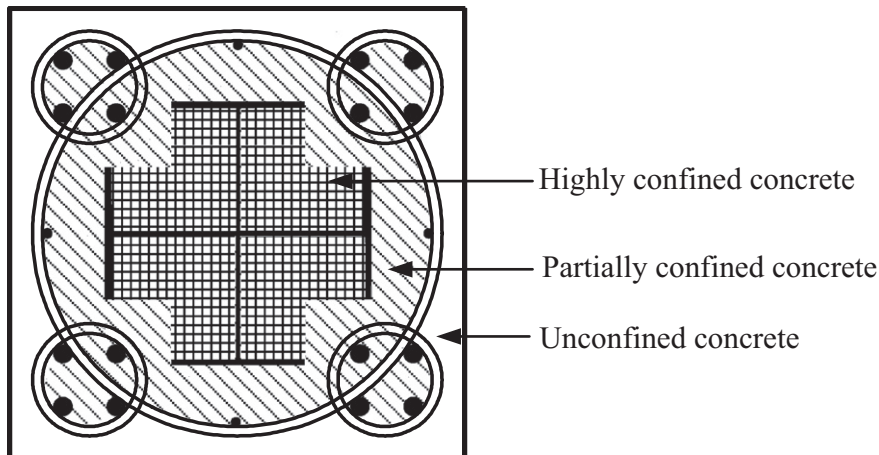


Fig. 12. Areas of unconfined, partially confined, and highly confined concrete.

**Table 4**  
Confinement factors and comparison between experimental and analytical results.

| Specimen                 | Confinement factor for partially confined concrete $K_p$ | Confinement factor for highly confined concrete $K_h$ | $P_{analy}$ (kN) | $\frac{P_{test}}{P_{analy}}$ |
|--------------------------|----------------------------------------------------------|-------------------------------------------------------|------------------|------------------------------|
| RC-SP-75                 | 1.669                                                    | –                                                     | 20,179           | 0.90                         |
| DH-TI-75                 | 1.542                                                    | 1.634                                                 | 20,271           | 0.90                         |
| DH-TI-90                 | 1.452                                                    | 1.608                                                 | 19,928           | 0.90                         |
| DH-SP-60                 | 1.780                                                    | 1.795                                                 | 22,056           | 1.05                         |
| DH-SP-75                 | 1.653                                                    | 1.674                                                 | 20,987           | 1.00                         |
| DH-SP-95                 | 1.529                                                    | 1.638                                                 | 20,512           | 0.99                         |
| DH-SP-115                | 1.443                                                    | 1.613                                                 | 20,190           | 1.02                         |
| BX-SP-95                 | 1.529                                                    | 1.786                                                 | 20,756           | 0.97                         |
| BX-SP-110                | 1.461                                                    | 1.773                                                 | 20,495           | 0.94                         |
| Average                  |                                                          |                                                       |                  | 0.96                         |
| Coefficient of variation |                                                          |                                                       |                  | 0.06                         |

where  $K$  is the confinement factor for confined concrete;  $f_l$  is the effective lateral confining stress; and  $f'_{co}$  and  $\epsilon_{co}$  are the unconfined concrete compressive strength and the corresponding strain, respectively. A stress–strain curve for unconfined concrete can be also specified based on  $f'_{co}$  and  $\epsilon_{co}$ . Moreover, to account for size effect, the unconfined concrete strength was set to 29.4 MPa which was obtained by multiplying a factor of 0.85 to the concrete compressive strength.

As observed from the test, the structural steel and longitudinal bars experienced no strain hardening, and the structural steel embedded in the core concrete remained its original shape without the sign of local buckling. Therefore, a stress–strain curve with linearly elastic, perfectly plastic behavior was used to model the structural steel. However, the longitudinal bars buckled after the columns reached their peak loads. The stress–strain curve for the longitudinal bar was assumed to a piecewise linear curve: linearly elastic, perfectly plastic, linearly dropped to 40% of the yield strength, and maintaining constant afterwards. The drop began at the axial strain of  $\epsilon_{co}$ , representing the buckling of the longitudinal bar occurred when the unconfined concrete cover spalled.

#### 4.2. Analytical results

The confinement factors  $K_p$  and  $K_h$  for partially and highly confined concrete, respectively, are listed in Table 4. The effects of the spiral spacing on the concrete confinement are demonstrated in the confinement factors. Smaller spiral spacing results in higher confinement factors. Because the confinement factor  $K_h$  for highly confined concrete takes into account lateral confining stresses from both the spiral and structural steel, the confinement factors for highly confined concrete are greater than those for partially confined concrete. Based on the confinement factors, the calculated compressive stress–strain curves for confined concrete are presented in Fig. 13.

Based on the assumption of axial strain compatibility for axial compressive stub composite column, the axial load of the composite column can be calculated by summing the individual strength from each structural material. The axial load of the composite column can be calculated as a function of the axial strain.

$$P_{analy} = f_{uc}A_{uc} + f_{pc}A_{pc} + f_{hc}A_{hc} + f_sA_s + f_rA_r \quad (7)$$

where  $f_{uc}$  and  $A_{uc}$  are the stress and area of the unconfined concrete, respectively;  $f_{pc}$  and  $A_{pc}$  are the stress and area of the partially confined concrete, respectively;  $f_{hc}$  and  $A_{hc}$  are the stress and area of the highly confined concrete, respectively;  $f_s$  is the stress of the structural steel; and  $f_r$  is the stress of the longitudinal bar.

Fig. 14 depicts the experimental and analytical axial load–displacement curves of the DH-SP series of specimens. The predicted behavior of the axial load–displacement relations is in good agreement

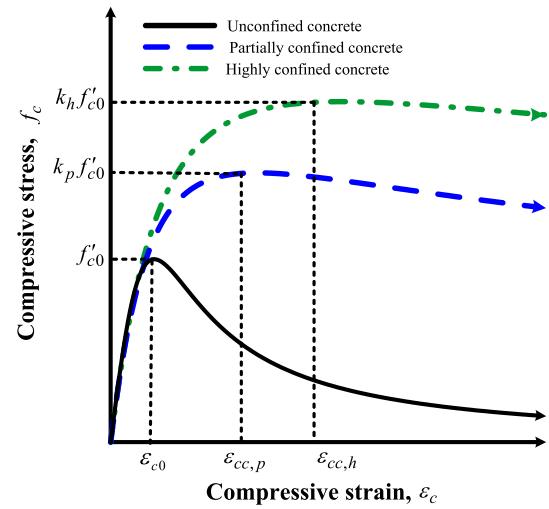


Fig. 13. Stress–strain curves for various concretes.

with the test results. Table 4 tabulates the maximum analytical axial loads for each specimen. As indicated from the ratios of  $P_{test}$  to  $P_{analy}$  in Table 4, the analytical model can predict well the peak test loads of the specimens. The average ratio of  $P_{test}$  to  $P_{analy}$  is 0.96 and the corresponding coefficient of variation is 0.06. Nevertheless, the average ratio of  $P_{test}$  to  $P_{squash}$  in Table 3 is 1.14. The squash loads underestimate the peak test loads of the specimens. The analytical model is more accurate to predict the peak test loads compared with the squash load calculation because the confinement effects on the core concrete are considered in the analytical model.

#### 5. Conclusions

Based on the test results of the nine full-scale square short columns confined by multiple spirals and the analytical modeling the behavior of the specimens, the following conclusions can be drawn.

1. The design of multiple interlocking spirals has been experimentally proven to be able to extend its application to square composite columns successfully because the multiple spirals can enhance concrete confinements.
2. The square composite columns with multiple spirals showed significant capability of axial compressive strength and deformation without a rapid deterioration of axial strength after reaching the peak load, and the performance was superior than that of the rectilinearly tied composite columns.
3. Because of the contribution of the structural steel on the confinement, the composite columns with multiple spirals demonstrated better strength and ductility than the reinforced concrete column with multiple spirals. The larger the area of the highly confined concrete surrounded by the structural steel section, the higher the strength and deformability of the columns.
4. Decreasing the spiral spacing resulted in the increase of the concrete compressive strength in the confined concrete core, axial load-carrying capacity, and ductility.
5. The proposed analytical model predicted well the behavior of axial load–displacement relations and axial compressive strength of the composite column reinforced by multiple interlocking spirals.

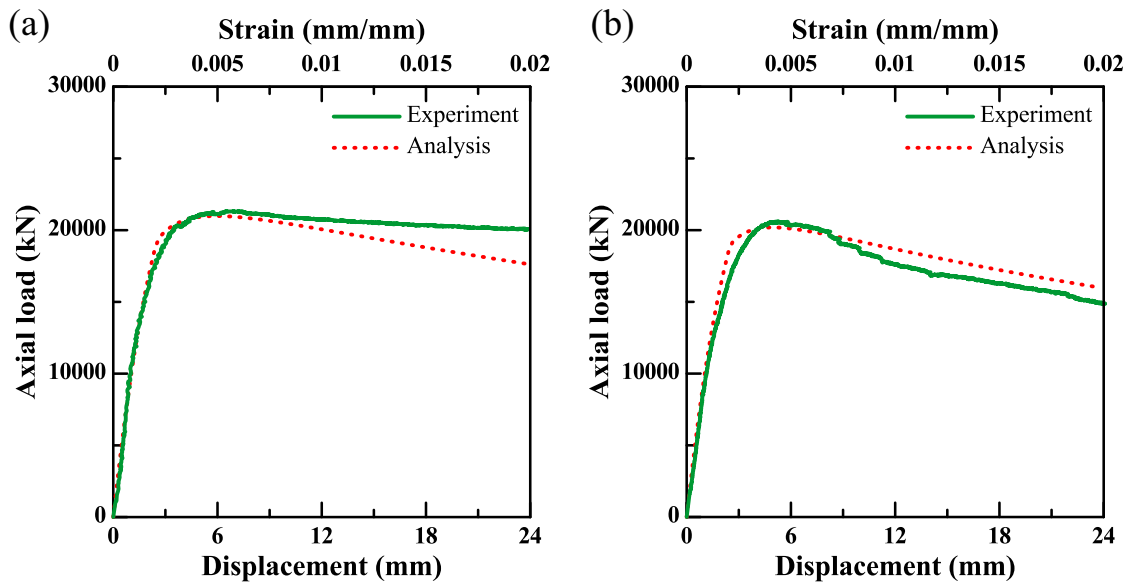


Fig. 14. Experimental and analytical axial load–displacement curves of the specimens: (a) DH-SP-75; (b) DH-SP-115.

### Acknowledgments

The authors would like to thank the Ruentex Engineering & Construction Co., Ltd. of Taiwan for financially supporting this research.

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