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Experimental research on square steel tubular columns filled with steel-reinforced self-consolidating high-strength concrete under axial load

Meichun Zhu [a,b], Jianxin Liu [a,*], Qingxiang Wang [c], Xiufeng Feng [d]

[a] *Architecture Engineering School, Shanghai Normal University, Shanghai 201418, China*

[b] *State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanhai 200092, China*

[c] *State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China*

[d] *Bureau of Land Supervision of Shanghai, Shanghai 200032, China*

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ABSTRACT

A new design model for steel–concrete composite columns, namely square steel tubular columns filled with steel-reinforced self-consolidating high-strength concrete, is proposed. In this type of steel–concrete composite column, a steel section is inserted into the square steel tube and self-consolidating high-strength concrete is filled into the tube. Eighteen composite column specimens were tested under axial compression. The effects of concrete strength, width-to-thickness ratio, length-to-width ratio, and ratio of steel section on the strength and deformation characteristics of these composite columns are discussed. The experimental results indicate that the encased steel section can restrain the generation of diagonal shear cracks in the core concrete thus changing the failure mode and the post-yield behavior of short composite columns. Formulas for calculating the ultimate strength of centrally loaded composite columns are proposed. The calculated values are in good agreement with the test results.

1. Introduction

Composite steel–concrete columns have been widely used in recent decades. The main advantages of composite columns are high load-bearing capacity, inherent ductility and toughness [1–3]. There are two main types of composite columns, namely the steel-reinforced concrete (SRC) column and the concrete-filled steel tube (CFT) column. In the case of SRC columns, steel sections are encased in concrete thus the shear resistance and fire resistance of the columns are enhanced. But the SRC columns need formwork for casting the concrete and transverse reinforcement is needed to prevent the concrete from spalling under axial load and fire. In the case of CFT columns, the steel tube serves as formwork and transverse reinforcement in the form of ties or spirals are eliminated. Furthermore, the steel tube provides continuous confinement to the concrete core, thus the compressive strength of the concrete is increased and the ductility of the concrete, including the high-strength concrete [4], is significantly improved. However the fire performance of CFT columns is not as good as that of SRC columns. Apart from using the various types of insulating methods, the CFT column has been studied for some time to determine how to enhance its fire resistance characteristics without external fire protection. Kodur and Lie [5–7] pointed out that steel tubular columns filled with bar-reinforced concrete and fiber-reinforced concrete can effectively enhance the fire resistance of the columns.

Considering the advantages and disadvantages of these two types of columns, a new design model of steel–concrete composite columns, namely a circular steel tubular column filled with steel-reinforced concrete was proposed by Wang et al. [8]. The advantages of the novel column form include: For a given load, section dimension of the columns can be reduced, thus providing more net floor space; the strength and ductility of the core concrete can be enhanced because of the confinement effect of the steel tube; no formwork and reinforced cage are required; it can be used in the case of very high axial compression; the inner steel section can surely improve the fire resistance of the columns compared with CFT. But the column might be heavy and uneconomical if a significant amount of steel is used as the steel section inside. So the rational amount of inner steel section should be determined according to the requirement of load-bearing capacity, fire resistance and material cost.

In recent years, the possibility of using self-consolidating concrete (SCC) in composite columns has been of interest to

* Corresponding author. Tel.: +86 021 57123505; fax: +86 021 57123505.
E-mail addresses: ljx163@163.com, liujx@shnu.edu.cn (J. Liu).

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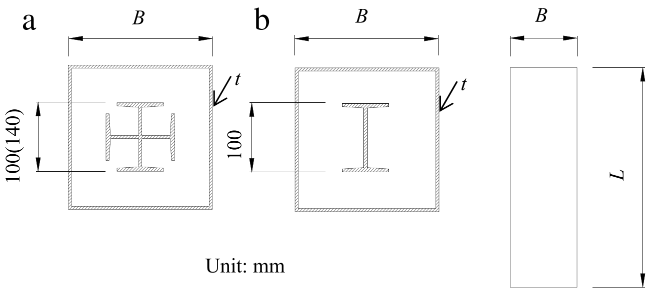

Fig. 1. Test specimens: (a) Cross-section of specimen with cruciform steel section; (b) Cross-section of specimen with I-shaped steel section.

structural engineers [9]. SCC represents a significant advance in concrete technology [10–14]. It can flow and compact in a mold or formwork under its own weight without vibration, thus the cost of vibration can be eliminated. Moreover, SCC also has advantages such as the elimination of noise, the reduction of construction time and labor cost, etc. It must be expected that SCC will be used in composite columns in the future because of its excellent performance.

Based on the above analysis, this paper presents an experimental study on the behavior and strength of square steel tubular columns filled with steel-reinforced self-consolidating high-strength concrete. Eighteen column specimens were tested under axial load. The objectives of these tests were to investigate the centrally loaded behavior of this new type of composite column, and to derive a method to evaluate the ultimate strength.

2. Experimental programme

2.1. Test specimens

Parameters for the tests are as follows: (1) concrete strength f_c ($f_c = 48.4$ MPa, 70.8 MPa), called the axial compressive strength of concrete, is determined by prisms with dimensions of 150 mm × 150 mm × 300 mm. f_c is the strength adopted in design according to the Chinese standard. The prism compressive strength f_c is less than the cylinder compressive strength f_c', and the ratio of them is approximately equal to 0.95; (2) tube width-to-thickness ratio ($B/t = 35, 43$); (3) length-to-width ratio ($L/B = 3, 6, 9, 12$); and (4) the ratio of steel section ($\rho_{ss} = 0\%$–12.3%), defined as the ratio of steel section area (A_s) to gross area ($A_c + A_s$), where A_c is the areas of concrete. Cross-sections of test specimens are shown in Fig. 1. Details of test variables for each specimen are given in Table 1. In the nomenclature for identifying specimens the first letter represents the type of the specimen (*S* represents the short specimen and *L* represents the long specimen), the first number represents the thickness of the tube in millimeters, 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 height of cross-section in centimeter for the steel section (omitting this number represents no encased steel section), the third letter represents special design variable (V represents the vibrated concrete, I represents the I-shaped steel section, C represents the cyclic load and omitting this letter represents self-compacting concrete, cross-shaped steel section and monotonic load respectively). For long column specimens, the last number represents the length-to-width ratio.

Before casting the specimens, steel frameworks were assembled first. In manufacturing the steel frameworks, the steel tubes and steel sections were accurately cut to size. Then a square steel plate was welded to one end of the steel section, with special attention paid to the centering and perpendicularity. The steel section was then surrounded with a steel tube. The steel tube was adjusted carefully in order to assure the steel section lies in the core of the steel tube. Finally, the steel tube was also welded to the steel plate. The welded steel frameworks are showed in Fig. 2. The specimens were then cast using the welded steel framework as moulds for the concrete. All specimens were cast and self-consolidated by directly pouring SCC from the top of the steel framework except two specimens S5L10V and S5H10V to which external vibration were applied. Then all the specimens were placed upright to air-cure in the laboratory until testing. Prior to testing, the top surface of each specimen was ground smooth and flat to ensure that the load was applied to the steel tube, the core concrete and the steel section simultaneously (see Fig. 3).

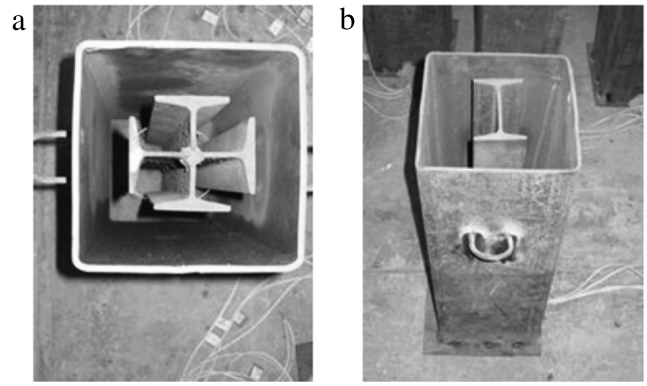

Fig. 2. Welded steel frameworks.

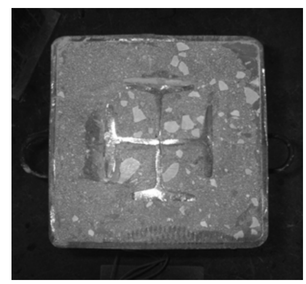

Fig. 3. Specimen surface before test.

2.2. Material properties

The SCC mixture proportions used in this study were determined by trial mixtures on the basis of general advice from Ref. [15]. Details of the concrete mixtures used are given in Table 2. Grade 52.5R Portland cement and Class 1 fly ash, both according to Chinese standards, were used. The former is equivalent to CEM I 52.5R Portland cement according to EN standard. The coarse aggregate was crushed limestone from local quarry with a maximum size of 20 mm. Based on extensive laboratory trials a special SCC superplasticizer, provided by Sika was used for the SCC mixtures. Concrete cubes with dimensions of 100 mm × 100 mm × 100 mm and prisms with dimensions of 150 mm × 150 mm × 300 mm were cast to determine the cube strength $f_{cu,10}$ ($f_{cu,10}$ represents the compressive strength obtained from 100 mm cube specimens), the prism strength f_c of the concrete and modulus of elasticity of the concrete according to Chinese standards, respectively. The averaged values of cube strength ($f_{cu,10}$) and elasticity modulus (E_c) are given in Table 2. The values of f_c for each specimen are listed in Table 1.

The outer tube adopted was a cold-formed square tube. The encased steel section was fabricated using hot-rolled I beam. To determine the steel material properties, tension coupons of tubes and I beams were prepared and tested according to relevant