AXIAL STRENGTH AND DUCTILITY OF RECTANGULAR SRC COLUMNS WITH INNOVATIVE DOUBLE-SPIRAL CONFINEMENTS

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ABSTRACT:

A series of full-scale rectangular steel reinforced concrete (SRC) columns confined with a new type of double-spiral were tested under monotonic axial compression. The double-spiral is a device of two interconnected spirals including a circular spiral at the center and a "star-shaped spiral" surrounding the perimeter of the rectangular column. The innovative application of the star-shaped spiral to rectangular SRC columns is to take its superiority in concrete confinement at the four corners of the rectangular column as well as its efficiency in automatic production for the precast construction industry. The major parameters of this study included the cost effectiveness of the double-spiral, the axial strength and the ductility of the spirally confined SRC columns. As compared to the reinforced concrete column tied with traditional rectangular hoops, the test results revealed that, with significant cost savings of the confinement reinforcement, the SRC columns confined with the double-spiral demonstrated excellent capability in both strength and ductility.

KEYWORDS: Double-Spiral; SRC Column; Strength; Ductility; Precast Construction; Cost Effectiveness.

INTRODUCTION

A successfully designed steel reinforced concrete (SRC) building may not only enjoy advantages of the steel (S) and the reinforced concrete (RC) structures, but also apply the two parts in a supplementary way to reach the safer and more cost-effective goals. In a eugenic perspective, the SRC structure is like a "eugenic baby" as an outcome of the "marriage" of the S and the RC structures [Weng et al., 2008].

For a concrete-encased SRC column, the concrete cladding the steel column surface may perform the following functions: (1) provision of fireproof coating of the steel column; (2) enhancement of rust protection of the steel column; (3) reduction in probability of buckling of the steel column. Traditionally, the confinement reinforcements in a rectangular SRC column typically consist of rectangular hoops (ACI, 2008; AIJ, 2001). Each of the hoops is formed with a single steel bar and closed at both ends by two hooks. The confinement reinforcements in the column are designed to hold the longitudinal bars in position and to provide the column with shear strength and passive confinement stress for the core concrete. However, experiences from the field practice indicated that the hoops with the 135-degree bend are not easy to setup in the SRC column, and the entire process is heavily relied on skilled labors, which is time-consuming and costly.

It is known that the confining efficiency of the confinement cage in a reinforced concrete column is influenced by both the geometry and the spacing of the confinement steel (Darwin, 1977; Mander et al., 1988). As compared to the rectangular hoops, the circular spirals in the columns have been shown to be more effective in concrete confinement (Shah et al., 1983; Sheikh and Toklucu, 1993). In addition, automatic production of the spiral cages are common in today's precast factory. It is because of the cost effectiveness and the lower demand of skilled labors which make the spiral cages a potential competitor. However, applications of the circular spirals to the rectangular cross-section RC and SRC columns are not common in today's engineering practice because the concrete at the four corners of the rectangular columns can not be effectively confined by the circular spirals.

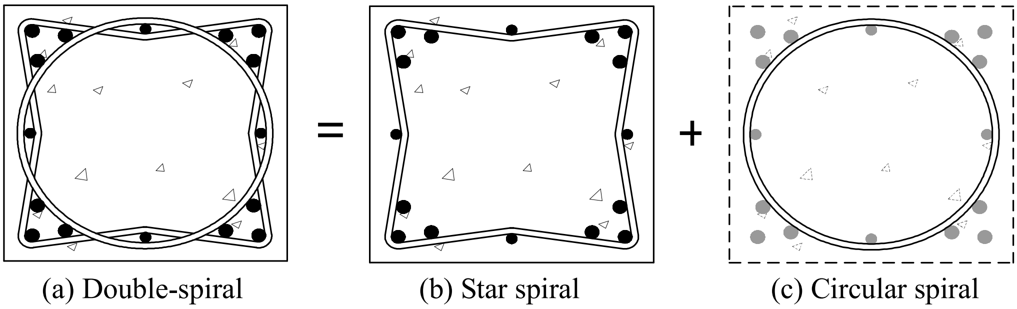


Fig. 1 The innovation of the "double-spiral" for a rectangular RC column

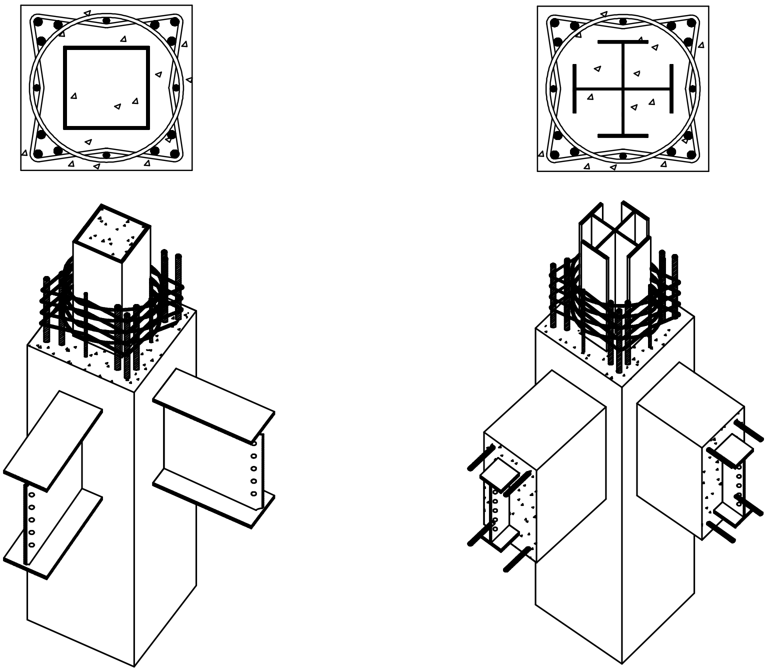


Fig. 2 Rectangular SRC columns confined with the double-spiral

As shown in Figs. 1 and 2, the double-spiral confinements will effectively solve the problem of the unconfined concrete at the four corners of rectangular RC and SRC columns. The concept of applying the double-spiral to rectangular columns was first put forward in 2006 by Dr. Y. L. Yin, CEO of Ruentex Group. The double-spiral is a device of two interconnected spirals including a circular spiral at the center and a star-shaped spiral surrounding the perimeter of the rectangular column. The innovative configuration breaks through the application restriction of the conventional spiral confinement to circular columns, overcomes the shortcomings of spiral application to rectangular cross-sectional columns and facilitates sound confinement of spiral to concrete at the corners of the rectangular column. Moreover, as the double-spiral can be manufactured with automatic machines in the precast factory, they are expected to substantially reduce manpower in bonding of conventional rectangular hoops and shorten the construction period.

The objective of this research is to investigate experimentally the efficiency of applying the double-spiral to the rectangular SRC columns. The major parameters of this study included the cost effectiveness of the double-spiral, the strength and ductility of the SRC columns. It is also hoped that this study will provide further insight on the mechanical behavior of this new type of SRC columns.

2. EXPERIMENTAL PROGRAMS

As shown in Table 1, a total of eight full-scale short columns were tested in monotonic axial compression, including six double-spirally confined SRC columns and two RC columns. All column specimens are 600 mm square and 1200 mm height. Two types of steel section in the SRC columns were investigated, including the welded built-up box section and the cross-H section. Specimens RC1 and RC2 were served as the benchmark for comparison purpose, and they were provided with the same total amount of longitudinal steel to yield the same expected compressive strength as for the SRC columns. The specimen RC1 was confined with the double-spiral; and the specimen RC2 was tied with the rectangular hoops.

In Table 1, the last column indicates the design guide used to determine the amount and spacing of the confinement reinforcement for each specimen. The "reduction factor" represents the "cost effectiveness" in terms of the volume ratio of the confinement steel for a specimen designed according to the Taiwan SRC Code (2004) or the Weng's formula (Weng et al. 2008; see Appendix for more details), relative to the volume of confinement steel needed if designed according to the ACI-318 Code (2008). In this study, the spacing of the confinement steel varies from 90 to 150 mm. The smallest reduction factor is 65% for specimens SRC5 and SRC6; both were designed according to the Weng's formula. The actual weight of the confinement steel per unit length of column used for each specimen is also shown in the table, which ranges from 226 to 405 N/m.

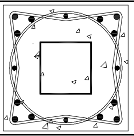
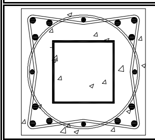
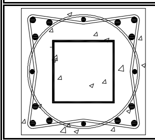
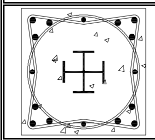
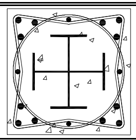
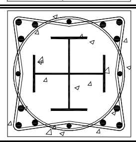
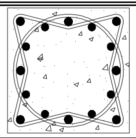
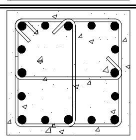
The steel shapes in the SRC columns included the cross-H and box sections. Steel plates of 6 and 9 mm thick were used, and the yield stresses vary from 386 to 421 MPa. The averaged compressive strength of the normal weight concrete is 38.0 MPa. The #8(D25), #10(D32) and #11(D36) deformed bars with yield stresses of 469, 452 and 530 MPa, respectively, were served as longitudinal bars. The #3(D10) and #4(D13) deformed bars with yield stresses of 552 and 525 MPa, respectively, were used as the confinement reinforcements.

Fig. 3 The 58800 kN test machine and the set-up of the test

Figure 3 shows the setup of the full-scale axial compression test of the short columns. A 58,800 kN (6,000 metric ton) hydraulic jack was used to apply the compressive force at a constant strain rate of 0.03 mm/sec. To achieve a more uniform load distribution on the specimen, an end cap was mounted on each end of the column.

During the test, a LVDT (linear variable differential transformer) extensometer was attached on the side of the specimen to monitor the axial shortening. To measure the strains within the specimens, strain gages were glued on the selected surfaces of the steel section and the reinforcing bars before casting the concrete.

Table 1 Column cross-section, designation and details of confinement reinforcements

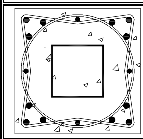
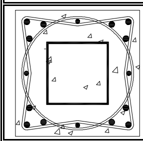
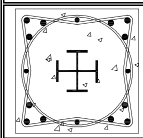
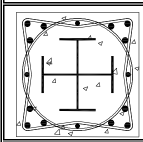
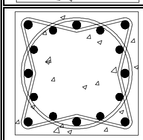
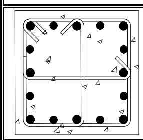
Column Cross-Section	Specimen Designation	Steel Ratio (ρ)	Spiral/Hoop Size		Spiral/Hoop Spacing (mm)	Spiral/Hoop Weight (N/m)	Spiral Reduction Factor	Spiral/Hoop Design Guide
			Circle	Star				
	SRC1-SB-TWN-115	1.63%	#4	#4	115	325	0.86	Taiwan SRC Code
	SRC2-SB-TWN-130	2.91%	#4	#4	130	286	0.78	Taiwan SRC Code
	SRC3-SB-TWN-100	2.91%	#4	#3	100	282	0.78	Taiwan SRC Code
	SRC4-SC-WENG-125	1.66%	#4	#4	125	298	0.80	Weng's Formula
	SRC5-SC-WENG-150	2.91%	#4	#4	150	248	0.65	Weng's Formula
	SRC6-SC-WENG-125	2.91%	#4	#3	125	226	0.65	Weng's Formula
	RC1-S-ACI-100	N.A.	#4	#4	100	376	1.00	ACI-318 Code
	RC2-H-ACI-90	N.A.	#4		90	405	1.00	ACI-318 Code

Note: (1) Column height：1200 mm；Cross-section dimensions：600 × 600 mm
(2) Steel sections in SRC columns：
Box section in SRC1: □250× 250 × 6× 6; ρ = 1.63%
Box section in SRC2 and SRC 3: □300× 300 × 9× 9; ρ = 2.91%
Cross H in SRC4: 2H220 × 100× 6 × 9; ρ = 1.66%
Cross H in SRC5 and SRC 6: 2H350 × 175× 6 × 9; ρ = 2.91%
(3) Longitudinal bars in SRC Columns：12#8(D25)；ρ_r = 1.69%
(4) Spiral reinforcements：#3(D10) or #4(D13)
(5) Longitudinal bars in RC columns：RC1 and RC2：8 # 10(D32) and 8 # 11(D36)；ρ_r = 4.05%

3. RESULTS AND DISCUSSIONS

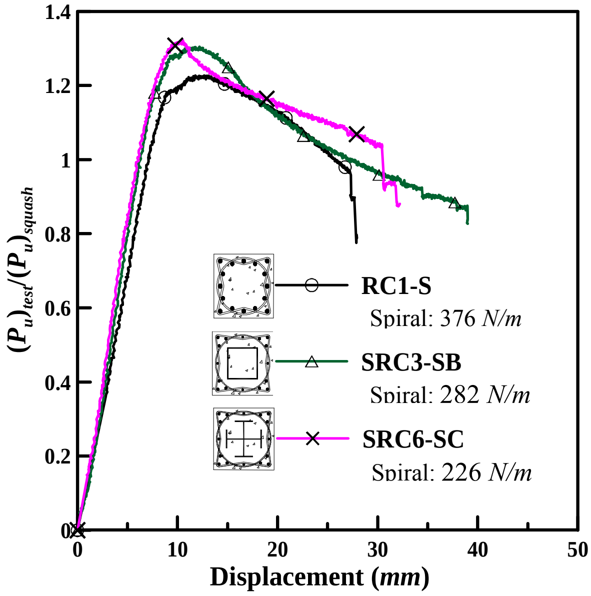
Table 2 summarizes the axial strength and the ductility ratios of the SRC and RC columns tested in this study, in which $(P_u)_{test}$ and $(P_u)_{squash}$ are the ultimate compressive strength from the test and the calculated squash strength of the column, respectively. The ductility index, μ , is defined as the ratio of the axial strain measured at 70% of the post-peak load, $\varepsilon_{0.7Pu}$, to the strain recorded at the peak load, ε_{Pu}. It is observed from the table that the strength ratios, $(P_u)_{test}/(P_u)_{squash}$, of the double-spirally confined SRC columns, SRC1 to SRC6, range from 1.24 to 1.32, which are significantly larger than that of 1.13 of the traditionally hoop-tied RC column, RC2. In addition, it is found that the ductility indices of the double-spiral SRC columns, SRC1 to SRC6, range from 3.03 to 3.99, which are also much greater than that of 2.15 of the traditionally hoop-tied RC column, RC2. These observations suggest that, with same amount of longitudinal steel, the double-spiral SRC columns are superior both in strength and ductility to those of the traditional RC column tied with rectangular hoops.

Table 2 Evaluation of strength, ductility and cost effectiveness of the tested specimens

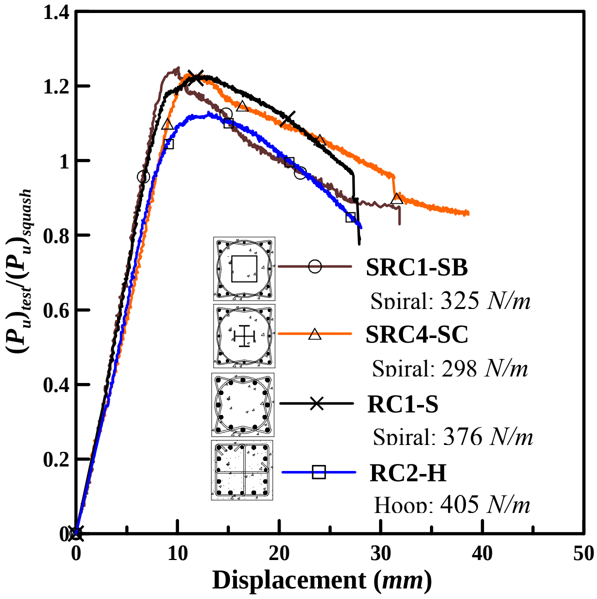
Column Cross-Section	Specimen Designation	$(P_u)_{test}$ (kN)	Strength Ratio $\frac{(P_u)_{test}}{(P_u)_{squash}}$	Ductility Index, μ $\frac{\delta_{0.7P_u}}{\delta_{P_u}}$	Cost Effectiveness: Weight of Hoop/Spiral (N/m)	Cost Effectiveness: Reduction Factor	Design Guide
	SRC1-SB-TWN-115	15559	1.25	3.21	325	0.86	Taiwan SRC Code
	SRC2-SB-TWN-130	17913	1.29	3.36	286	0.78	Taiwan SRC Code
	SRC3-SB-TWN-100	18139	1.30	3.12	282		
	SRC4-SC-WENG-125	15323	1.24	3.18	298	0.80	Weng's Formula
	SRC5-SC-WENG -150	18541	1.32	3.99	248	0.65	Weng's Formula
	SRC6-SC-WENG -125	18639	1.32	3.03	226		
	RC1-S-ACI-100	17501	1.23	2.35	376	1.00	ACI-318 Code
	RC2-H-ACI-90	16108	1.13	2.15	405	1.00	ACI-318 Code

Note: (1) $(P_u)_{squash}$ is the calculated squash strength of column: $(P_u)_{squash} = 0.85\,(f_c')_{test}\,A_{cc}+A_s(f_{ys})_{test}+A_r(f_{yr})_{test}$
(2) The ductility index, μ , is defined as the ratio of the axial strain measured at 70% of the post-peak load, $\varepsilon_{0.7Pu}$, to the strain recorded at the peak load, ε_{Pu}.

The cost effectiveness of the lateral reinforcements of each specimen is also shown in Table 2. As mentioned earlier, the reduction factor represents the cost saving of the confinement steel for a specimen designed according to the Taiwan SRC Code or the Weng's formula, relative to the amount of confinement steel needed if designed according to the ACI-318 Code. As compared to the reduction factor of 1.0 for the bench mark RC column, RC2, the smallest reduction factor is 65% for SRC specimens SRC5 and SRC6. The weight of confinement reinforcement per unit length of column used for specimens SRC5 and SRC6 are only 248 and 226 N/m, which is much more economical than that of 405 N/m for specimen RC2. These observations reveal that, with a significant saving of 35% of the confinement steel, the double-spirally confined SRC columns can still perform better, both in strength and ductility, than the traditional hoop-tied RC column.

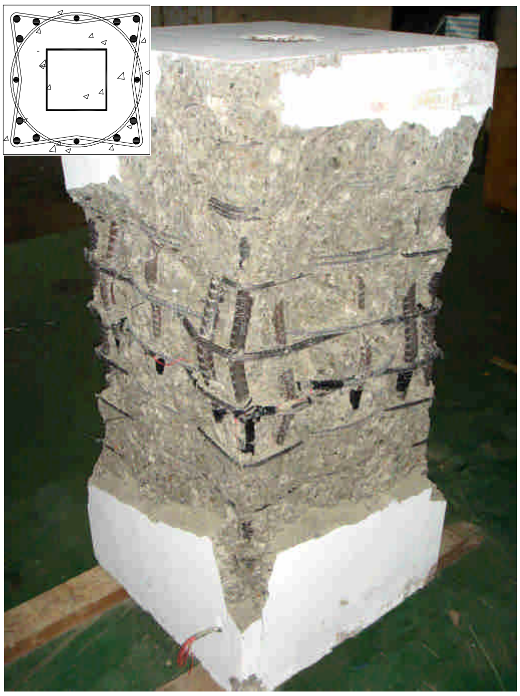


(a)



(b)

Fig. 4 Comparisons of normalized load-displacement curves of RC and SRC columns



(a) Specimen SRC1

(b) Specimen SRC3

Fig. 5 Double-spiral confined SRC columns after compression test

Figure 4 makes a comparison between the normalized load-displacement curves between the double-spiral SRC columns and the traditional hoop-tied RC columns. It is observed from Figs. 4(a) and (b) that the strength ratios and the ductility of the double-spiral SRC columns are all superior to those of the RC columns. The rectangular SRC columns confined with double-spiral showed significant capability of sustaining large deformation without quick deterioration of axial strength after reaching the peak load. In addition, Figs. 5(a) and (b) show the final conditions of specimens SRC1 and SRC3 after removing the spalled concrete cover. It is observed that the concrete confined by the double-spiral was generally remained sound, which indicates that the double-spiral provided satisfactory confinement effect to the SRC columns.

4. SUMMARY AND CONCLUSIONS

This paper presents an innovative application of double-spiral confinements to SRC columns with rectangular cross-section. A series of full-scale SRC columns with double-spiral confinements were tested under monotonic compression. For comparison purpose, two reinforced concrete columns of the same size were also tested. The following conclusions can be drawn based on the test results of this study:

1. A new type of double-spiral confinement reinforcement has been experimentally proven to be able to successfully applied to the rectangular SRC columns.
2. As compared to the RC column tied with rectangular hoops, the SRC columns confined with the new double-spiral demonstrated excellent performances in both strength and ductility.
3. As compared to the ACI-318 Code requirements for confinement reinforcements, the test results indicated that the Weng's formula can provide significant cost benefit in savings of the confinement steel.
4. The experimental results showed that, with satisfactory performances in strength and ductility, the double-spiral confinement reinforcement designed according to the Weng's formula needs only 65% of the volume of the confinement steel if designed according to the ACI-318 Code.
5. In general, the test results have demonstrated the advantages in "strength and ductility improvement" as well as in "cost effectiveness" of applying the newly innovated double-spiral to rectangular SRC columns.
6. For seismic safety, the rectangular SRC columns confined with the double-spiral showed significant capability of sustaining large deformation without quick deterioration of axial strength after reaching the peak load, which is one of the important characteristics for achieving successful seismic resistance.

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APPENDIX: The "Weng's Formula" for Design of SRC Column Confinement Reinforcements

In recognition of the superior confinement effect provided by the flanges of the steel section in the SRC column, Weng et al.(1998; 2008) proposed a new set of formulas for the design of confinement reinforcements in the SRC columns to account for this beneficial effect. It was proposed that

1. For a spirally confined SRC column, the volumetric ratio, ρ_s, of the spiral reinforcement shall not be less than the followings:

$$\rho_s = 0.45\left(\frac{A_g}{A_c} - 1\right)\left(\frac{f'_c}{f_{yh}}\right)\left[1 - \left(\frac{P_s + P_{hcc}}{(P_n)_u}\right)\right] \tag{1}$$

and

$$\rho_s = 0.12\left(\frac{f'_c}{f_{yh}}\right)\left[1 - \left(\frac{P_s + P_{hcc}}{(P_n)_u}\right)\right] \tag{2}$$

2. For a SRC column tied with rectangular hoops, the cross-sectional area of the confinement reinforcement, A_{sh}, shall not be less than the followings:

$$A_{sh} = 0.3sh_c\left(\frac{f'_c}{f_{yh}}\right)\left(\frac{A_g}{A_{ch}} - 1\right)\left[1 - \left(\frac{P_s + P_{hcc}}{(P_n)_u}\right)\right] \tag{3}$$

and

$$A_{sh} = 0.09\, sh_c\left(\frac{f'_c}{f_{yh}}\right)\left[1 - \left(\frac{P_s + P_{hcc}}{(P_n)_u}\right)\right] \tag{4}$$

where $(P_n)_u$ is the nominal axial capacity of SRC column; P_s and P_{hcc} are, respectively, the axial capacities provided by the steel section and the highly confined concrete.

$$P_s = f_{ys} A_s \tag{5}$$

$$P_{hcc} = 0.85 f'_c A_{hcc} \tag{6}$$

where A_{hcc} is the area of highly confined concrete surrounded by the steel flanges. It is noted that the bracket at the end of equations (1) to (4) is a reduction factor which accounts for the contribution of the flanges of the steel section in confining the core concrete of the SRC column.