Proceedings of the 7th International Conference on Civil Structural and Transportation Engineering (ICCSTE'22)
Niagara Falls, Canada – June 05-07, 2022
Paper No. 218
DOI: 10.11159/iccste22.218

Behavior and Design of Circular Concrete-Filled Double Steel Tubular Slender Columns under Axial Loading

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Abstract – This paper presents an experimental investigation on circular concrete-filled double steel tubular (CFDST) slender columns under axial loading. The test parameters include the column slenderness ratio and the thickness of the inner steel tube. Test results show that the common failure mode of CFDST slender columns is the global failure of the columns. It is found that increasing the column slenderness decreases the ultimate strengths of the columns and the thickness of the inner steel has an insignificant influence on the ultimate strength of the columns. The design model specified by Eurocode 4 for conventional CFST slender columns is shown to overestimate the ultimate strength of CFDST slender columns under axial loading.

***Keywords*:** *Concrete-filled steel tubes; axial loading; slender columns; composite columns.*

1. Introduction

Concrete-filled steel tubular (CFST) columns have been widely used to carry large axial loads in high-rise buildings and bridge piers [1-3]. The steel tube provides confinement to the core concrete and acts as permanent formwork. The CFST columns offer improved strength, ductility, and fire and seismic resistance over reinforced concrete columns. The circular steel tube provides effective confinement to the core concrete which improves the strength and ductility of the CFST columns. However, to carry large axial loads of superstructures, the size of CFST columns is designed to be very large [4]. On the other hand, the application of high-strength concrete (HSC) and ultra-high-strength concrete (UHSC) in CFST columns reduces their ductility significantly. To overcome these issues, researchers have proposed circular concrete-filled double steel tubular (CFDST) columns, where two steel tubes are placed concentrically and filled with concrete, as illustrated in Fig. 1, where D0 and Di are the diameter of the outer and inner tube, respectively and t0 and ti are the thickness of the outer and inner steel tube, respectively. The inner tube provides additional confinement to the core concrete, thus the strength and ductility of a circular CFDST column are higher than those of a conventional circular CFST column [5-7]. Moreover, in a CFDST column, the sandwiched concrete between two tubes and the core concrete within the inner tube can be designed to have different strengths to maintain a good ductility.

Experiments on circular CFDST columns have been primarily focused on investigating the performance of short columns, where the length-to-diameter ratio (L/D_0) was limited to 4 to prevent the global buckling from occurring [5, 6, 8, 9]. A circular CFDST slender column with an L/D_0 ratio greater than 4 may fail due to global buckling, which reduces the ultimate strength of the column significantly. However, experimental investigations on circular CFDST slender columns have been very limited. Ibañez et al. [10] carried out tests on CFDST slender columns under eccentric loading. The influences of concrete strengths on the performance of CFDST slender columns were investigated, where the concrete with compressive strength up to 149 MPa was used to construct these column specimens. It was found that due to the second-order effects, the application of UHSC in CFDST columns was not effective. Ahmed et al. [11] developed a mathematical model to investigate the performance of CFDST slender columns under eccentric loading and proposed interaction equations for designing

CFDST beam-columns. Considering a lack of test on circular CFDST slender columns, this paper presents test of six circular CFDST slender columns under axial loading. The test parameters include the slenderness ratio and the thickness of the inner steel tube.

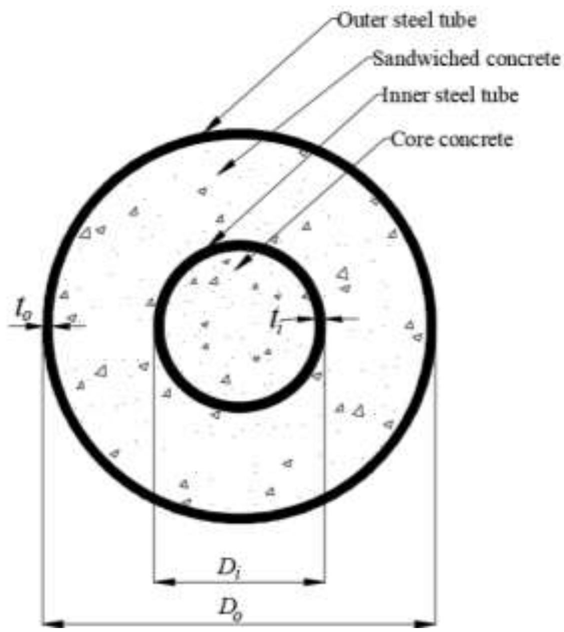

Fig. 1: The cross-section of a circular CFDST column.

2. Experimental Program

2.1. General

Six CFDST columns with different slenderness ratios were constructed. The outer diameter of all CFDST specimens was 219 mm with a thickness of 5 mm. Two different thicknesses of the inner steel tube of 2.5 and 3.5 mm were chosen to study the effects of the thickness of the inner steel tube on the performance of CFDST slender columns. The tested specimens were divided into two groups (G1 and G2) according to their thickness. For each group, different slenderness ratios of the columns were investigated. Columns in group G1 had the length to outer steel diameter ratio (L/D_0) varied from 5 to 7, 9 and 11 whereas columns in group G2 had L/D_0 ratios varied from 7 to 11. The details of the tested specimens are summarized in Table 1.

The specimens were made of readily available steel hollow tubes having a nominal yield strength of 235 MPa. In preparing CFDST specimens, the outer and inner steel tubes were welded using two thin steel bars to ensure that the steel tubes were placed concentrically. The filled concrete in all CFDST columns had the same compressive strength.

Table 1: Summary of the test specimens.

Group	**Specimen**	**Outer tube**		**Inner tube**		**L (mm)**	**L/D_o**	**f'_{cu} (MPa)**	**N_{exp} (kN)**	**N_{des} (kN)**	**N_{des}/N_{exp}**
		D_o (mm)	t_o (mm)	D_i (mm)	t_i (mm)						
G1	C-1-5	219	5	114	3.5	1095	5	47	3208	3430	1.07
	C-1-7	219	5	114	3.5	1533	7	47	2879	3262	1.13
	C-1-9	219	5	114	3.5	1971	9	47	2808	3090	1.10
	C-1-11	219	5	114	3.5	2409	11	47	2757	2905	1.05
G2	C-2-7	219	5	114	2.5	1533	7	47	2805	3098	1.10

C-2-11	219	5	114	2.5	2409	11	47	2752	2753	1.00
Mean										1.08
Standard Deviation (SD)										0.05
Coefficients of Variance (COV)										0.04

2.2 Material properties

The material properties of steel tubes were measured from the average test results of three tensile coupon tests performed according to GB/T 228.1-2010 [12]. The yield strengths of the steel tubes with 2.5, 3.5 and 5 mm thickness were measured as 314, 329 and 332 MPa, respectively. The measured tensile strengths of the steel tubes with 2.5, 3.5 and 5 mm thickness were 375, 415 and 417 MPa, respectively. The elastic modulus of the steel tubes with 2.5, 3.5 and 5 mm thickness was determined as 198, 205 and 203 GPa, respectively. The compressive strength of concrete was obtained by means of conducting compression tests on three concrete cubes (150 mm × 150 mm × 150 mm) cast at the same time as CFDST specimens and tested after 28 days of casting. The average compressive cube strength was 47 MPa.

2.3. Test setup

The columns were tested at Beijing University of Technology, China using a 4000 kN hydraulic testing machine. As the height of the longest test specimens- (C-1-11 and C-2-11) exceeded the height of the reaction frame, for safety all specimens were tested horizontally. In addition, both ends of all the specimens were clamped by steel clamps to eliminate possible elephant foot buckling failure mode. Two sets of loading devices were custom-designed that comprised of loading and adapter plates. To ensure the evenness and to eliminate any gap between the column and loading plates, the end faces of the specimens were coated with superhard gypsum prior to loading the column in the testing frame. The typical test setup of a specimen is shown in Fig. 2.

The strain distributions of the specimens were measured at the midspan both at the compression and tension sides of the specimens using bi-directional strain gauges attached to the outer tube. Each bi-directional strain gauge included a pair of strain gauges to measure both the axial and hoop strains. The axial and lateral displacement of the specimens were measured using displacement sensors. Generally, three displacement sensors were used to measure the lateral displacement of the test specimens, however, for specimens C-1-11 and C-2-11, five displacement sensors were used to record the lateral displacement. The axial displacements of specimens were measured using two displacement sensors. The specimen was preloaded to 100 kN before the data was recorded to remove any possible gap between the specimens and the loading devices. The specimens were tested using displacement control at the rate of 1 mm/min. When the axial displacement of the specimens reached 30 mm, the test was stopped. The DH18 acquisition system was used to record data for applied load, strain gauges and displacement sensors.

Fig. 2: Test setup of CFDST slender column under axial compression.

3. Results

Figure 3 shows the typical failure mode of the tested specimens which was due to the global buckling of the columns. Increasing the slenderness ratio significantly reduced the ultimate strength of CFDST columns, as can be seen in Table 1. Increasing L/D_0 ratio from 5 to 7, 9 and 11 decreased the ultimate strength of CFDST columns. For group G1, when L/D_0 ratio increased from 5 to 7, 9 and 11, the ultimate load of the CFDST column decreased by 10.3%, 12.5% and 14.1%, respectively. However, for group G2, when the L/D_0 ratio increased from 7 to 11, the ultimate load of the CFDST column only decreased by 1.9%. This could be due to the uncertainty of the actual concrete strength of the tested specimens as the average concrete strength measured using concrete cube was used for comparison purposes. In addition, test results showed that the thickness of the inner steel tube had an insignificant influence on the ultimate strength of CFDST slender columns. Decreasing the thickness of the inner steel tube from 3.5 mm (specimen C-1-7) to 2.5 mm (specimen C-2-7) reduced the ultimate strength by only 2.6%. This is because the column failed by the overall buckling and the inner steel tube could not contribute much to the ultimate strength of the columns.

Fig. 3: Typical failure mode of circular CFDST slender columns under axial loading.

Figure 4 shows the axial load-midspan displacement curves of the tested specimens recorded during the tests. It is found that increasing the slenderness ratio increased the mid-span displacement of the tested columns. In addition, as the slenderness ratio of the columns increased, the initial deviation of the load-displacement curves can be observed.

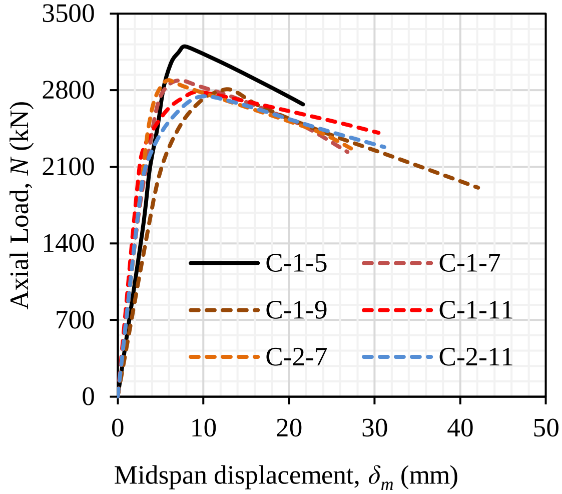

Fig. 4: Axial load-midheight lateral displacement curves of circular CFDST slender columns.

4. The ultimate strength of CFDST slender columns

There is no design specification recommended by design codes in predicting the ultimate strength of CFDST slender columns. This study investigates the accuracy of the existing design specifications given by Eurocode 4 [13] for conventional circular CFST columns in predicting the ultimate strength of circular CFDST slender columns under axial loading. Based on Eurocode 4 [13], the ultimate strength of circular CFDST short columns (N_u) can be calculated as:

$$N_u = \eta_a A_{so} f_{syo} + A_{co} f_{co}^{'} (1+\eta_c \frac{t_o}{D_o} \frac{f_{syo}}{f_{co}^{'}}) + \eta_a A_{si} f_{syi} + A_{ci} f_{ci}^{'} (1+\eta_c \frac{t_i}{D_i} \frac{f_{syi}}{f_{ci}^{'}}) \tag{1}$$

where A_{so}, A_{si}, A_{co} and A_{ci} are the cross-sectional area of the outer tube, inner tube, sandwiched concrete and core concrete, respectively; D_o and D_i are the diameter of the outer and inner tube, respectively; t_o and t_i are the thickness of the outer and inner tube, respectively; f_{syo} and f_{syi} are the yield stress of the outer and inner tube, respectively; $f_{co}^{'}$ and $f_{ci}^{'}$ are the concrete cylindrical compressive strength of sandwiched and core concrete, respectively. As in this study, the compressive strength of concrete was measured using compression tests of concrete cube, the concrete cube strength was converted to cylindrical strength using a factor of 0.85 proposed by Oehlers and Bradford [14]. In Eq. (1) parameters η_a and η_c are calculated as

$$\eta_a = 0.25\,(3+2\bar{\lambda}) \qquad (\eta_a \le 1.0) \tag{2}$$

$$\eta_c = 4.9 - 18.5\,\bar{\lambda} + 17\,\bar{\lambda}^2 \quad (\eta_c > 0) \tag{3}$$

where $\bar{\lambda}$ is the relative slenderness ratio of the column expressed as:

$$\bar{\lambda} = \sqrt{\frac{N_u}{N_{cr}}} \tag{4}$$

where N_{cr} is the Euler buckling calculated as:

$$N_{cr} = \frac{\pi^2 (EI)_{eff}}{L^2} \tag{5}$$

where $(EI)_{eff}$ is the effective flexural stiffness calculated as:

$$(EI)_{eff} = E_{s,so} I_{s,so} + 0.6 E_{cm,co} I_{c,co} + E_{s,si} I_{s,si} + 0.6 E_{cm,ci} I_{c,ci} \tag{6}$$

$$E_{cm} = 22000\left(\frac{f_c^{'}+8}{10}\right)^{1/3} \quad (7)$$

where $E_{s,so}$ and $E_{s,si}$ are the elastic modulus of outer and inner steel tube, respectively; $E_{cm,co}$ and $E_{cm,ci}$ are the elastic modulus of sandwiched and core concrete, respectively; $I_{s,so}$ and $I_{s,si}$ are the second moment of area of the outer and inner steel tube, respectively; $I_{c,co}$ and $I_{c,ci}$ are the second moment of area of the sandwiched and core concrete, respectively.
A slenderness reduction factor χ is suggested by Eurocode 4 to consider the slenderness ratio in calculating the ultimate loads of slender section written as:

$$N_{u,EC4} = \chi N_u \quad (8)$$

where χ is suggested in Eurocode 3 [15] as:

$$\chi = \frac{1}{\varphi + \sqrt{\varphi^2 - \bar{\lambda}^2}} \leq 1.0 \quad (9)$$

$$\varphi = \frac{1+\alpha(\bar{\lambda}-0.2)+\bar{\lambda}^2}{2} \quad (10)$$

where α is the imperfection factor corresponding to the relevant buckling curve taken as 0.49 based on buckling curve 'c' for CFDST columns.

Table 1 shows the comparisons of the test and the predicted ultimate strength of CFDST slender columns under axial loading. It is seen that Eurocode 4 generally overestimates the test ultimate strength of the columns. The mean $N_{des} / N_{\mathbf{exp}}$ was calculated as 1.08 with a standard deviation of 0.05.

5. Conclusion

This paper has presented the behavior of circular CFDST slender columns under axial loading. A total of 6 specimens with various slenderness ratios have been tested to failure to examine the effects of the thickness of the inner steel tube and the column slenderness ratio on the ultimate strength of the columns. The accuracy of the design model specified by Eurocode 4 for conventional circular CFST columns in designing CFDST slender columns has been evaluated. It has been shown that the ultimate strength of CFDST slender columns decreases as the slenderness of the columns increases. In addition, the strength of CFDST slender columns is not sensitive to the change in the thickness of the inner steel tube due to the effects of second-order. The comparative study has demonstrated that Eurocode 4 generally overestimates the ultimate strength of CFDST slender columns under axial loading.

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