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Effect of reinforcement stiffeners on square concrete-filled steel tubular columns subjected to axial compressive load

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ABSTRACT

Eight stiffened square concrete-filled steel tubular (CFST) stub columns with slender sections of encasing steel and two non-stiffened counterparts were tested subjected to axial compressive load. Four types of reinforcement stiffeners and steel tensile strips were introduced to postpone local buckling of steel tubes, in which the tensile strip was first used as stiffener in CFSTs. The stiffening mechanism, failure modes of concrete and steel tubes, strength and ductility of stiffened square CFSTs were also studied during the experimental research. A numerical modeling program was developed and verified against the experimental data. The program incorporates the effect of the stiffeners on postponing local buckling of the tube and the tube confinement on concrete core. Extensive parametric analysis was also conducted to examine the influencing parameters on mechanical properties of stiffened square CFSTs.

1. Introduction

In structural systems using square concrete-filled steel tubular (CFST) columns, regular indoor space is provided and joint construction is facilitated and fast tracked. However, the lateral pressure from square steel tube is unevenly distributed in the square concrete cross-section. The lateral pressure near the web centers is weaker than that near the corners. On the other hand, the steel tube is prone to buckle, especially when depth-to-thickness ratio is large. These disadvantageous mechanical behaviors of concrete and steel tube mentioned above can attribute to their inadequate interaction. To enhance the interaction between the steel and concrete and further increase their resistances, other scholars introduced stiffeners into square CFSTs. The patterns of stiffeners are shown in authors' previous paper [1].

The plate rib is the most commonly used stiffener in square CFST columns. Experimental studies were carried out to investigate its anti-buckling behavior [2–4]. The plate ribs are welded on the inner surfaces of the tube to reinforce the tube by enlarging bending rigidity of steel plate sections. After the HyogokenNanbu earthquake, the plate rib was introduced in bridge piers and frame columns with huge cross-sections [5]. To simplify fabricating procedure, stiffeners sometimes can be formed by bending steel plates. Curling ribs and oblique curling ribs were studied in the experiments [6,7] by welding cold-formed channels or isosceles angle irons with curling edges. Test results show that, under low compression ratio, the curling ribs and oblique curling ribs can effectively improve static ultimate strength and enhance ductility of the structure in resisting earthquake load. However, the embedment of these ribs in concrete, depending on frictional force between stiffeners and concrete, cannot guarantee the interaction between the concrete and steel tube, and is also weakened by concrete expansion. Meanwhile, the full penetration butt weld may lead to residual stresses in steel plates. Curling ribs may also encounter fabricating problems in bending curling edges, especially for thick plates.

To improve the embedment of stiffeners in concrete, other types of stiffeners, mainly employing steel tensile property, were introduced into square CFST columns. Studies on performance of square CFST members, by utilizing pairs of tie rods, also known as binding bars, at possible plastic hinge locations, were conducted in experiments [8,9]. Constitutive relationship was developed for square CFSTs with binding bars [10], in which, the concrete constitutive relationship took a similar form to that of Mander model. However, the convex tie rods obstruct indoor space. To improve this disadvantage, tension sheets was introduced with similar stiffened scheme [6]. Furthermore, oblique tie bars, as an enhanced stiffened scheme by decreasing welding spacing in cross section, was employed [11]. The stiffeners, such as tie rods, binding bars and oblique tie bars, can effectively avoid concrete cracking,

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restrain the out-of-plane deformation of plates and therefore delay local buckling of steel tubes.

The previous research showed that the proposed stiffeners can obviously delay local buckling of the tube and provide enhanced strength and ductility compared to square CFST columns. However, the existing stiffeners may have limitations in material efficiency or fabrication feasibility. Innovative types of reinforcement stiffeners were proposed in authors' previous experimental research [1] in 2012. Preliminary results on behavior of reinforcement stiffeners were obtained. It is found that, some types of reinforcement stiffeners can increase steel tensile capacity, however, the remaining types cannot.

The study in this paper was performed to investigate the static behavior of square CFST cross-sections with reinforcement stiffeners or tensile strips. On the basis of previous tests conducted by the authors, the post-buckling properties and constraint effect for concrete were studied. Both experimental and analytical researches were carried out to assess the proposed stiffeners. Numerical analysis was made on stiffened square CFST cross-sections to study various parameters such as material strengths, material consumptions and stiffener arrangement type.

Compared to the previous research [1], material efficiency was achieved by promoting improved stiffened scheme for steel tubes in this paper. The steel tensile strip was first used as stiffener in the CFSTs. The range of steel tube ratio to the concrete was extended to get more behavioral understanding of CFST specimens. Loading devices were improved to stably record the load–displacement curves during load descending stage. Based on the test observation, local buckling was included in the strength of steel tubes in numerical analysis.

2. Experimental program

2.1. Test specimens

Table 1 summarizes the basic geometrical properties of the specimens. The specimens consist of ten stubs with eight stiffened specimens and two non-stiffened counterparts. The cross sections of the specimens with stiffeners are showed in Fig. 1. The longitudinal arrangement of stiffeners on steel tubes is showed in Fig. 2.

The depth b and length L of all the specimens are 200 mm and 600 mm respectively. Two nominal steel plate thicknesses t (2.0 mm and 3.5 mm) were chosen for steel tubes and hot-rolled plate. Reinforcements with nominal diameter d and tensile strips with cross-sectional dimensions $d_r \times t_r$ were employed as stiffeners. Based on the nominal steel plate thickness t, the specimens are divided into two groups: group I (t=2.0 mm and corresponding depth-to-thickness ratio b/t=100) and group II (t=3.5 mm and corresponding depth-to-thickness ratio b/t=57). In Table 1, α_s is the ratio of steel tube cross-sectional area A_s to concrete cross-sectional area A_c; α_r is the ratio of reinforcement volume V_r to concrete volume V_c. The details of the stiffeners in the same stiffened scheme are described in groups as follows:

S1 and S5: non-stiffened specimens, shown in Fig. 1(a), designed as referential specimens.

S2 and S6: stiffened specimens with battlement-shaped reinforcements, shown in Figs. 1(b) and 2(a). The battlement-shaped reinforcements were made through bending straight reinforcements and welded tangentially on the inner surfaces of the steel tube. The stiffeners were expected to restrain the tube at the welds and the battlement shape guarantees embedment in concrete. During fabricating the stiffened specimens, the steel plates were folded into L shape, the inner sides of which were welded with reinforcement stiffeners. Then two L-shaped parts were welded to form a hollow square tube. This fabrication procedure reduced adverse influence caused by welding residual stress compared to traditional workmanships.

S3 and S8: stiffened specimens with oblique battlement-shaped reinforcements, shown in Figs. 1(c) and 2(b). The battlement-shaped reinforcement was positioned near the corners of the tube and welded tangentially to the inner surfaces of the two adjacent steel plates. The weld divided the steel plate cross section into three parts with widths of 65 mm, 70 mm, and 65 mm respectively. An oblique battlement-shaped reinforcement was welded between two adjacent plates, therefore square steel tube should be formed before stiffener welding.

S7: stiffened specimen with welded circular stirrups, shown in Figs. 1(d) and 2(c). Six circular stirrups were welded uniformly spaced along the length onto the inner surfaces of the steel tube. The stirrups were expected to confine the concrete core and restrain the possible outward deformation of the encasing steel at the location of welds. A circular stirrup was welded on four plates, therefore square steel tube formation should be prior to stiffener welding.

S4, S9 and S10: stiffened specimens with tensile strips, shown in Figs. 1(e) and 2(d). The tensile strips, with cross-sectional dimensions of 20 mm (height) $\times$2.0 mm (thickness) or 20 mm (height) $\times$3.5 mm (thickness), were installed through the pre-fabricated holes with dimensions slightly larger than those of the stiffeners. The tensile strips were then welded at two ends, with the spacing of 100 mm along the length. The steel tensile strips were made of the same steel plates of the tubes. This hole-drilling fabricating method can avoid heat-induced initial imperfection by traditional gas-cutting method.

After fabrication of the stiffened tube, an end plate was welded at the bottom for subsequent concrete casting procedure. Accordingly, another end plate was welded to seal the top end of the specimen

Table 1
Parameters of specimens.

Specimen	Stiffener type	Tube thickness t (mm)	Cross-sectional dimension of stiffener $d/d_r \times t_r$ (mm)	Longitudinal spacing of stiffener's welds s (mm)	Steel ratio of tube α_s (%)	Steel ratio of stiffener α_r(%)
S1	None	2.01	–	–	4.2	0
S2	Battlement-shaped reinforcement	1.90	8.0	80	4.2	0.84
S3	Oblique battlement-shaped reinforcement	1.90	8.0	80	4.2	1.08
S4	Tensile strip	1.90	20.0 $\times$ 3.49	100	4.2	0.70
S5	None	3.49	–	–	7.5	0
S6	Battlement-shaped reinforcement	3.49	8.0	80	7.5	0.84
S7	Welded circular stirrup	3.49	8.0	80	7.5	0.86
S8	Oblique battlement-shaped reinforcement	3.49	8.0	80	7.5	1.08
S9	Tensile strip	3.49	20.0 $\times$ 3.49	100	7.5	0.70
S10	Tensile strip	3.49	20.0 $\times$ 2.01	100	7.5	0.40