SUSTAINABLE CONCRETE COLUMNS WITH INNOVATIVE MULTI-SPIRAL SHEAR REINFORCEMENT

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ABSTRACT

Lateral reinforcement used to provide shear strength, concrete confinement, and support to longitudinal steel reinforcement. The efficiency of the confinement generally depends on the shape and spacing of the confinement steel. Spirals are usually used in circular columns, while rectilinear stirrups, with or without cross ties, are generally used in rectangular columns. It has been recognized that rectilinear stirrups are less effective for concrete confinement because of the uneven distribution of the lateral confining stress. This paper presents the development of an innovative multi-spiral confinement design for rectangular concrete columns. The development involved testing and evaluation of a large number of full-scale reinforced concrete columns in axial compression and lateral cyclic loadings. Test results concluded that rectangular columns with interlocking multi-spiral design exhibit higher compressive strength and ductility as compared to columns with conventional stirrup design. Based on the laboratory research and practical design and construction experience, a proposed design approach for multi-spiral confinement design is presented. Case studies of sustainable design of concrete columns with multi-spiral shear reinforcement are also presented. Lower consumption of steel required for multi-spiral confinement design results in energy saving and carbon reduction and; therefore, the multi-spiral confinement design offers a sustainability advantage.

Keywords: Concrete column; concrete confinement; ductility; shear strength; spiral reinforcement; stirrups; sustainability

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INTRODUCTION

Lateral reinforcement in columns is used to provide shear strength, concrete confinement, and support to longitudinal bars. As a result of confinement, concrete columns display significant improvement in ductility and, in some cases, additional strength. The efficiency of the confinement generally depends on the shape and spacing of the confinement steel[1-3]. Spirals are usually used in circular columns, while rectilinear stirrups, with or without cross ties, are generally used in rectangular columns. It has been recognized that rectilinear stirrups are less effective for concrete confinement compared with circular spirals because of the uneven distribution of the lateral confining stress. Furthermore, construction of stirrups is more laborious that leads to highly expensive operation. Recently, an innovative interlocking multi-spiral confinement design for rectangular concrete columns has been developed by Yin et al[4], typical examples of which are shown in Figures 1(g) and 1(h). This development involved testing and evaluation of a large number of full-scale reinforced concrete columns in axial compression and lateral cyclic loadings. Test results clearly verified that columns with interlocking multi-spiral confinement design exhibit higher compressive strength and ductility as compared to columns with conventional stirrup design.

EXPERIMENTAL PROGRAM

In Phase I of the experimental program, full-scale reinforced concrete columns were tested under axial compressive loading. Ten specimens with different steel configurations, as shown in Figure 1, were designed to study confinement in square columns. These included typical rectilinear lateral steel stirrups arrangements as well as different types of multi-spirals and combinations of spiral and ties.

All the specimens in this phase were 600 mm square and 1200 mm high. The nominal compressive strength of concrete at 28 days was 35 MPa. The tensile strength of both transverse and longitudinal reinforcement was 280 MPa. Figure 2 shows the test setup for the axial compression tests. A 6,000 metric ton hydraulic jack was used to apply the axial compressive force at a constant strain rate of 25 $\mu\varepsilon$/sec.

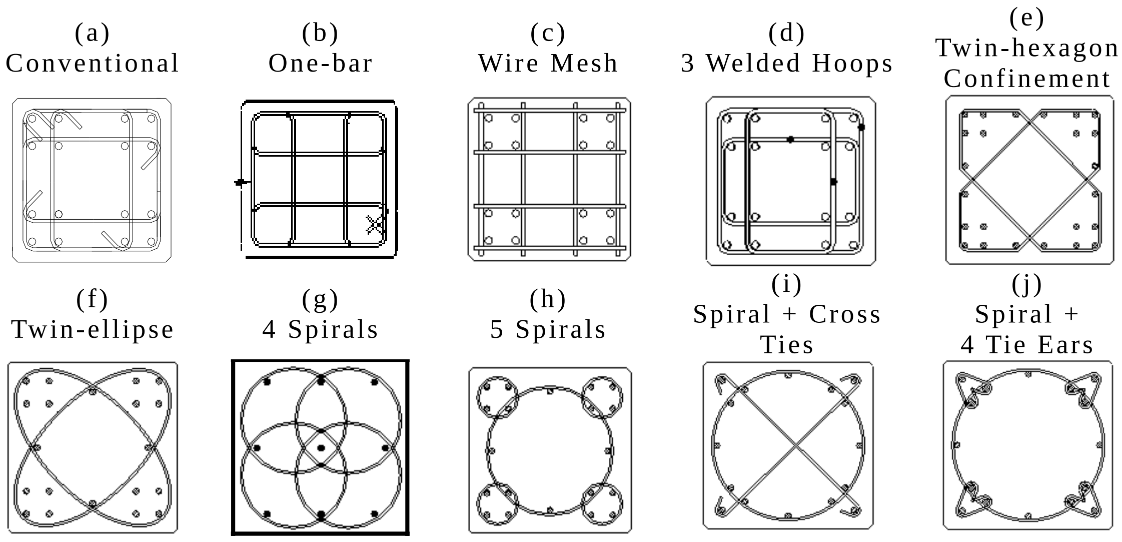


Fig. 1 Confinement configuration details of the Phase I tests

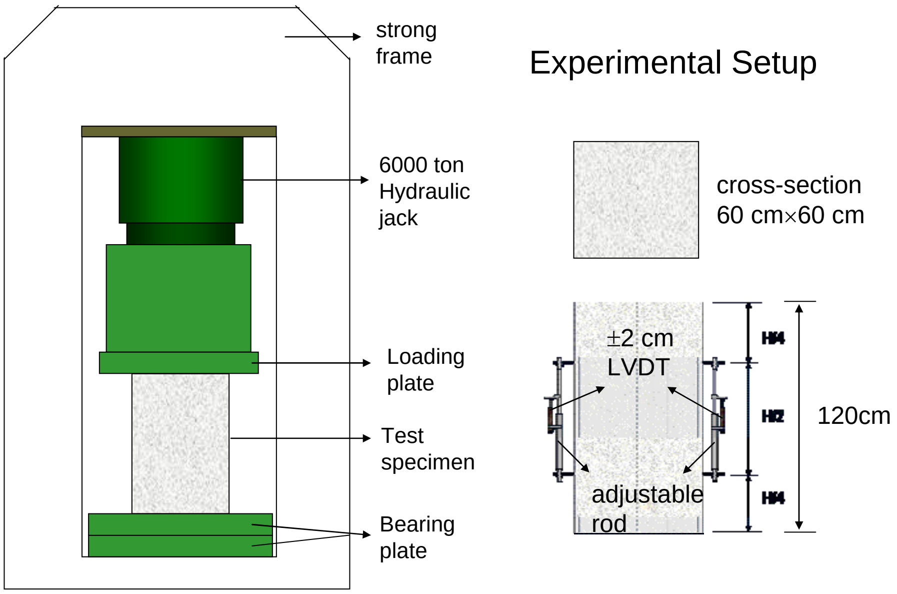


Fig. 2 Experimental setup for axial compression tests

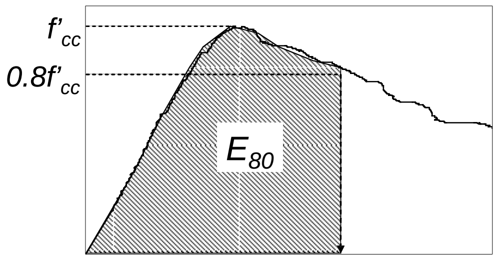
Table 1 lists the results of the Phase I tests. The unconfined compressive strengths (f'_c) of the concrete cylinders for the three groups of specimens were 35.6, 43.0, and 37.6 MPa, respectively. The peak strengths (f'_{cc}) of the test specimens with the different confinement details were all greater than their corresponding unconfined concrete compressive strengths. The f'_{cc} was defined as P_c/A_g, where P_c is the load carried by concrete (i.e., total load –

load carried by steel) and A_g is the gross area of concrete section.

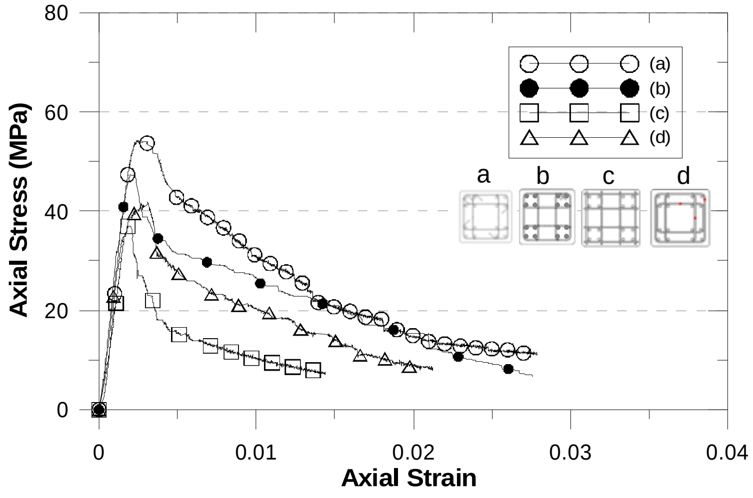
The ratio of f'_{cc} to f'_c varied from 1.04 to 1.68. The cumulative strain energy E_{80} of the test specimens given in Table 1 is defined as the area below the stress-strain curve up to the strain value corresponding to 0.8 f'_{cc}. The cumulative strain energies of the test specimens with different confinement details varied from 0.05 N-mm/mm^3 to 1.21 N-mm/mm^3. The energy ratios ($E_{80}/E_{80(a)}$) of the tested specimens with respect to the benchmark (specimen a) ranged from 0.28 to 6.34.

Table 1 Details of Specimens in Phase I

No.	Confinement (See Fig.2)	Strength(MPa)			Strain Energy	
		f'_c *MPa*	f'_{cc} *MPa*	f'_{cc}/f'_c	E_{80} N-mm/mm^3	$E_{80}/E_{80(a)}$
1	(a)	35.6	54.2	1.52	0.19	1.00
2	(b)	35.6	42.1	1.18	0.14	0.74
3	(c)	35.6	37.0	1.04	0.05	0.28
4	(d)	35.6	41.4	1.17	0.11	0.57
5	(e)	43.0	64.9	1.51	0.66	3.44
6	(f)	43.0	53.5	1.25	0.40	2.07
7	(g)	43.0	59.2	1.38	1.04	5.44
8	(h)	37.6	57.7	1.53	1.21	6.34
9	(i)	37.6	63.2	1.68	0.80	4.15
10	(j)	37.6	50.6	1.34	0.55	2.86



The stress-strain responses of concrete columns under axial compressive loading are shown in Figures 3a, 3b, and 3c. The test results showed that the multi-spiral designs provide significant contributions to concrete confinement that enhances strength and ductility of the columns. The columns with four or five interlocking spirals (Specimen g and h) have better ductility than the other columns.



80
60
40
20
0
Axial Stress (MPa)
0
0.01
0.02
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0.04
Axial Strain
(a)
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a
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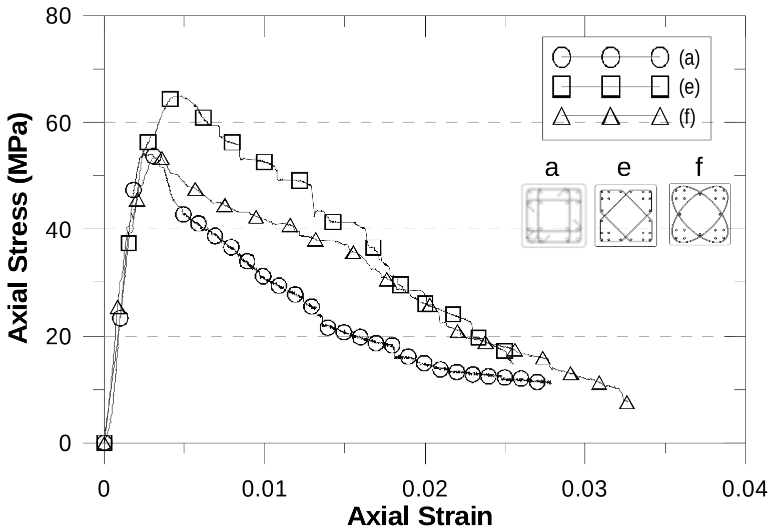
c
d

(a)



80
60
40
20
0
Axial Stress (MPa)
0
0.01
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0.03
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Axial Strain
(a)
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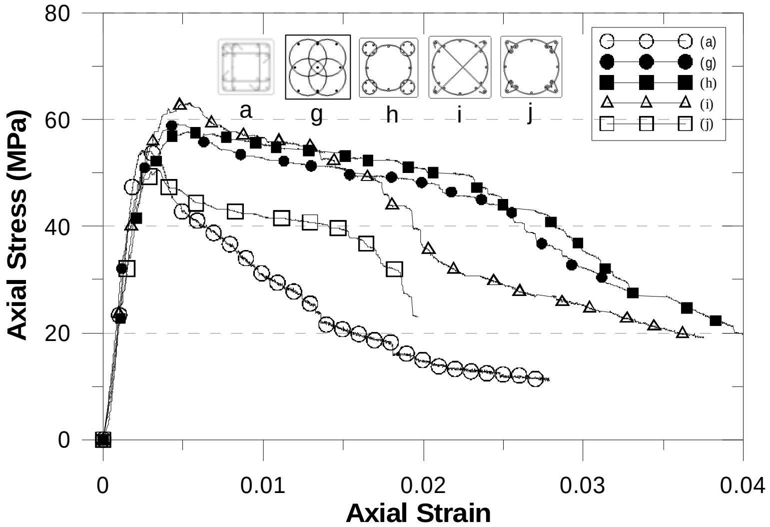
(b)



(c)

Fig. 3 Stress-strain response of concrete columns with different confinement arrangements

Test results of Phase I revealed that most of the test specimens with spiral confinements exhibited higher compressive strength and energy capacity than the specimens with rectilinear confinement. Among them, the multi-spiral designs (Specimens g and h in Fig. 1) and a design with a spiral and cross ties (Specimen i in Fig. 1) exhibited better confinement effectiveness and therefore they were selected for further investigations.

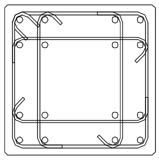
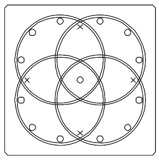
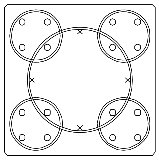
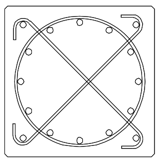
In Phase II of the test program, the specimens were subjected to axial compressive loads. Table 2 lists the design details of the 18 specimens tested under axial compression in Phase II. All the specimens were also 600 mm square in cross section and 1200 mm high. Four types of confinement designs including the traditional stirrup design (T), the combination of a spiral and cross ties (ST), the combination of four spirals (4S), and the combination of five spirals (5S) were tested. As shown in Table 2, the compressive strength (f_c') of concrete was 34.4 MPa in all columns except three in which it was 68.7 MPa. The yield strengths (f_{yt}) of the confinement steel was 274.7 MPa in the columns made with 34.4 MPa concrete and 412.0 MPa in the three columns that used higher strength concrete (68.7 MPa). Sixteen No. 8 (area = 506.7 mm^2) longitudinal bars with yield strength of 412 MPa were used for all specimens. The confinement reinforcement sizes varied from No. 3 (area = 71.3 mm^2) to No. 5 (area = 198.6 mm^2). The spacing of the confinement reinforcement varied from 45 mm to 100 mm.

Figure 4 shows the typical failure modes of the specimens with multi-spiral design and traditional stirrup design. For traditional stirrup design, lateral dilation of concrete resulted in the failure of cross ties at the 90-degree bends of the stirrups (see Figure 4b). This is similar to failure reported by earlier investigators[5]. For specimens with multi-spiral confinement design, the fracture of the spiral reinforcement followed by buckling of the longitudinal bars as can be seen in Figure 4a. The fracture of the spiral confinement was caused by the large lateral dilation of the concrete and the bearing of the buckled reinforcement against the spirals.

(a) (b)

Fig. 4 Typical Failure Modes of Compression Test Specimens

Table 2 Details of Specimens in Phase II

	Concrete	*Confinement Reinforcement*					
Specimen	*f'c (MPa)*	*Pitch (mm)*	*Bar size*	*f_{yt} (Mpa)*	ρ^* (%)	$\rho^*_{(req)}$ (%)	*shape*
T1	34.4	85	#4	274.7	2.2	2.26	
T2	68.7	65	#4	412.0	2.9	3.01	
4S1	34.4	75	#4	274.7	2.05	1.63	
4S2	68.7	50	#4	412.0	3.07	2.17	
4S3	34.4	50	#5	274.7	4.74	1.63	
4S4	34.4	65	#5	274.7	3.65	1.63	4-ϕ360 mm
4S5	34.4	100	#4	274.7	1.54	1.63	
5S1	34.4	50	#4	274.7	2.64	1.64	
5S2	68.7	75	#4	274.7	1.76	2.19	
5S3	34.4	70	#5	274.7	2.24	1.64	
		70	#4	274.7			
5S4	34.4	60	#4	274.7	2.2	1.64	1- ϕ 420 mm 4- ϕ 210 mm
5S5	34.4	50	#3	274.7	1.26	1.64	
ST1	34.4	*spiral 60*	#4	274.7	1.55	/	
		ties 60	#3	274.7			
ST2	68.7	*spiral 95*	#5	412.0	2.09	/	
		ties 95	#5	412.0			
ST3	34.4	*spiral 75*	#5	274.7	2.06	/	
		ties 75	#4	274.7			
ST4	34.4	*spiral 45*	#5	274.7	2.75	/	1- ϕ 520 mm
		ties 45	#3	274.7			
ST5	34.4	*spiral 55*	#5	274.7	2.25	/	
		ties 55	#3	274.7			
ST6	34.4	*spiral 80*	#5	274.7	1.55	/	
		ties 80	#3	274.7			

ρ^* is the volumetric ratio of the confinement reinforcement to the gross area of concrete section of the specimen.

$\rho^*_{(req)}$ is the minimum volumetric ratio of the confinement reinforcement as required by ACI 318-08 in Sections 10.9.3 and 21.6.4.4

Figure 5(a) shows the monotonic compression stress-strain relationships for specimens with traditional stirrup design. Figures 5(b) to 5(d) show the stress-strain relationships for the other three confinement designs. A comparison of the behavior of different columns in these figures shows that the confined concrete response can be improved with closer spiral pitches and higher volumetric ratios of confinement steel. It can also be seen that a more brittle response of higher strength concrete can be compensated by higher strength lateral steel. The results demonstrated that the multi-spiral confinement designs perform much better than the traditional lateral reinforcement detail consisting of stirrups and cross ties.

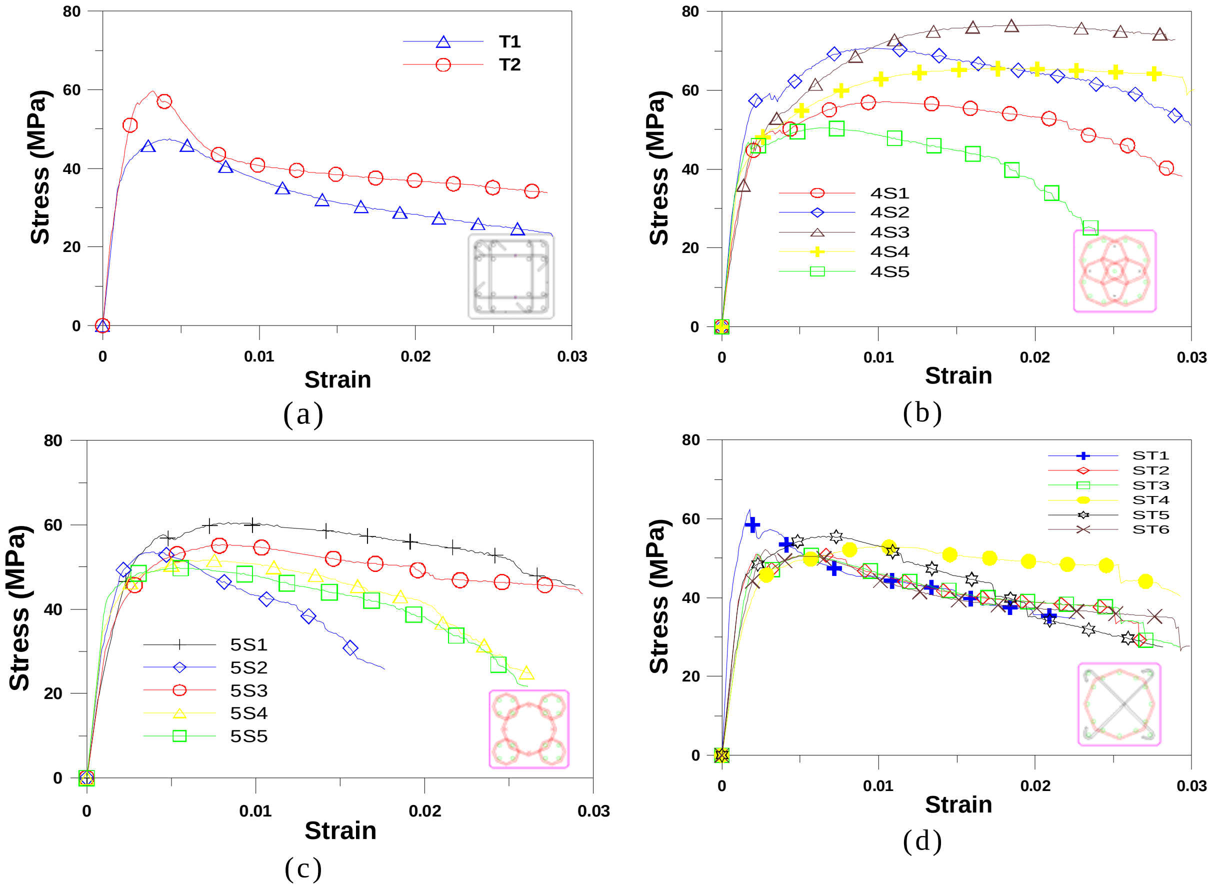


Fig. 5 Effect of amount of lateral reinforcement and spacing on concrete response

In Phase III, the specimens were subjected to combined axial compression and lateral cyclic loads. Figure 6 shows the test setup of the combined axial compression and lateral cyclic loading tests. The confinement designs used for the three column specimens were: a traditional stirrup design as the benchmark (CT), and two multi-spiral designs denoted as S4 and S5. All the specimens had a cross section of 600 mm square and were 2.5 m high. An axial force of 126 tons ($\sim 0.1f'_c A_g$) was applied at the top of the specimens by a 200 ton jack that remained constant throughout the test.

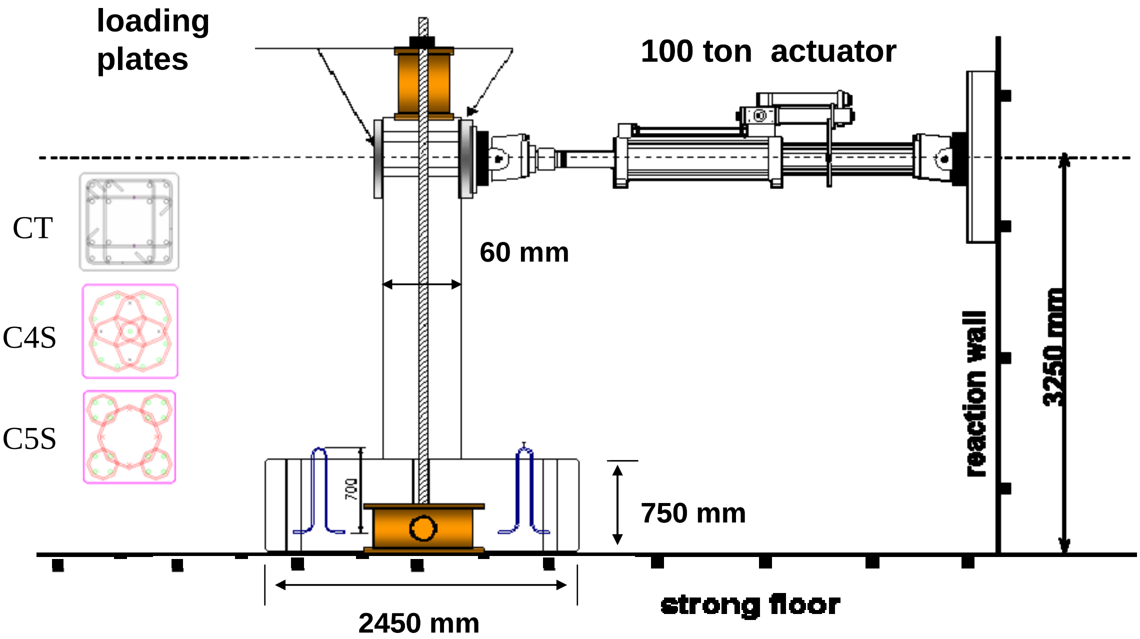


Fig. 6 Experimental setup of the lateral cyclic loading tests

Table 3 lists the design details of the Phase III specimens. The confinement layout for Specimen CT was the same as that of specimen T1 in Table 2. Specimens C4S and C5S are columns with multi-spiral confinement designs and were the same as that of the specimens 4S1 and 5S4 in Table 2.

Table 3 Details of specimens in phase III

Specimen	$f'c$ (MPa)	Longitudinal Bars	Confinement Reinforcement				
			Design	Size (mm)	f_y (MPa)	Spacing (mm)	ρ_s (%)
CT	34.4	f_y=412 MPa 16-#8	CT	13	274.7	85	2.2
C4S	34.4		4S	13	274.7	75	2.05
C5S	34.4		5S	13	274.7	60	2.2

Figure 7 shows the lateral load vs. displacement hysteresis loops of the three specimens tested under lateral cyclic loading while subjected to constant axial load. Specimen C5S exhibited the highest strength and ductility capacity among the three columns. The response of specimen C4S was close to that of C5S, whereas specimen CT exhibited the lowest strength and ductility capacity, as expected.

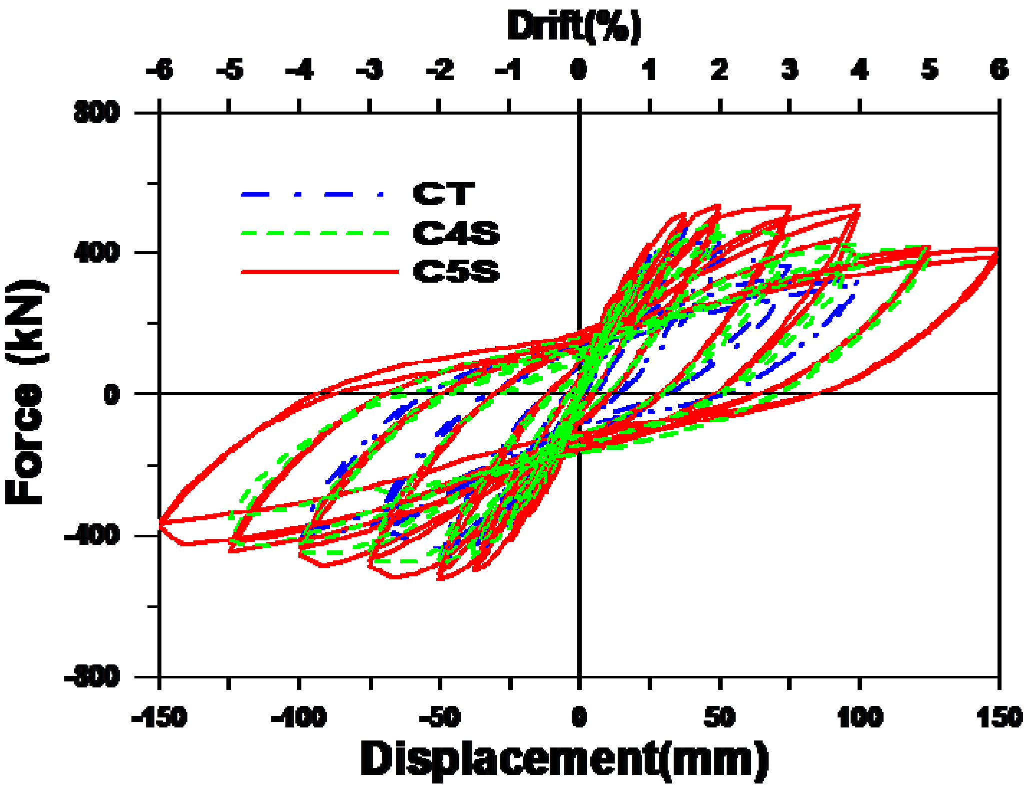


Fig. 7 Force-displacement relations for the three test specimens

PROPOSED DESIGN APPROACH

Based on the experimental and analytical research, as well as practical design and construction experience, the proposed design approach for multi-spiral shear reinforcement for columns is as follows.

The volumetric spiral reinforcement ratio, ρ_s, required for multi-spiral should be determined according to Equations (10-5) and (21-3) of ACI 318-08.

$$\rho_s \geq 0.45(\frac{A_g}{A_{ch}} - 1)\frac{f_c^{'}}{f_y} \qquad \text{Eq. (10-5)}$$

$$\rho_s \geq 0.12\frac{f_c^{'}}{f_y} \qquad \text{Eq. (21-3)}$$

For columns with interlocking multi-spirals, the volumetric spiral reinforcement ratio provided for each spiral should be calculated independently. The volumetric spiral reinforcement ratio provided by each spiral should not be less than the ρ_s required by Eq. (10-5). For the calculation of the required ρ_s, the area A_{ch} in Eq. (10-5) is measured to the outside edges of the spirals as defined in Section 2.1 of ACI 318-08 and A_g is the gross area of concrete section.

COST ADVANTAGES OF MULTI-SPIRAL DESIGN

The multi-spiral design has been successfully used for 14 construction projects such as office and factory buildings, shopping malls, high-rise residential buildings, public stadium, and bridge piers in Taiwan. The cost advantage of the multi-spiral design is significant. First, the improvement of confinement efficiency can greatly reduce the total amount of lateral steel. More importantly, the multi-spiral detail can be produced automatically in the prefabrication plants. The time-consuming bending and labor required for conventional stirrups are greatly reduced, which can result in lower cost as well as shortened total construction time. Table 4 shows the cost evaluation of multi-spiral confinement design for an 11-story apartment project in Taiwan. It can be seen that the cost of the total confinement steel reduced by 41% when the multi-spiral confinement is used instead of the conventional stirrups. Considering the even higher labor cost in the developed countries, its economical advantages will be more pronounced.

Table 4 Cost evaluation of multi-spiral design

Item	Stirrup	Weight	Unit price NT$/kg			Total stirrup price	
	fy MPa	Ton	Material	Bending	Assemble	Million	%
Conventional stirrups	420	717	14.6	0.00	3.36	12.9	100
Multi-spirals	420	407	14.6	1.76	2.24	7.6	59

SUSTAINABLE CONCRETE COLUMNS – CASE STUDIES

CASE I. SPORTS COMPLEX FOR THE 21ST SUMMER DEAFLYMPICS

The design of the sports complex for the 21st Summer Deaflympics in Taipei, Taiwan started in December 2006 and the construction was completed in April 2009. This sports complex consists of three major structures: main stadium, sports center, and warm-up field (Fig. 8). The multi-spiral shear reinforcement design for columns in this sports complex results in energy saving and carbon reduction.

a. Use of multi-spiral shear reinforcement design for columns. The use of multi-spiral shear reinforcement design instead of the conventional stirrups in rectangular columns reduces the amount of shear steel by 144 tons. It was estimated that manufacture of each ton of steel emits about 923 tons of CO_2. Therefore, reduction of 144 tons of steel results in 133 tons of CO_2 reduction.

b. Replace 20% of portland cement with slag in concrete mixtures. The total portland cement and slag used for columns in this project were 294 tons and 68 tons, respectively. Since each ton of cement and slag contribute about 880 kg and 68 kg of CO_2, respectively, the slag replacement reduced 55 tons of CO_2 emissions in this project. Concrete containing slag not only meets the strength requirements but also enhances the durability and promotes structural longevity.

Figure 8 Sports Complex for the 21st Summer Deaflympics, 2009

CASE II: RUENTEX RITZ APARTMENT, TAIPEI, TAIWAN

The Ruentex Ritz Apartment in Taipei, Taiwan (Fig. 9) is an 11-story apartment building. As can be seen from Table 4, the use of multi-spiral shear reinforcement design instead of the conventional stirrups in rectangular columns reduces the amount of shear steel by 388 tons resulting in 358 tons of CO_2 reduction. Lower consumption of steel required for multi-spiral confinement design results in energy saving and carbon reduction.

Figure 9 Ruentex Ritz Apartment Building

CONCLUDING REMARKS

The innovative interlocking multi-spiral confinement design offers an attractive and superior alternative to traditional stirrup confinement design for rectangular concrete columns. The laboratory tests and field experience have shown clearly that multi-spiral confinement design can provide effective confinement with increased strength and ductility, and reduced cost. Furthermore, the multi-spiral confinement design is also the most efficient layout in terms of automatic assembly. These reinforcement cages can be built quickly and economically and are very cost-effective for precast construction. Lower consumption of steel required for multi-spiral confinement design results in energy saving and carbon reduction and; therefore, the multi-spiral confinement design offers a sustainability advantage.

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