BEHAVIOR AND STRENGTH OF SQUARE STEEL TUBE COLUMNS FILLED WITH STEEL-REINFORCED SELF-COMPACTING HIGH-STRENGTH CONCRETE

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Abstract

The square steel tube columns filled with steel-reinforced self-compacting high-strength concrete is a new combination of steel-concrete composite columns. In this type of composite columns, section steel is inserted into square steel tube and self-compacting high-strength concrete is filled into the tube. To investigate the behavior of the composite columns, fourteen short composite column specimens were tested under axial compression. The main parameters were the concrete strength, the width-to-thickness ratio and the section steel ratio. The experimental results indicate that the composite columns have very high strength and good ductility because of the interaction between the square steel tube, self-compacting high-strength concrete and section steel; the behavior of self-compacting columns and vibrated columns is almost the same; the concrete strength, the width-to-thickness ratio and the section steel ratio have significant effects on behavior and strength of the composite columns. A formula is proposed to calculate the ultimate strength of the composite columns under axial load. The calculated values agree well with the experimental results.

1. INTRODUCTION

The use of composite structures has become more widespread in recent decades. Two main types of composite columns are the steel-reinforced concrete (SRC) column and the concrete-filled steel tube (CFT) column. In the case of SRC columns, section steel is encased in concrete thus the shear resistance and fire resistance of the columns are enhanced. Moreover, the concrete encasement makes the steel core more effective against both local and overall bucking [1]. But the SRC columns need formworks for casting the concrete and transverse reinforcement is needed to prevent the concrete from spalling. In the case of CFT columns, the steel tube serves as formwork and transverse reinforcement in the form of ties or spirals is eliminated. Furthermore the steel tube provides the continuous confinement to the concrete core, thus the compressive strength of the concrete is increased and the ductility of the concrete especially the high-strength concrete is significantly improved [2]. But the fire...
performance of the CFT columns is not as good as that of the SRC columns and additional fire-resistant insulation is required for the CFT columns. Considering the advantages and disadvantages of the two types of columns, a new design model of steel-concrete composite columns, namely circular steel tubular column filled with steel-reinforced concrete was proposed by Wang et al. [3]. The experimental results showed that this type of composite columns had very high strength, ductility and capacity of energy absorption.

Self-compacting concrete (SCC) represents one of the most significant advances in concrete technology for decades [4]. It can flow and compact in a mould or formwork under its own weight without the need for vibration. Using SCC in steel tube columns can provide great convenience during the construction. Moreover SCC can improve the compaction of the core concrete which significantly influences the strength of the concrete-filled steel RHS columns [5].

Based on the above analysis, this paper presents an experimental study on behavior and strength of square steel tubular short columns filled with steel-reinforced self-compacting high-strength concrete under axial load. The effects of the concrete strength, the width-to-thickness ratio, and the section steel ratio on the load-deformation response of the columns are discussed. A formula is also given to calculate the compressive capacity of the columns.

2. EXPERIMENTAL PROGRAM

2.1 Material properties

Two classes of concrete were designed. Details of the concrete mixes and basic properties are summarized in table 1. The cement was 52.5R grade Portland cement. The fly ash was Class I (Chinese standard) fly ash from Sui Power Plant of Huludao. The coarse aggregate was crushed limestone with a maximum size of 20 mm. Concrete admixtures were provided by Sika. Two kinds of concrete specimens were used to describe the compressive strength of the concrete: (1) Cube with dimensions of 100mm×100mm×100mm; and (2) prism with dimensions of 150mm×150mm×300mm. The concrete cubes and prisms were sampled from the concrete batch used to fill the test specimen, and they were cured in standard conditions. The measured values of cubic strength, $f_{cu,10}$, are given in table 1. The measured values of prismatic strength, $f_{cp}$, for two kinds of concrete on the test day were 53.83MPa and 78.66Mpa respectively. Considering the difference between curing conditions of the concrete inside the steel tube and that of the concrete prism, the compressive strength of the core concrete, $f_c$, was adopted as 0.9 $f_{cp}$ [6]. The values of $f_c$ for each specimen are listed in table 2.

Table 1: Mixture proportions and basic properties of concrete used

<table>
<thead>
<tr>
<th>Mixture proportions (kg/m$^3$)</th>
<th>Slump (mm)</th>
<th>SFS (mm)</th>
<th>$f_{cu,10}$ (MPa)</th>
<th>$E_c$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>FA</td>
<td>W</td>
<td>S</td>
<td>CA</td>
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<td>925</td>
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<td>467</td>
<td>155</td>
<td>168</td>
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Note: C-cement, FA-fly ash, W-water, S-sand, CA-coarse aggregate, A-admixture; SFS-slump flow spread; 81d-the day of test; $E_c$-elastic modulus.
The outer jackets of the specimens were manufactured using 195×4.5 mm and 195×5.5 mm longitudinally welded square tubes. The encased steel sections were made of No.10 and No.14 hot-rolled I beams. To determine the steel material properties, tension coupons of the tubes and the I beams were prepared and tested according to relevant Chinese standard. Their average yield strengths are shown in Table 2.

2.2 Test specimen

A total of 14 specimens were tested under axial load. The length of stub columns was chosen to be three times the width of square steel tubes to avoid the effects of overall bucking and end conditions [6]. The concrete strength, the width-to-thickness ratio, and the section steel ratio (defined as the ratio of area of section steel $A_i$ to area of concrete $A_c$) were selected as the main parameters. Table 2 shows the details for different specimens in the test series. In the nomenclature for identifying specimens the first letter represents the shape of the tube, the second number represents the thickness of the tube, the second letter represents the strength of concrete (L represents $f_c = 48.4$ MPa and H represents $f_c = 70.8$ Mpa), the second number represents the No. of I beams (omitting this number represents no encased section steel), the third letter represents special design variable (V represents the vibrated concrete, I represents the I-shaped section steel, C represents the cyclic load and omitting this letter represents self-compacting concrete, cross-shaped section steel and monotonic load).

Table 2: Parameters and results of specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$B/t$</th>
<th>$f_c$ (MPa)</th>
<th>$A_c$ (mm²)</th>
<th>$f_{yt}^c$ (MPa)</th>
<th>$A_t$ (mm²)</th>
<th>$f_{yt}^s$ (MPa)</th>
<th>$A_s$ (mm²)</th>
<th>$N_u^{exp}$ (kN)</th>
<th>$N_u^{cal}$ (kN)</th>
<th>$N_u^{exp}/N_u^{cal}$</th>
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</table>

Note: $B/t$ is the width-to-thickness ratio; $f_c$ is the compressive strength of concrete; $A_c$, $A_t$, and $A_s$ are the cross-section areas of concrete, steel tube, and section steel respectively; $f_{yt}^c$ and $f_{yt}^s$ are the yield stress of steel tube and section steel respectively; $N_u^{exp}$ is experimental ultimate strength; $N_u^{cal}$ is calculated ultimate strength.
Before casting the specimens, steel frameworks were assembled at first (figure 1 (a) and figure 1 (b)). The specimens were cast using the steel frameworks as moulds for the concrete. All specimens were cast and self-compacted by directly pouring the concrete from the top except two contrastive specimens to which external vibration were applied. The specimens were placed upright to air-dry until testing. Prior to testing, the top surfaces of the specimens were ground smooth and flat using a grinding wheel with diamond cutters (figure 1(c)). This was to ensure that the load was applied to the steel tube, the core concrete and the section steel simultaneously.

2.3 Test set-up

All the tests were performed on a 5000kN universal testing machine. Two displacement transducers were attached to the head and base platens to measure the axial shorting. Four strain gauges glued to the flange of each steel section at mid-height to measure the axial and lateral strains. Fourteen strain gages were glued to the external surface of the square steel tube to measure axial deformation and perimeter expansion of the steel tube wall. A typical instrumentation layout is shown in figure 2.

3. EXPERIMENTAL RESULTS

3.1 Failure mode

All of the specimens behaved in a relatively ductile manner and testing proceeded in a smooth and controlled way. For all specimens, square steel tube crinkled seriously when test terminated. But failure mode of specimens with section steel was quite different from that of specimens without section steel as shown in figure 3. For specimens without section steel, two bugles occurred at different heights on the opposite sides of the specimen and there was a visible shear-sliding plane between the bugles (see figure 3(a)). In the case of specimens with section steel, generally two or three bugles occurred along the height, and no shear-sliding
plane was observed (see figure 3(b)). In the place where the bugles were most obvious, a ring was almost formed. In this place the perimeter stresses in the steel tube have developed to very high values thus leading to strong confinement to the core concrete. The difference between failure modes of two types of columns is due to the fact that the presence of section steel effectively delays or restrains the generation of shear sliding crack in the high-strength concrete. Thus the new type of composite column has higher ductility and higher vertical residual load-carrying capacity after failure than the CFT columns.

3.2 Load-axial strain relationship

Figure 4-5 show the load-axial strain curves (or \( N - \varepsilon \) curves) for part of the specimens. To investigate the influence of vibrating on column behavior, two specimens were cast on a vibrating table. The two specimens were denoted as S5L10V and S5H10V which were identical to specimen S5L10 and specimen S5H10 respectively except that specimen S5L10 and specimen S5H10 were not vibrated. Figure 4 gives the \( N - \varepsilon \) curves for the above four specimens. Figure 4 reveals that the couple specimens share very similar \( N - \varepsilon \) curves which indicates that self-compacting concrete can achieve compaction in the composite columns thus it is unnecessary to vibrate the columns. On the other hand, it also indicates that proper vibrating is unlikely to deteriorate the properties of the SCC.

The section steel and steel tube were the same for specimen S5L10 and specimen S5H10 in figure 4. For specimen S5H10 with high concrete strength (\( f_c = 70.8 \text{ Mpa} \)), the ultimate strength \( N_u \) was much larger than that of specimen S5L10 with low concrete strength (\( f_c = 48.4 \text{ Mpa} \)), but its bearing capacity after \( N_u \) decreased more rapidly. So, with the enhancement of concrete strength, the strength of composite column increases but its ductility
decreases. The concrete strength was the same and the section steel ratio was the approximately same for specimen S4L10I and specimen S5L10I in figure 5. When the width-to-thickness ratio increased from 35 to 43, both the strength and the ductility of the columns decreased. It indicates that the confinement effect of the steel tube on the concrete decrease with the increase of width-to-thickness ratio. The concrete strength and the steel tube were the same for specimens S4L, S4L10I and S4L10 in figure 5. It is clear that the strength and ductility of the columns are all increased when the section steel ratio increases. And it can be included that inserting section steel in the high-strength concrete-filled square steel tubes can significantly improve the behavior of the columns.

4. CALCULATION OF ULTIMATE STRENGTH

Based on the equation for the prediction of the ultimate strength of stub circular CFT columns under axial compression deduced by Cai [7], the formula for calculating the ultimate strength of circular steel tubular columns filled with steel-reinforced concrete was given by Wang [3] as

$$N_u = A_f f_y (1 + \sqrt{\theta} + \theta + \rho)$$

(1)

where confinement index $\theta = A_f f_y / (A_f f_c)$ and structural steel index $\rho = A_f f_y / (A_f f_c)$ . The coefficient $\sqrt{\theta}$ was used to considered the benefits of confinement for increasing the ultimate strength of the composite columns. Square tubes are less effective in confining the concrete core than circular tubes because the wall of the square tube resists the concrete pressure by plate bending, instead of the membrane-type hoop stress. Referring to the method used for concrete confined by different types of transverse reinforcement [8], the influence of the steel tube shape on the confinement effectiveness is taken into account by introducing a confinement effectiveness coefficient $k$ which is defined as the ratio of area of effectively confined concrete core $A_c$ to area of concrete core $A$. $A_c$ is the part of the concrete core where the confining stress has fully developed due to arching action which is assumed to occur in the form of a second-degree parabola with an initial tangent slope of 45°, thus the confinement effectiveness coefficient $k$ is

$$k = \frac{A_c - 2(B - 2t)^2 / 3}{A_c}$$

(2)

when $k$ is introduced, the benefits of confinement provided by square steel tube for increasing the ultimate strength of the composite columns can be expressed as $\kappa \sqrt{\theta}$. A unified equation can be used for calculating the ultimate strength of steel-reinforced CFT columns:

$$N_u = A_f f_y (1 + \alpha \theta + \rho)$$

(3)

where $\alpha$ is equal to $1 + 1 / \sqrt{\theta}$ for circular steel tube and $1 + k / \sqrt{\theta}$ for square steel tube respectively ; and $k$ is given by Eq. 2.

The comparison between experimental ultimate strength $N_u^{\text{exp}}$ and calculated ultimate strength $N_u^{\text{cal}}$ is shown in table 2. The results show that values calculated with Eq. (3) are very close to those obtained from the tests. The average of $N_u^{\text{exp}} / N_u^{\text{cal}}$ is 0.998 and the mean square deviation is 0.002.
5. CONCLUSIONS

− The behavior of self-compacting columns and vibrated columns is almost the same which indicates that SCC can achieve compaction in the composite columns and that proper vibrating is unlikely to deteriorate the properties of the SCC.

− Concrete strength, width-to-thickness ratio and section steel ratio have significant effect on the ultimate strength and ductility of the columns.

− When section steel is inserted into the CFT columns, the stiffness and strength of the columns are effectively improved. The presence of the encased steel section can delay or restrain the generation of shear sliding crack in the high-strength concrete thus improving the ductility of the columns.

− The ultimate strength of the composite columns under axial load can be predicted using the proposed formula.

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REFERENCES


