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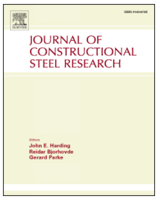

Pseudo-static tests of terminal stirrup-confined concrete-filled rectangular steel tubular columns

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ABSTRACT

This paper mainly presents a pseudo-static test program on 12 terminal stirrup-confined square concrete-filled steel tube (SCFT) columns and 14 rectangular SCFT columns under constant axial pressure. The effects of various factors on the hysteretic behavior of specimens are investigated. These factors include with or without stirrups, height of terminal stirrup region, equivalent stirrup ratio, stirrup form, loading direction, height-length ratio (L/B), length-width ratio (B/D), axial compression ratio (n) and sliding support. The failure mode, strain ratio, hysteretic curve, skeleton curve, ultimate bearing capacity, ductility, stiffness degradation, energy dissipation, as well as the residual deformation of the specimens are analyzed. The results indicate that: (1) When n is relatively larger, the bidirectional stirrups can effectively delay the local buckling of steel tube and greatly increase the ultimate bearing capacity, stiffness, equivalent damping viscosity index, residual deformation rate and ductility index, and further significantly improve the seismic behavior of the rectangular SCFT columns; (2) Axial pressure can improve the confinement effect from the steel tube to the core concrete, also bidirectional stirrups can directly confine the core concrete to decrease strain ratio of the steel tube; (3) With the same value of n, increasing the height of terminal stirrup region or increasing the equivalent stirrup ratio can effectively improve the seismic behavior of the rectangular SCFT columns; (4) The influence of loading direction, L/B and B/D on the ductility of rectangular SCFT columns are not obvious.

1. Introduction

Concrete filled steel tubular (CFT) columns have been increasingly used in bridges and high-rise buildings due to their enhanced compressive strength and stiffness, improved ductility and higher energy absorption capacity compared to the conventional steel or concrete structures. With such benefits, the use of CFT columns is becoming more commonplace and the performance of CFT columns has caught more and more research attention [1–9]. Several studies have demonstrated that circular CFT stub columns can provide sufficient constraint from the steel tube to the core concrete [1–4]. However, the flexural rigidity and flexural capacity are comparatively low and, in particular, the configuration of joints connecting the circular CFT columns and beams is complex. In comparison, the confining effect from the steel tube to the core concrete in square or rectangular CFT columns is relatively weak, despite that the section moment of inertia (therefore bending stiffness) is improved and the joint configuration is more convenient [5–9]. However, the confining effect from the steel tube to the concrete in rectangular CFT columns is relatively weak and the load-bearing capacity and ductility under seismic action are therefore reduced. The seismic behavior of rectangular CFT members is increasingly becoming a critical problem in the engineering field [10–12].

Pseudo-static tests are usually used to study the seismic performance of CFT columns, that is, axial compression and lateral cyclic load are applied to columns simultaneously. Amit H. Varma et al. [10] conducted a pseudo-static test study on 8 square CFT columns to investigate the effects of parameters include width to thickness ratio, steel yield strength and axial compression ratio n on the seismic behavior of such members. The experimental results show that there is no obvious difference of the displacement ductility index when the steel ratio of cross section is changed from 7.5% to 11.0%. Also, when n is 0.21, the displacement ductility index of conventional steel specimens is not obviously different from high strength steel specimens. Similarly, Liu et al. [11] conducted a seismic behavior test study on 9 square CFT columns with the steel ratio ranged from 6.9% to 12.4% under constant axial load and lateral cyclic load. Effects of n, width to thickness ratio, height-length ratio and concrete strength on the ductility and energy dissipation ability were studied. Han et al. [12] focused on ultimate bearing capacity and ductility on 12 square CFT columns and 18

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rectangular CFT columns with the steel ratio during 8.6%–14.5% under a pseudo-static test study. Three key parameters including n, length-width ratio and core concrete strength were considered in the experimental study. The results from the above studies reflected that when n is more than 0.5, the ductility and energy dissipation of the square CFT columns and rectangular CFT columns are generally low.

Moreover, many researchers have proposed different structural measures on square CFT columns in order to increase the confinement effect from the steel tube to the core concrete and improve their seismic performance. These structural measures include steel jacket welded outside the steel tube [13], encased profile steel [14], longitudinal stiffening ribs [15] and horizontal binding bars [16] arranged inside the steel tube. Mao et al. [13] proposed 3 forms of steel jackets welded to the potential plastic hinge region to delay the local buckling of the steel tube and ensure a ductile behavior of CFT members. However, due to the limitation of welding technology, the improvement of ultimate bearing capacity and stiffness is not obvious. The structural measures outside the steel tube are mainly applied to the reinforcement of the existing CFT members. On the other hand, for the new CFT members, increasing the internal steel is usually applied to improve the steel ratio. For example, Zhu et al. [14] proposed profile steel embedded in core concrete to prevent the fracture surface of concrete under failure load. When the equivalent amount of steel is increased by 97.8%, ultimate bearing capacity, displacement ductility index, energy-dissipation index are increased by 9.5%, 15.4%, 13.5%. Zhang et al. [15] proposed longitudinal stiffening ribs on 2 inner faces or 4 inner faces of square steel tubes. It was found that when n is 0.4 and 0.5, compared to the specimen of 2 stiffening ribs, the specimen with 4 stiffening ribs have no obvious improvement in the ultimate bearing capacity compared to the specimen with 2 stiffening ribs. However, its displacement ductility index is increased by 30%. Wang et al. [16] proposed a measure by bolting horizontal binding bars inside the square steel tubes to postpone their local buckling and improve the seismic behavior of CFT specimens. The results show that when n is 0.2, the ultimate bearing capacity is almost unchanged while the ductility index is increased by 67%. Moreover, when n is 0.6, the ultimate bearing capacity is increased by 10% and the ductility index is increased by 30%.

However, it is difficult to perform the welding work for large-dimensional CFT columns due to their too thick steel tube in practical project. Consequently, the thin-walled rectangular CFT columns have been widely used. However, the latters' low steel ratio will weaken their seismic performance. In order to improve the axial compressive performance of thin-walled square CFT stub columns, Ding et al. [17] conducted a comparison study of four structural measures including studs, circular stirrups, rhombus stirrups and bidirectional stirrups, based on which they proposed a way of welding the bidirectional stirrups to the inner wall of the square steel tube. This method was proved to exert the most effective constraint on the core concrete and hence was applied to round-ended CFT stub columns under axial compression [18]. Similarly, it can also be applied to the rectangular CFT columns for the study on seismic performance.

It is known that the weak region of a CFT frame column is located at its terminal section, the idea of stirrups encryption in joint area of reinforced-concrete structure can be applied to CFT columns. In order to reduce the amount of steel, improve the economic efficiency and optimize the construction, the authors put forward the terminal stirrup-confined rectangular CFT (SCFT) columns in which the bidirectional stirrups are welded inside the rectangular steel tube at the columns ends with large bending moment. For large-dimensional CFT columns, it is convenient for operators entering the steel tube and welding stirrups only at the columns ends.

In conventional standards, storey height and storey number are limited in order to limit n of the columns and ensure their seismic performance. However, in actual high-rise and super high-rise buildings, n of columns is often very large, even reaching 0.8. The aim of this study, therefore, is to focus on the advantage of rectangular SCFT columns under high n even up to 0.8. More specifically, two objectives are included in this study: (1) to investigate the seismic behavior of rectangular SCFT columns through a pseudo-static test study on 26 specimens; (2) to study the effects of 9 main factors on the hysteretic behavior of specimens include with or without stirrups, height of terminal stirrup region, equivalent stirrup ratio, loading direction, height-length ratio (L/B), length-width ratio (B/D), axial compression ratio (n) and sliding support.

2. Experimental investigation

2.1. Specimens and materials

In this test program, 26 specimens were designed, including 12 square SCFT columns and 14 rectangular SCFT columns. Each specimen consisted of concrete filled steel tubular column, top plate, bottom plate and stiffening ribs. Figs. 1 and 2 exhibit a schematic view and the actual photos of the specimens, respectively. The details of the labels and parameters of specimens are listed in Table 1. In the label of specimen, the first letter "s" or "r" represents square or rectangle, the second letter "c" means column, the third letter "h" indicates that the loading mode is hysteretic. B is the length (longer side) of rectangular section, D is the width (shorter side) of the rectangular section, t is the wall thickness of the steel tube, L is the effective height of column excluding the height of stiffening ribs. ρ_s is the steel ratio of the cross section, calculated by $\rho_s = A_s / (A_s + A_c)$, where A_s and A_c are the area of steel tube and core concrete, respectively. a_s, b_s and d_s are horizontal spacing, longitudinal spacing and diameter of stirrups, respectively. h_1 and h_2 are height of terminal stirrup region at the bottom and top of specimens. Stirrups of h_1 mainly bear the bending moment and shear force, while stirrups of h_2 are constructional reinforcement to prevent the core concrete from premature crushing failure. f_{cu} is the cubic compressive strength of concrete, f_c is uniaxial compressive strength of concrete prism. According to Ding et al. [19], the conversion relationship between f_c and concrete compressive strength f_{cu} is $f_c = 0.4f_{cu}^{7/6}$. f_s and f_{sv} is the yield strength of steel tube and stirrup, respectively. ρ_{sa} is equivalent stirrup ratio defined as $\rho_{sa} = \rho_{sv} \times f_{sv}/f_s$, where ρ_{sv} is the stirrup ratio. n is axial compression ratio, calculated by $n = N/N_u$, where N is the constant axial pressure and N_u is the nominal bearing capacity. N_u is obtained from formula $N_u = f_cA_c + f_yA_s$ [11,15,16]. P^+ and P^- are the maximum positive and negative horizontal bearing capacity. DI is the displacement ductility index obtained from the average value of positive and negative displacement ductility index. K_1 is the initial stiffness obtained from the average value of positive and negative initial stiffness.

Among these specimens, sch1 and sch3 are without stirrups while the others are with bidirectional stirrups on the cross-sections of specified spacing. Besides, sch1, sch2 and sch5 were tested without sliding support because the n of sch1, sch2 is 0 and sch5 is used to compare the effect of sliding support with sch3. Moreover, the stirrup diameter of sch8 is 8 mm and sch9 is with ring stirrups. Particularly, the n of rch1~4–0.8 is up to 0.8.

For each specimen, the steel tube was welded from two right angle tubes which were firstly bent using the Q235 hot-rolled steel plates. The welding was performed according to the standard GB 50017-2003 [20] and the ends of the steel grooves (as the sites of welding) were kept smooth after welding. Both ends of stirrups were firstly bent to right angle with bent length of 20 mm and then welded to the two ends of the steel tubes in a certain range. Moreover, spot welds were adopted at the intersections of bidirectional stirrups and thus they form a steel mesh.

The bottom plate and stiffening ribs were welded to the bottom of the steel tube. Then the concrete was pumped into the tube from the top and was vibrated to be well compacted. The commercial concrete of grade C40 was adopted for all the specimens. Moreover, 9 standard concrete cubes with a dimension of 150 mm × 150 mm × 150 mm were prepared and cured at the same condition as those of SCFT