Structural behaviour of recycled concrete filled steel tube columns strengthened with CFRP sheets under axial loading

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1 General Introduction

In recent years, concrete filled steel tube (CFST) columns encompassing the use of steel and concrete have been widely used in structural engineering. This is mainly due to the combination of the advantages of steel and concrete, which gives excellent earthquake resistance in terms of high strength, ductility and energy absorption [1].

At present, recycled aggregate concrete filled steel tube (RCFST) columns have been the interest of structural engineers, as this is beneficial for saving of natural resources and the environmental preservation and is also the need of low carbon economy. Although various types of RCFST columns are reported in the literature, however, the two most common RCFST columns are the solid and hollow ones [2]. In comparison with CFST columns, RCFST columns show a similar failure mode and a higher ductility, but a lower load carrying capacity, which can be strengthened by attaching fibre reinforced polymer (FRP) composites. Externally bonded FRP composites have been widely used as confining materials for RCFST columns [3]. As a result of FRP confinement, both the compressive strength and the ductility of FRP confined steel tube columns can be significantly enhanced [4-6].

There has been extensive experimental research on either the behaviour of RCFST columns or the FRP confined CFST columns [7-10]. However, few attempts have been made to study the structural behaviour of RCFST column strengthened with FRP materials. This paper presents experimental results of RCFST columns strengthened with carbon fibre reinforced polymer (CFRP) sheets subjected to axial loading. Twenty circular and square steel tube columns were made, which are comprised of ten solid and ten hollow ones, filled with normal and recycled aggregate concrete (RAC) and strengthened with two layers of CFRP sheets externally bonded along the circumferential direction. The main parameters studied in the tests were (1) the tube configuration, i.e. circular or square, solid or hollow; (2) concrete type, normal concrete or RAC; (3) the reinforcing arrangement, full wrapping or partial wrapping. Deformation and failure modes of the RCFST columns are also presented and discussed.

2 Experimental Programmes

2.1 Test Columns

Twenty columns were prepared and tested, including six normal concrete filled steel tubes and fourteen recycled concrete filled steel tubes. The ratio of the external tube diameter to the wall thickness of the tube sections varied from 50 to 57 covering compact sections. The columns have three different lengths, 250, 350 and 400 mm, which give the ratio of the length to the external tube diameter in the range from 2.2 to 4.0.

The columns were divided into four series, i.e. circular solid steel tubes, circular hollow steel tubes, square solid steel tubes and square hollow steel tubes. The only major difference at given series lies in the recycled concrete used. The detailed cross sections of steel tube tested were shown in Fig. 1.

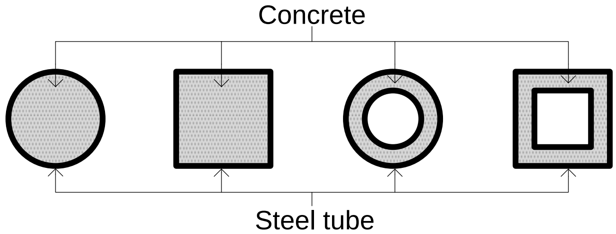


Fig.1. Cross sections of concrete steel tubes tested.

2.2 CFRP Sheets

The CFRP confined steel tube columns were formed in a wet lay up of CFRP sheets with epoxy resin. Two layers of continuous CFRP sheets was wrapped around the steel tube to form a jacket, with the finishing end of the fibre sheet overlapping its starting end by 150 mm to ensure circumferential continuity [4]. Two reinforcing arrangement, i.e. full wrapping and partial wrapping, were applied to strengthen the steel tubes.

Before the strengthening, the surface of steel tube columns where CFRP sheets to be bonded was ground with an abrasive disk to enhance the bond between the steel and the CFRP. The smoothed surface was cleaned by a solvent-based cloth [3].

2.3 Material Property

Two types of concrete mixes were prepared, i.e. natural and RAC. In the RAC produced, 50% of the recycled coarse aggregate and 50% of the normal aggregate were used. The averaged 28-day cube strengths of the natural aggregate concrete and RAC were 42.6 and 43.9 MPa, respectively. The recycled coarse aggregate were obtained by crushing the earthquake waste concrete, which was taken from the failure structures in Dujiangyan after the Sichuan earthquake on 12th May, 2008, sieving with a mesh size of 18 mm.

The average yielding strength, tensile strength, and elastic modulus of the circular and square steel tube are 300 MPa, 390 MPa, 195 GPa, and 336 MPa, 435 MPa, 193 GPa, respectively.

The CFRP sheets used for the tests have a thickness, nominal tensile strength, nominal elastic modulus and ultimate strain of 0.111 mm, 4103 MPa, 242 GPa and 1.7%, respectively.

2.4 Test Setup and Instrumentation

For each column, four bi-direction strain gauges were attached at the mid height of the steel tube to measure the longitudinal and circumferential strains during the test. For the externally reinforced columns, these strain gauges were affixed to the outermost layer of CFRP sheets. The vertical displacement was recorded using linear variable displacement transducers (LVDTs).

All the columns were concentrically loaded in axial compression to failure. The loads were applied through a hydraulic actuator with 5000 kN capacity [6]. The load increment of 30 kN was used, which was held for about 5 minutes to record the strain readings and the displacements. The load increment was adjusted to 15 kN in the later stage of the test.

3 Results and Discussion

The ultimate strengths, displacements, the relationships between the applying load and the axial or the hoop strain, and the failure modes of all columns tested were presented.

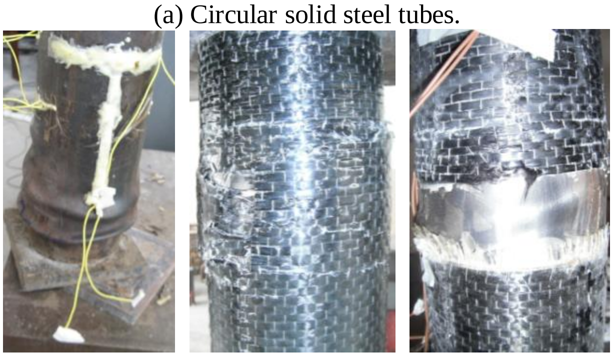
3.1 Failure Modes

The failure modes of CFST and CFRP confined steel tube columns with circular and square and/or solid and hollow section are shown in Fig. 2. The failure of the steel tubes was typically initiated by steel yielding over the entire cross section, followed by local buckling of the steel tube (Fig. 2a). Failure of the CFRP confined steel tubes was initiated by sudden rupture of the CFRP sheets at the mid height or near the bottom of the column strengthened, followed by crushing of the concrete or buckling of the steel tube, as shown in Figs. 2a and 2b.

It can be seen that the failure modes for columns with circular sections are quite similar even though the lateral outward deformations for the partially CFRP wrapped columns are larger that those of the fully wrapped ones.

Failure modes for square tubes are of similar characteristics to those of the circular ones, i.e. local buckling associated with CFRP debonding and rupture (Figs. 2c and 2d). In comparison to the circular tubes, the square ones seem having higher buckling modes, i.e. higher eigenvalues. However, they show quite different buckling loads, which is to be discussed in the next section.

(a) Circular solid steel tubes.



(b) Circular hollow steel tubes.

(c) Square solid steel tubes.

(d) Square hollow steel tubes.

Fig.2. Failure modes of the steel tubes tested.

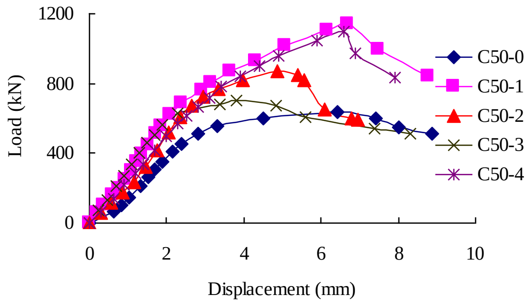
3.2 Load-Axial Shortening

Table 1 shows the height of the columns (*H*), the concrete strength applied (f_c), the ratio between the areas of CFRP strengthened surface and the external surface of columns (*A*), the ultimate compressive load (N_{ue}) and the final displacement (*V*) for all steel tube columns tested. The ultimate load of the circular solid steel tube columns, C50-1 and C50-2, which are fully or partially strengthened with two layers of CFRP sheets, are 84.5% and 37.4% higher than that of the reference column C50-0 due to the restraining effect of CFRP. The results also show that the specimen with full wrapping arrangement of CFRP has a higher load carrying capacity than the partial one due to the larger strengthening area. However, the ultimate load of C50-4 is 56.3% higher than that of the C50-3, but is 6% lower than that of the C50-1, which has a higher height than C50-4. The results show that the column height investigated has little influence on the ultimate load carrying capacity of the columns with the same reinforcement, which was also found in the square solid steel tubes (S50-1 and S50-3). The similar results were also obtained by Wong et al. [5]. However, this is likely applied to the relatively short columns investigated.

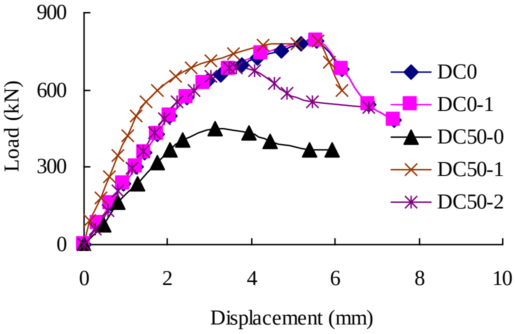
Table 1 Test results of columns tested.

Specimens	*H* (mm)	f_c (MPa)	*A* (%)	N_{ue} (kN)	*V* (mm)
C50-0	400	42.6	0	634	8.87
C50-1	400	43.9	100	1170	8.77
C50-2	400	43.9	75	871	6.97
C50-3	250	43.9	0	701	8.32
C50-4	250	43.9	100	1096	7.93
DC0	400	42.6	0	568	5.11
DC0-1	400	42.6	100	792	7.41
DC50-0	400	43.9	0	449	5.93
DC50-1	400	43.9	100	788	6.16
DC50-2	400	43.9	75	687	6.80
S50-0	400	43.9	0	559	4.91
S50-1	400	43.9	100	780	6.89
S50-2	400	43.9	75	668	6.10
S50-3	350	43.9	100	748	5.49
S50-4	350	43.9	71	687	6.48
DS0	400	42.6	0	550	7.43
DS0-1	400	42.6	100	652	4.99
DS50-0	400	43.9	0	458	5.38
DS50-1	400	43.9	100	598	5.69
DS50-2	400	43.9	75	570	4.59

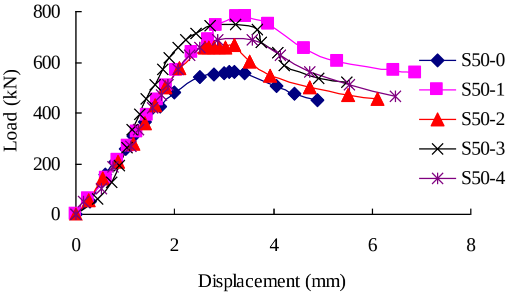
The load-axial displacement relationships for each test serials of steel tube columns are plotted in Fig. 3, which gives comparisons of the behaviour for different cross sections with full wrapping and partial wrapping of CFRP sheets [7]. For circular solid columns, the ultimate carrying capacities are higher than the unconfined columns, as expected. It also can be clearly seen that the columns with full wrapping reinforcement are the most stiff (Fig. 3a). The ultimate carrying capacities and stiffness of circular hollow columns increased greatly when they were reinforced. It also can be seen that the stiffness of columns DC50-1 and DC50-2, could be increased effectively by fully arrangement of CFRP (Fig. 3b). The results show that the RAC may decrease the carrying capacity and stiffness of the steel tube columns strengthened. This can also be found in square hollow columns of DS0 and DS50-0 (Fig. 3d). As shown in Fig. 3c, the ultimate carrying capacities of square solid steel tubes increased greatly when the CFRP reinforcing arrangement applied, which has similar characteristics to those of circular solid ones (Fig. 3c). However, the initial stiffness of square solid steel tubes was not clearly influenced. The similar phenomena were also observed by Yu et al. [8]. These results indicate that the efficiency of CFRP confinement depends not only on the natural concrete or RAC applied but also on external configuration of the columns reinforced.



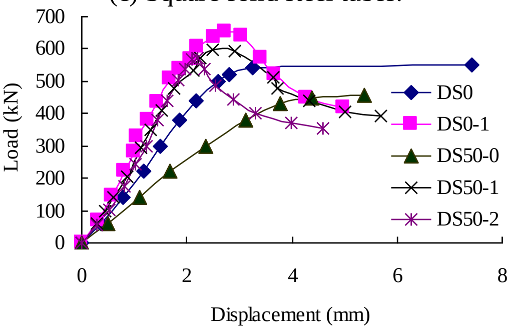
(a) Circular solid steel tubes.



(b) Circular hollow steel tubes.



(c) Square solid steel tubes.

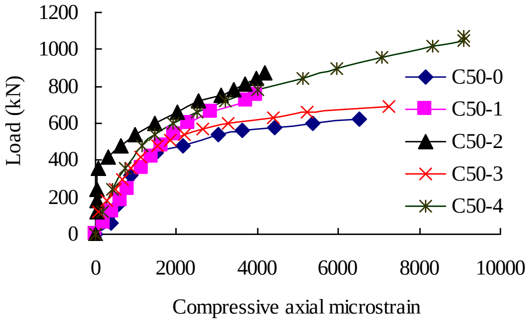


(d) Square hollow steel tubes.

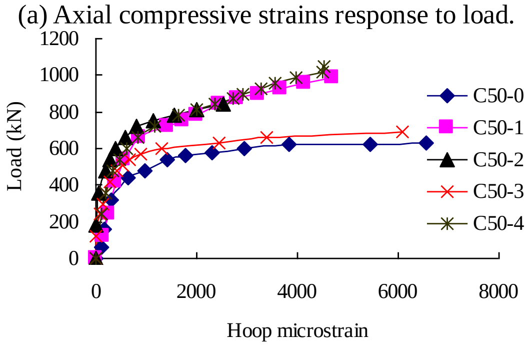
Fig.3. Load-axial displacement curves.

3.3 Load versus Strain Response

The typical load-strain curves for circular solid steel tube columns are shown in Fig. 4. There are a little difference of compressive strains on the columns strengthened and non-strengthened at the initial loading stage. However, the columns strengthened give the smaller compressive strains at a given load than those of the non-strengthened columns when the steel tubes start yielding, as shown in Fig. 4a. The hoop strains on the C50-3 are smaller than those of the C50-0 at a given load, which may be caused by the shorter height of the C50-3. It can be seen that the columns strengthened give a smaller hoop strains than those of the non-strengthened steel tube columns (C50-0 and C50-3). It also shows that the column of C50-2, which was partially wrapped of CFRP, give the lowest of compressive axial strains and hoop strains at a given load than those of the full wrapping ones (C50-1 and C50-4), which may be caused by the buckling of steel tube of C50-1 was initiated near the top of the column, but the strain chips was attached in the middle height of the column (Figs. 2a and 4b).



(a) Axial compressive strains response to load.



(b) Hoop strains response to load.

Fig.4. Load-strain curves of the circular solid steel tube columns.

4 Conclusions

This paper has presented the uses of CFRP confinement to enhance the ultimate strength and ductility of square and circular, solid or hollow, steel tube columns. The test results show that both types of reinforcing arrangements enhance the ultimate carrying capacities and stiffness of the column strengthened greatly in comparison to the reference ones, and the full wrapping arrangement is more effective than the partial wrapping arrangement in increasing the ultimate compressive load and the stiffness of the columns tested. The column height investigated in this paper seems has little influence on the ultimate load carrying capacity of the columns which were reinforced by fully or partially wrapping of CFRP sheets. Moreover, stiffness of the strengthened columns was increased greatly due to the restraining offered by the reinforcement on the hoop deformations during the compressive loading.

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