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Axial strength and ductility of square composite columns with two interlocking spirals

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The axial compressive capacity and load–displacement behaviour of composite columns confined by two interlocking spirals were experimentally and analytically investigated. The innovative spiral cage used for a square column was fabricated by interlocking a circular spiral and a star-shaped spiral to enhance the confinement effect for the core concrete. Eight full-scale square composite columns were tested under monotonically increased axial compression. Experimental results demonstrated that, with significant savings of the transverse reinforcement, the composite columns confined by two interlocking spirals achieved excellent axial compressive strength and ductility capacity. Moreover, an analytical model was developed to take into account the concrete confinement due to the structural steel in addition to the transverse reinforcement and distributions of the longitudinal bars. The analytical results accurately predicted the axial compressive capacity and load–displacement behaviour of the specimens. Consequently, the application of the two interlocking spirals in a square composite column appears to be very affirmative.

1. Introduction

Various experimental and numerical studies have shown that transverse reinforcement in columns functions as follows: (1) holding longitudinal bars in position; (2) preventing longitudinal bars from premature buckling; (3) providing shear strength for columns; (4) providing passive confinement for core concrete; and (5) improving axial compressive strength and ductility of columns [1–7]. Square columns are traditionally reinforced with rectangular hoops, and each hoop is formed from a single steel bar with hook at both ends [8]. However, field experiences reveal that hoops with a 135-degree bend are difficult to setup in a composite column, and the entire construction is heavily relied on skilled labors that is time-consuming and costly.

Spirals are a continuously wound transverse reinforcement and can be fabricated automatically in a factory. The fabrication of helical spirals is faster and cheaper than that of rectilinear hoops. Moreover, helical spirals in a column are more effective in providing concrete confinement compared to rectilinear hoops [9,10]. Mirza and Skrabek [11,12] studied the behaviour of short and slender composite columns subjected to axial force and bending moment. Ricles and Paboojian [13] investigated the seismic behaviour of composite columns through experiments. They concluded that the strength and toughness of composite columns were affected by the confinement status of the core concrete. Exactly how the spirals apply to columns with square cross section is of interest. Fig. 1(a) shows a square column reinforced by a circular helical spiral. Because the concrete at the four corners of the square column cannot be confined by the circular spiral, applications of the circular spiral to square columns are not common in engineering practice.

This research proposes an innovative spiral confinement as shown in Fig. 1(b). The confinement is achieved by two interlocking spirals, consisting of a circular spiral and a star-shaped spiral, with longitudinal bars located around the perimeter of the square column. The interlocking spirals overcome the shortcomings of applications of a circular spiral to square cross-sectional columns, and facilitate sound confinement for the concrete at the four corners of the square column. Moreover, the manpower and construction time to fabricate reinforcement cage can be substantially reduced because the spirals can be fabricated by automatic machines in the factory. Fig. 2 illustrates the construction of the two interlocking spirals.

This work elucidates experimentally and analytically the effectiveness of the two interlocking spirals used in square composite columns. Eight full-scale columns, including six spirally reinforced composite columns and two reinforced concrete columns, were tested under monotonically increased axial compression. An analytical approach was also conducted to calculate the axial compressive strength and the load-deformation relationships of the specimens.

2. Experimental program

2.1. Design of test specimens

Table 1 presents the details of the specimens. Six of the specimens (SRC1 ~ 6) were composite columns reinforced with two spirals. The

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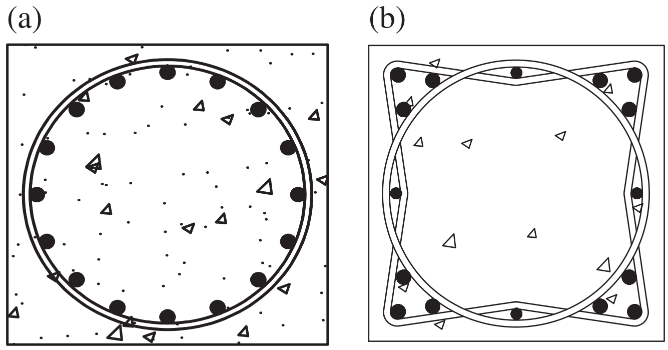

Fig. 1. Spiral confinements for a square column: (a) a circular spiral; (b) two interlocking spirals.

other two specimens (RC1 and RC2) were reinforced concrete columns with rectilinear hoops. The test specimens were 600 mm square in the cross section and 1200 mm long. Two types of structural steel sections used were welded built-up box section (□250 × 250 × 6 × 6 and □300 × 300 × 9 × 9) and cross-H section (2-H220 × 100 × 6 × 9 and 2-H350 × 175 × 6 × 9). The ratios of the area of structural steel section to gross section of the column are presented in the table.

Regarding the design of the transverse reinforcement, different design specifications were considered, including ACI 318 building code [8] and AISC seismic provisions [14]. Specimen RC2, served as the benchmark, was designed to have minimum rectilinear hoops according to ACI 318 building code.

$$A_{sh} = 0.3sh_c \frac{f_c^{'}}{f_{yt}}\left(\frac{A_g}{A_{ch}} - 1\right) \tag{1a}$$

$$A_{sh} = 0.09sh_c \frac{f_c^{'}}{f_{yt}} \tag{1b}$$

where A_{sh} is the total cross-sectional area of hoop reinforcement within spacing s; A_g and A_{ch} are the gross cross-sectional area of the column and the cross-sectional area measured to outside edges of hoop reinforcement, respectively; $f_c^{'}$ is the specified compressive strength of concrete; f_{yt} is the specified yield strength of hoop reinforcement; s is the center-to-center spacing of hoop reinforcement; and h_c is the width of confined core concrete.

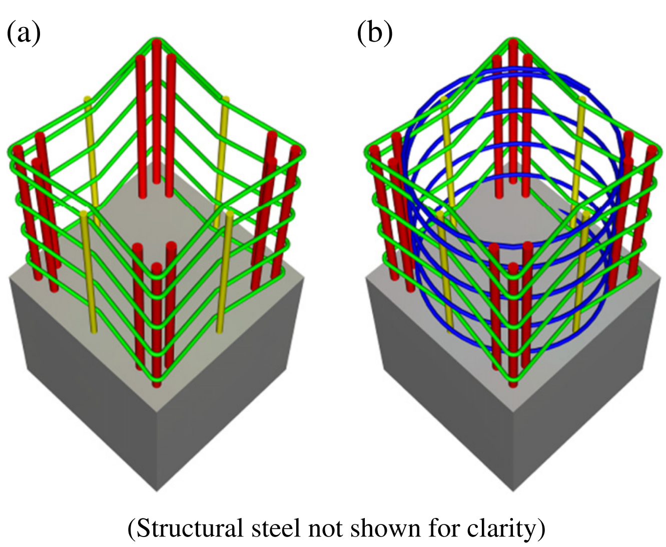

Fig. 2. Construction of the two interlocking spirals: (a) fabricated cage of the star-shaped spiral; (b) insert of the circular spiral.

For the spirally reinforced concrete column, specimen RC1, ACI 318 building code stipulates that the volumetric ratio, ρ_s, defined as the ratio of the volume of spiral reinforcement to the volume of core concrete, shall not be less than the following requirement:

$$\rho_s = 0.45 \frac{f_c^{'}}{f_{yt}}\left(\frac{A_g}{A_{ch}} - 1\right) \tag{2a}$$

$$\rho_s = 0.12 \frac{f_c^{'}}{f_{yt}} \tag{2b}$$

Regarding the transverse reinforcement used in composite columns, AISC seismic provisions propose a formula based on ACI 318 building code. A reduction factor of $(1 - f_{ys}A_s/P_n)$ is used to reduce the requirement for the tie reinforcement to take into account the structural steel core. The minimum tie reinforcement shall meet the following:

$$A_{sh} = 0.09sh_c \frac{f_c^{'}}{f_{yt}}\left(1 - \frac{f_{ys}A_s}{P_n}\right) \tag{3}$$

in which A_s and f_{ys} are the cross-sectional area and specified yield strength of the structural steel, respectively; P_n is the nominal axial compressive strength of the composite column calculated in accordance with the AISC specification [15]. Hence, for designing the spirally reinforced composite columns, specimens SRC1 ~ 3, a formula adopting a reduction factor according to the same design philosophy is proposed as follows.

$$\rho_s = 0.45 \frac{f_c^{'}}{f_{yt}}\left(\frac{A_g}{A_{ch}} - 1\right)\left(1 - \frac{f_{ys}A_s}{P_n}\right) \tag{4}$$

Moreover, in recognition for the superior confinement provided by the structural steel section in composite columns [12,16], as indicated in Fig. 3, Weng et al. [17] proposed a formula to account for reducing transverse reinforcement due to the highly confined concrete in composite columns. The following equation was used to design the required spirals for specimens SRC4 ~ 6.

$$\rho_s = 0.45 \frac{f_c^{'}}{f_{yt}}\left(\frac{A_g}{A_{ch}} - 1\right)\left(1 - \frac{P_s + P_{hcc}}{P_o}\right) \tag{5a}$$

where

$$P_o = f_{ys}A_s + f_{yr}A_r + 0.85f_c^{'}A_c \tag{5b}$$

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

$$P_{hcc} = 0.85f_c^{'}A_{hc} \tag{5d}$$

where P_o is the nominal axial compressive strength of the composite column; P_s and P_{hcc} are the compressive strength provided by the structural steel and highly confined concrete, respectively; f_{yr} is the specified yield strength of the longitudinal reinforcement; A_r is the cross-sectional area of the longitudinal reinforcement; A_c is the cross-sectional area of the concrete section; and A_{hc} is the area of highly confined concrete.

Accordingly, the use of the transverse reinforcement for each specimen is shown in Table 1. Besides, the weights of the transverse reinforcement per unit length of the column are also presented. On the basis of the reduction for the transverse reinforcement specified in Eqs. (4) and (5), composite columns (specimens SRC1 ~ SRC6) utilized less transverse reinforcement compared to the reinforced concrete columns (specimens RC1 and RC2). Fig. 4 depicts the details of the cross section of specimen SRC2, confined by two interlocking spirals.