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Behavior of steel fiber reinforced concrete-filled steel tube columns under axial compression

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HIGHLIGHTS

- Study on steel fiber reinforced concrete-filled steel tube column under axial load.
- Steel fibers have no obvious effects on the failure mode and the load capacity.
- Steel fibers significantly improve the ductility.
- Design equations for axial load capacity and ductility index are proposed.

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ABSTRACT

This paper presents an experimental work for short steel tube columns filled with plain concrete and steel fiber reinforced concrete under axial load. The study aimed to explore the effect of steel fiber on the behavior of concrete-filled steel tube (CFST) columns with different concrete strengths and thicknesses of steel tube. Thirty-six specimens were tested with steel fiber volume percentages of 0%, 0.6%, 0.9% and 1.2%, thicknesses of steel tube of 3, 4 and 5 mm and concrete strengths from 50 to 70 MPa. The failure modes, ultimate loads and axial load-axial shortening relationships are presented. Experimental results show that steel fiber fails to change the failure mode of CFST columns, but delays the local buckling of steel tube through bridging the plastic cracks near the sliding plane and improving the shear-frictional resistance of concrete. This beneficial effect from steel fibers also leads to significant improvement of the ductility and the energy dissipation capacity of CFST columns. Compared with thicker steel tube, adding steel fibers to concrete is a more effective and economical method in enhancing the ductility of CFST columns. The results also indicate that the presence of steel fibers has no obvious effect on the ultimate load of CFST columns. Design formulas for the load capacity and ductility of CFST columns are proposed, and the predictions agree well with the experimental results from this study and the literature.

1. Introduction

Concrete-filled steel tube (CFST) columns have been widely used in modern structures. This is mainly due to the combination of the advantages of both steel and concrete, such as the high strength, ductility, stiffness and fire resistance, and economic and rapid construction [1]. The enhanced mechanical properties of CFST columns can be explained in terms of composite action between the perimeter steel tube and the concrete core. The steel tube provides lateral confinement to the infill concrete while the concrete prevents inward local buckling of the steel tube.

High strength concrete has recently become an attractive alternative to normal strength concrete in CFST columns because of smaller column size and less self weight. However, high strength concrete is characterized by a reduced dilation and a more brittle failure in comparison with normal strength concrete [2]. This is rather unfavorable to concrete confinement and load transfer, and consequently a sharp drop of axial load happens for those CFST columns with high strength concrete [3,4]. To obtain a ductile behavior, a tube with high strength or small diameter-to-thickness ratio is needed [5,6], which is certain to increase the construction cost. In this situation, improving the performance of concrete has been expected to be another way of achieving a better behavior of the steel tube columns filled with high strength concrete.

Adding fibers into plain concrete has been proved to be an effective method of eliminating its inherent brittleness. The fibers

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bridge the cracks in the matrix and transfer the applied load to the matrix, thus fiber reinforced concrete has better post-crack behavior than plain concrete. For example, when a diagonal shear crack occurs in steel fiber reinforced concrete, steel fibers crossing the shear failure plane provide additional shear frictional resistance. This helps to a shear transfer across the shear plane, and then a smoother drop of axial load [7]. The presence of fibers also leads to higher impact resistance and greater flexural and tensile strengths [8]. These property enhancements depend on a number of factors, such as matrix strength, fiber volume and fiber surface bonding characteristics [9,10].

The use of fiber reinforced concrete as infilling to improve the behavior of CFST columns has been studied for several decades. The earlier studies on this subject were carried out to validate the feasibility of enhancing their fire resistance [11–15]. In recent years, the behavior of fiber reinforced concrete-filled steel tube columns at room temperature has been an increasing concern. The behavior of steel tube columns filled with fiber reinforced low, and normal strength concrete have been investigated by Campione et al. [16,17], Gopal and Manoharan [18], Ellobody and Ghazy [19], Ellobody [20,21], Tao et al. [22] and Gopal [23]. In those studies, the CFST columns were of slender columns or/and tested under eccentrically load, and the enhanced flexural and tensile strengths of fiber reinforced concrete were applied to ease the increasing strain gradient associated with increasing flexure. Therefore, some beneficial effects of composite behavior in terms of strengths are obtained. In addition, the presence of steel fibers provides a higher stiffness, which delays the increasing of lateral deflection, and then enhances the ductility and the energy dissipation capacity of CFST columns.

With the increasing use of high strength concrete in CFST columns, steel fibers has also been introduced into high strength concrete to obtain a ductile behavior. In the case of steel tube columns filled with high strength concrete, like the above mentioned studies, the enhanced tensile and flexural strengths and higher stiffness of steel fiber reinforced concrete were applied to improve their behavior. Tokgoz and Dundar [24] stated that when rectangular steel tube columns filled with steel fiber reinforced high strength concrete were subjected to eccentric load, the use of fiber reinforced concrete improved the ductility and the deformation capacity but had little effect on the ultimate strength. Portolés [25] reported experimental investigations on slender steel tube columns filled with normal, high and ultra-high strength concrete under eccentric load. The infill concrete included plain concrete, steel fiber reinforced concrete and bar reinforced concrete. The results showed that in the case of normal strength concrete, the steel tube columns filled with fiber reinforced concrete exhibited better performance than the steel tube columns filled with plain concrete and similar performance to the steel tube columns filled with bar reinforced concrete. However, the addition of steel fibers did not help in the case of high and ultra-high strength concrete because the global behavior predominated over the section behavior for slender columns. Liew and Xiong [26] presented an experimental investigation of short CFST columns with ultra-high strength concrete of compressive strength close to 200 MPa. They reached the conclusions that the ductility and strength of steel tube columns filled with ultra-high strength concrete can be improved by adding steel fibers into concrete, and at least 1% volume of steel fibers is needed to obtain an effective enhancement. Tao et al. [27] conducted an experimental study to find an effective method to improve the ductility of CFST columns with square cross section. The authors concluded that in the aspect of increasing the ductility of stub CFST columns, improving the performance of concrete core by adding steel fibers is a more effective and economic way than enhancing the local buckling of steel tube. This is reasonable because most of the load capacity of CFST columns, especially those with thin-wall tubes, was contributed by the concrete core. To realize a minimum cost design of SFRCFST columns, Hatzigeorgiou and Beskos [28] developed a computer program. In this program, the cost of CFST columns was taken as the optimization module, and the strength and stability requirements were described as the constraints of the optimum design.

Based on the above analysis, it seems that using fiber reinforced concrete as infilling in CFST column is an effective method to improve their behavior in many cases. However, the studies on the steel tube columns filled with fiber reinforced concrete are relatively recent, and those on the steel tube columns filled with steel fiber reinforced high strength concrete are especially lacking. Furthermore, those tests were focused on the beneficial effects of enhanced the tensile and flexural strengths and stiffness compared with plain concrete. Because the length-to-diameter of low story columns of high-rise buildings are relative small, and those columns with high strength concrete are more susceptible to a brittle shear failure under axial load [29], we conducted experimental tests to investigate the reinforcing effect of steel fibers on the short steel tube columns filled with high strength concrete. Specifically, thirty-six specimens, including nine plain concrete-filled steel tube (PCFST) specimens and twenty-seven steel fiber reinforced concrete-filled steel tube (SFRCFST) specimens, were tested under axial load. The failure modes, ultimate loads and axial load-axial shortening relationships were obtained from the tests. The confined concrete strength is calculated based on the experimental results. The effects of the steel fiber volume percentage, the concrete strength and the thickness of steel tube on the ultimate load and the ductility of SFRCFST columns are discussed in this paper. Furthermore, Design formulas are proposed to predict the load capacity and the ductility of steel tube columns filled with plain concrete and those filled with steel fiber reinforced concrete.

2. Experimental program

2.1. Test specimens

Thirty-six concrete-filled steel tube (CFST) specimens, including nine plain concrete-filled steel tube (PCFST) specimens and twenty-seven steel fiber reinforced concrete-filled steel tube (SFRCFST) specimens, were tested under axial load. The tested parameters included concrete strength, thickness of steel tube, and steel fiber volume percentage. All specimens had the same length to diameter ratio of 3. The details of all specimens are summarized in Table 1. The specimens are labeled as follows. Letter C represents the concrete, followed by the concrete strength grade. The following numbers represent the thickness of steel tube and steel fiber volume percentage, respectively. The specimens are classified into nine groups according to concrete strength grade and thickness of steel tube. Each group includes one benchmark PCFST specimen and three SFRCFST specimens. These four columns have the same concrete strength grade and thickness of steel tube, but different steel fiber volume percentages. In Table 1, D is the external diameter of steel tube, t is the thickness of steel tube, L is the length of the specimens, f_y is the yield strength of steel tube, f_{cu} is the cubic compressive strength of concrete, including plain concrete (PC) and steel fiber reinforced concrete (SFRC) in this study, θ is the confinement index of the steel tube and V_f is the steel fiber volume percentage.

2.2. Material properties

The steel frameworks of all specimens were fabricated from seamless circular steel tubes. Three different tube thicknesses of 3, 4 and 5 mm were used to achieve different diameter-to-thickness ratios. The average values of yield strength, ultimate tensile strength and elastic modulus for the steel tubes were 306 MPa, 417 MPa and 205 GPa, respectively. Three different concrete strength grades of C50, C60 and C70 were considered. The concrete mixtures were made with Portland cement, river sand, granite stone of particle size 5–10 mm, fly ash and silica fume. Super-plasticizer was used to ensure a workability of self-consolidating. The mix designs for plain concrete are shown in Table 2. The slump flow of fresh concrete and the cube strength were determined according to Chinese codes CECS 203: 2006 [30] and GB/T 50081–2002 [31], respectively. The mean measured cube strengths at 28 days for the C50, C60 and C70 concrete were 53.7, 60.9 and 69.7 MPa, respectively. The slump flows for three concrete mixtures were all about 650 mm.