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RECTANGULAR HYBRID FRP-CONCRETE-STEEL DOUBLE-SKIN TUBULAR COLUMNS: STUB COLUMN TESTS

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ABSTRACT

Hybrid FRP-concrete-steel double-skin tubular columns (DSTCs) are a new form of hybrid columns. The most common sectional form of hybrid DSTCs consists of a layer of concrete sandwiched between a circular inner steel tube and a circular outer FRP tube whose fibre directions are close to the hoop detection in order to provide effective confinement to the concrete. Much recent research has been conducted on circular hybrid DSTCs, which has demonstrated that the combination of the three constituent materials leads to several advantages not available with existing forms of columns. Rectangular (including square) hybrid DSTCs may be needed for practical applications, due to aesthetic and other reasons. When a column is subjected to different load levels in the two horizontal directions, rectangular columns are preferred. This paper extends the existing work on circular and square hybrid DSTCs to rectangular hybrid DSTCs which consist of a rectangular outer FRP tube and two circular inner steel tubes. Rresults from a series of stub column tests are presented and interpreted. The test results show that the concrete in these rectangular hybrid DSTCs is effectively confined by the tubes, leading to a very ductile response.

KEYWORDS

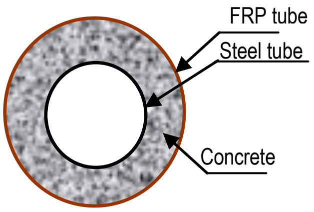
Hybrid tubular columns, confinement, FRP, concrete, steel, rectangular columns, stress-strain behavior.

INTRODUCTION

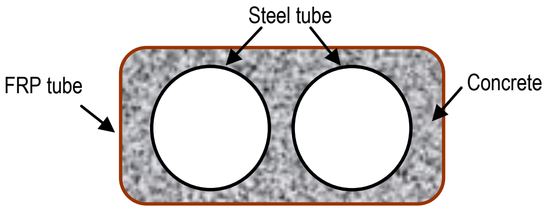
Hybrid FRP-concrete-steel Double-Skin Tubular Columns (referred to as hybrid DSTCs) are a new form of hybrid columns proposed at The Hong Kong Polytechnic University (Teng *et al.* 2007). A hybrid DSTC consists of a layer of concrete sandwiched between an outer tube made of FRP and an inner tubes made of steel. In a hybrid DSTC, the FRP tube offers mechanical resistance primarily in the hoop direction to confine the concrete and to enhance the shear resistance of the member; the steel tube acts as the main longitudinal reinforcement and prevents the concrete from inward spalling. Hybrid DSTCs may be constructed in-situ or precast, with the tubes acting as the stay-in-place form. This new form of hybrid members represents an innovation which combines the advantages of all three constituent materials and those of the structural form of DSTCs to deliver excellent structural and durability performance.

In the most common sectional form of hybrid DSTCs, both tubes are circular (Figure 1a); such hybrid DSTCs are referred to herein as circular hybrid DSTCs. A large amount of research has recently been completed by the second author and his colleagues on circular hybrid DSTCs (Figure 1a) (e.g. Teng *et* *al.* 2007; Yu 2007; Wong *et al.* 2008; Yu *et al.* 2010a, 2010b). These studies have led to a good understanding of and a simple design approach for circular hybrid DSTCs under static loading, and this design approach has been adopted by the Chinese national standard *"Technical Code for Infrastructure Application of FRP Composites"* (GB 50608 2010). It has been shown that the concrete in circular hybrid DSTCs is very effectively confined by the two tubes and local buckling of the steel inner tube is either delayed or suppressed by the surrounding concrete, leading to a very ductile response under various loading scenarios (Yu 2007).

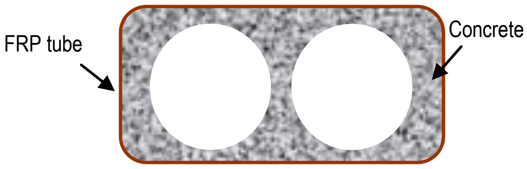
Rectangular (including square) hybrid DSTCs may be preferred in some structural applications, due to aesthetical and other reasons. If a column is subjected to different load levels in the two horizontal directions, rectangular columns are preferred. This paper therefore presents the first ever study on the axial compressive behavior of rectangular hybrid DSTCs with a rectangular FRP outer tube and two circular steel inner tubes (Figure 1b). Circular inner tubes are preferred over square or rectangular inner tubes as the former provide better confinement to the concrete and are less prone to local buckling. In this paper, results from a series of stub column tests are presented and interpreted, where the performance of rectangular DSTCs is compared with that of two related column forms, namely, rectangular FRP-confined hollow columns (rectangular FCHCs) with two circular inner voids (Figure 1c), and rectangular FRP-confined solid columns (rectangular FCSCs) (Figure 1d). The purpose of the axial compression tests is twofold: (1) to examine the behaviour of rectangular hybrid DSTCs under axial compression; (2) to examine the stress-strain behaviour of the confined concrete in the column.



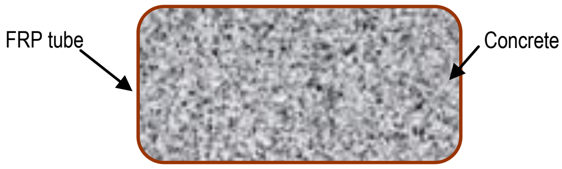
(a) Circular DSTC



(b) Rectangular DSTC



(c) Rectangular FCHC



(d) Rectangular FCSC

Figure 1.Typical cross-section of DSTC, FCHC and FCSC

EXPERIMENTAL PROGRAM

Test Specimens

A total of 9 specimens were constructed and tested, including 7 DSTC specimens, 1 FCSC specimen and 1 FCHC specimen. The specimens all had a rectangular FRP tube with an inner breadth of 185 mm, an inner width of 105 mm, and a height of 370 mm except for one specimen (i.e. B9) which had a different height (i.e. 230 mm) to investigate that effect. The FRP tubes used had glass fibers mainly in the hoop direction and were prefabricated using unidirectional fiber sheets via a resin infusion process. The main test variables included the dimension of the void, the corner radius, the thickness of the FRP tube and the steel tube. Other details of the specimens are summarized in Table 1.

Material Properties

Tensile tests of four flat FRP coupons were conducted. These tests showed that the FRP used had an average tensile strength of 1986 MPa and an average elastic modulus of 80.84 GPa in the hoop direction based on a nominal thickness of 0.5 mm per ply. For each type of steel tubes, two hollow steel tubes were tested under axial compression. The steel tubes had the same nominal height as those in most DSTC specimens (i.e. 370 mm). All these steel tubes showed large plastic deformation and eventually failed by a combination of overall buckling and local buckling. The peak axial stresses were found to be 389.7 MPa, 446.0 MPa and 399.8 MPa for types A-C tubes, respectively. All specimens were cast in the same batch except specimen A1 which was cast earlier as a trial specimen. Standard concrete cylinders (100 mm x 200 mm) were tested to determine the compressive strength of concrete during the testing period of the 9 specimens. The average concrete strengths obtained from these tests are given in Table 1.

Table 1. Details of Specimens

Name	Type	FRP tube (plies)	Corner radius (mm)	Steel tube, D(t) (mm)	f'_{co} (MPa)
A1	DSTC	6	30	Type A, 60.3(2.3)	32.1
B2	DSTC	6	30	Type B, 60.3(2.9)	35.8
B3	FCHC	6	30	N/A	35.8
B4	DSTC	6	30	Type C, 48.3(2.9)	35.8
B5	FCSC	6	30	N/A	35.8
B6	DSTC	10	30	Type A, 60.3(2.3)	35.8
B7	DSTC	4	30	Type A, 60.3(2.3)	35.8
B8	DSTC	6	15	Type A, 60.3(2.3)	35.8
B9	DSTC	6	30	Type A, 60.3(2.3)	35.8

Preparation of Specimens

The FRP tubes were prefabricated by a resin infusion process using glass fibre sheets and epoxy vinyl ester resin, with an overlapping zone of 120 mm on one of the long sides of each tube. Additionally, two glass strips with a width of 30 mm were added near each end of the FRP tubes to avoid premature failure in those regions. The FRP tubes were then used together with the steel tubes (for DSTC specimens) or void formers (for FCHC specimens) as the moulds for casting concrete.

Test Set-Up and Instrumentation

Two LVDTs were used to obtain the total axial shortening of each specimen. Five hoop strain gauges with a gauge length of 20 mm were installed at the mid-height of the FRP tube for all specimens except specimen A1. In addition, two axial strain gauges were attached at the mid-height of the two steel tubes respectively. For specimen B2, two additional axial strain gauges were attached at the mid-height of the FRP tube. All compression tests were carried out using a Denison 5000 kN compression testing machine with a displacement control rate of 0.3 mm/min (Figure 2a). All test data, including the strains, loads, and displacements, were recorded simultaneously by a data logger.

TEST RESULTS AND DISCUSSIONS

General Behaviour

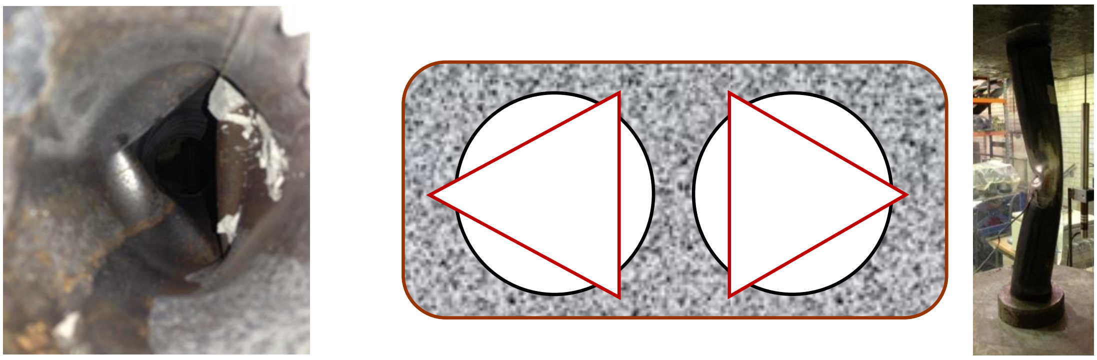
All DSTC and FCSC specimens showed a similar damage process: (1) the specimen deformed approximately linearly until the concrete approached approximately its unconfined strength which was associated with micro-cracking noises; (2) the axial load-strain behavior then became nonlinear, and a lateral crack near the mid-height of the FRP tube typically occurred at an axial strain of around 0.0012 (Figure 2b); the lateral crack was due to the failure of the FRP tube in the axial direction and was normally accompanied with a minor load drop; (3) the load could generally still increase after that, and the final failure was caused by the rupture of the FRP tube in the hoop direction at a much larger axial strain (Figure 2c). By contrast, the FCHC specimen (i.e. specimen B3) showed quite different behavior: it had a smooth descending branch after the peak load, but exhibited no clear failure point: no explosive FRP rupture was observed during the test but considerable concrete damage on the inner surface was found at the end of test. The test of the FCHC specimen was terminated after an axial strain of around 0.05.

(a) (b) (c)

Figure 2. Specimens before, during and after test

Buckling Behaviour of Inner Steel Tubes

Buckling of steel tubes was found to occur in all DSTC specimens except specimen B4 where the steel tubes had the lowest diameter-to-thickness ratio out of those used in the tests. The typical buckling mode is displayed in Figures 3a and 3b (i.e. the approximately triangular shapes). This buckling mode is different from that observed in the compression tests of hollow steel tube (i.e. a combination of overall buckling and outward local buckling, see Figure 3c), confirming that the surrounding concrete effectively restrains the steel tubes against overall or outward local buckling.



(a) (b) (c)

Figure 3. Buckling of steel tube

It should be noted that this observation is different from those obtained from tests of circular DSTCs (Yu 2007); no buckling was observed for steel tubes with a similar or greater diameter-to-thickness in those tests. This is probably due to the more complex interaction between the concrete and the steel tubes in rectangular DSTCs than in circular DSTCs. In circular DSTCs, the inner edge of concrete moves outward and typically with a rate higher than the lateral expansion of the steel tube; the inner steel tube works mainly to prevent the local damage and inward spalling of the concrete near the inner edge. However, in rectangular DSTCs with two inner steel tubes, the outwards expansion of the centre concrete (i.e. the concrete between the two steel tubes) leads to direct non-uniform pressure onto the steel tubes. In addition, the concrete in rectangular DSTCs is subject to more efficient confinement from the corners than from the flat sides of the FRP tube, which means that the lateral expansion of concrete near the corner is more effectively constrained from the outside, making it more likely to develop significant interaction with the steel tubes. The discussions above also explain the unique buckling mode observed in rectangular DSTCs (Figures 3a and 3b).

Axial Load-Axial Strain Behaviour

A typical axial load-axial strain curve of DSTC specimens is shown in Figure 4, where the curve is terminated when explosive rupture of the FRP tube occurred. The axial load-axial strain curves of each constituent (i.e. concrete and steel tube) and their sum (the curve denoted by "sum") are also shown in Figure 4 for comparison; the curves denoted by "concrete alone" and "steel alone" were derived from the results from material tests of concrete and steel tubes respectively. The direct contribution of the FRP tube to the axial load capacity was not included in this sum as the majority of the fibers were in the hoop direction. It is obvious that the DSTC reached an ultimate load and an ultimate strain which are significantly higher than may be expected from the simple addition of those of the axial load-strain curves of steel and concrete. It is also evident that the load enhancement was more significant for DSTCs with a thicker FRP tube or a larger corner radius, but did not seem to be much affected by the dimension of the void.

Table 2. Key test results

Specimen	Ultimate load P_c (kN)	Ultimate load of steel tube P_s (kN)	Ultimate load of concrete section P_{co} (kN)	$P_{co}+P_s$ (kN)	$\frac{P_c}{(P_{co}+P_s)}$
A1	921.7	326.9	415.4	742.3	1.24
B2	1037.3	468.1	463.3	931.4	1.13
B4	1010.8	331.8	536.6	868.4	1.18
B6	1119.3	326.9	463.3	790.2	1.41
B7	779.3	326.9	463.3	790.2	0.98
B8	863.0	326.9	484.0	810.9	1.05
B9	960.8	326.9	463.3	790.2	1.20

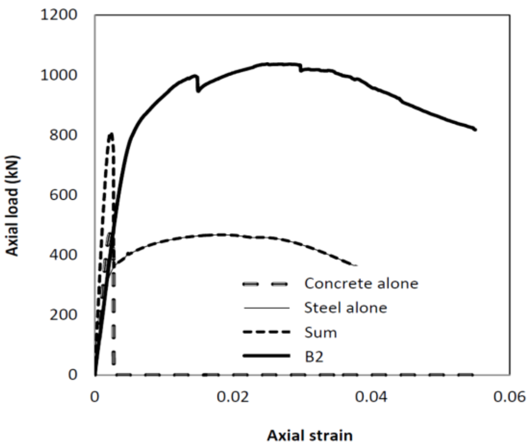


Figure 4. Axial load-axial strain curves

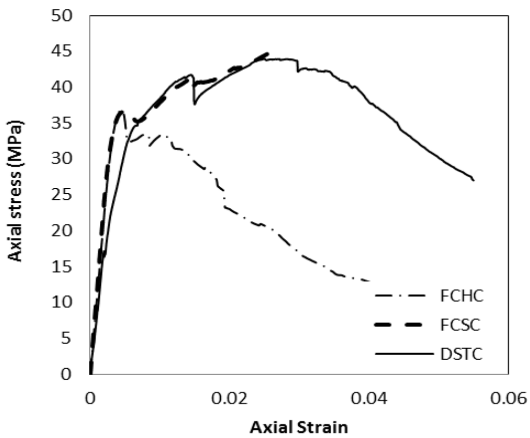


Figure 5. Axial stress-axial strain curves

The key test results of all 7 DSTC specimens are summarized in Table 2. In this table, P_c is the ultimate load of the DSTC from the test, P_{co} is equal to the unconfined concrete strength times the area of the concrete section in DSTCs, P_s is equal to the ultimate load of the two hollow steel inner tubes, and $(P_{co}+P_s)$ represents the ultimate load of the DSTC if the constituent parts do not interact and the axial stiffness of the FRP tube is ignored. Table 2 indicates that the strength enhancement of DSTCs increases with the thickness of FRP and the corner radius, but is not affected much by the void ratio.

Comparison between DSTC, FCSC and FCHC

Figure 5 shows a comparison of the axial stress-strain curves of the concrete in the FCHC specimen (B3), the FCSC specimen (B5) and specimen B2. The only difference between the three specimens is the section configuration. The axial stresses shown in Figure 5 are the average stresses of the concrete section in a specimen, which were obtained by dividing the load taken by concrete by the area of the concrete section. The axial strains were calculated from the LVDT readings. It is apparent that the stress-strain behavior of concrete in the DSTC is superior to that of concrete in the FCHC. In FCHCs, the concrete near the inner edge suffers from early loss of resistance as a result of local spalling failure, but in DSTCs, the steel inner tube effectively restrains the inner edge concrete against local spalling failure. As a result, the concrete in the DSTC possessed a much higher compressive strength and much better ductility.

In general, the stress-strain curve of the DSTC specimen is very similar to that of the FCSC specimen, in terms of the first two branches and the compressive strength, indicating that the inner steel tube in the DSTC specimen provided effective constraint to the inner edge of the annular concrete section. The DSTC specimen is also shown to possess an additional gradually descending branch before explosive rupture of FRP tube, with a larger ultimate axial strain. This is believed to be due to the inward movement of the concrete associated with the inward local buckling of steel tubes in the DSTC (Figure 3), which significantly reduced the increase rate of the hoop strain in the FRP tube.

CONCLUSIONS

This paper has presented results from a series of axial compression tests on hybrid FRP-concrete-steel DSTCs with a rectangular FRP outer tube and two circular steel inner tubes. Based on the test results and discussions presented in the paper, the following conclusions may be drawn:

(1) The concrete in rectangular hybrid DSTCs is effectively confined by the tubes, leading to a very ductile response.
(2) The overall buckling and outward local buckling of the steel tubes were restrained by the surrounding concrete, but inward buckling was found in most tested rectangular DSTCs, indicating that the diameter-to-thickness ratio of the steel tubes is a more critical parameter in rectangular DSTCs than in circular DSTCs.
(3) Rectangular hybrid DSTCs are superior to rectangular FCHCs. The compressive strength of concrete in a rectangular DSTC is similar to that in a corresponding rectangular FCSC. The ultimate axial strain in a rectangular DSTC may, however, be considerably higher than that of FCSCs with the same FRP tube and concrete.

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