Concrete-filled Double-skin Tubular Columns with External Steel Rings

C.X. Dong[1] and J.C.M. Ho[2]

ABSTRACT

Concrete-filled-steel-tube columns have been adopted widely for column construction of tall buildings due to its excellent confining effect. However, the central part of concrete in CFST columns have relatively small contribution towards bending and torsion resistance, which can be effectively replaced by another hollow steel tube with much smaller area without reducing the load-carrying capacity due to composite action. This structural form with the in-between annulus of inner and outer steel tubes filled with concrete is called concrete-filled double-skin tubular (CFDST) columns. Nonetheless, similar to CFST columns, the imperfect steel-concrete interface bonding of the outer tube will take place in the initial elastic stage because steel dilates more than concrete. It consequently reduces the confinement and stiffness of the CFST columns. To resolve the problem, it is proposed in this study to use external steel ring confinement to restrict the dilation of the outer steel tube in CFDST columns. A series of uni-axial compression tests was performed on CFDST columns with and without external steel rings. From the test results, it was found that the external steel rings could effectively restrict the dilation of the outer steel tube, and improve significantly the uni-axial strength, elastic strength and ductility of CFDST columns when compare with those specimens without rings.

Keywords: Columns; Concrete-filled-steel-tube; Confinement; Double-skin; Rings

1. Introduction

It is well know that the flexural strength and ductility performance of reinforced concrete (RC) columns can be significantly improved by installing more transverse reinforcement (Watson and Park 1996; Bayrak and Sheikh 1998; Paultre *et al*. 2001; Ho and Pam 2003; Zhou *et al*. 2010; Ho 2011) within the potential plastic hinge or critical regions or by steel-concrete composite columns (Pam and Ho 2009; Zhou *et al.* 2012). Nevertheless, the effectiveness of confinement decreases as the concrete strength increases (Pam and Ho 2001). Therefore, high-strength concrete (HSC) columns need larger amount of confinement if the same level of strength and ductility need to be provided (Lam et al. 2009). Consequently, it causes problematic steel congestion problem within the plastic hinge region of columns, which adversely affects the quality of concrete placing at these locations.

To resolve the problems and maintain sufficient confinement for ductility provision, composite concrete-filled-steel-tube (CFST) columns are advocated. However, CFST columns have some

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disadvantages: (1) Under uni-axial compression, steel shares a larger part of the external load than concrete per same cross-section area because of higher stiffness under composite action. (2) Under flexure, the central concrete, which is close to the neutral axis, has insignificant contribution to the flexural strength. (3) Under torsion, the central concrete has insignificant contribution to the torsion strength. (4) The initial elastic dilation of concrete under compression is small and thus the confining pressure provided by the steel tube to concrete is relatively low during elastic stage. It can only develop more rapidly until micro-cracking of concrete have been formed (Wei *et al.* 1995a, 1995b) at large strain. It is convinced to replace the central concrete by a hollow steel tube. This type of column is known as concrete-filled double skin tubular (CFDST) column.

CFDST column consists of inner and outer steel tube with the annulus between the skins filled with concrete. This form of column has higher strength (uni-axial, flexural and torsion)(Zhao and Grzebieta 2002; Yang and Han 2008; Han *et al*. 2009, 2011; Li *et al*. 2012). The strength-to-weight ratio is improved significantly by replacing the central part of concrete with a hollow steel tube. The confining pressure builds up more rapidly than CFST column because the inner steel tube would expand outward to increase the confining pressure. There were already some tests conducted on CFDST columns in the past (Wei *et al.* 1995a; Elchalakani *et al.* 2002; Han *et al.* 2004; Tao *et al.* 2004; Uenaka *et al*. 2010; Han *et al*. 2011; Li *et al*. 2012). However, one major problem that is the imperfect interface bonding was found by previous researchers (Persson 1999; Ferretti 2004; Lu and Hsu 2007; Liao *et al*. 2011). In the initial elastic stage, the Poisson's ratio of concrete and steel is about 0.2 and 0.3 respectively. The dilation of concrete is less than that of steel tube so the concrete is unconfined at elastic stage. To improve this problem, external steel rings were proposed to restrict the lateral expansion of CFDST column by authors. The external steel rings can not only strengthen the outer steel tube but also provide a more uniform and continuous confining pressure to the concrete core.

In this study, the uni-axial behaviour of CFDST columns with external steel rings was investigated in terms of strength and stiffness. The obtained load-displacement curves, Poisson's ratio, axial strength and stiffness for these columns were then compared with those of CFDST columns without external confinement. From the experimental data, it is found that load-carrying capacity, stiffness and ductility were enhanced significantly. In order to verify the effectiveness of the proposed external confinement in restricting the lateral dilation of CFDST columns, the representative Poisson's ratios of the specimens were listed.

2. Test Programme

In this study, a total of 10 CFDST column specimens have been fabricated and tested in a uni-axial compression machine of capacity 5,000 kN. The CFDST column specimens are divided into 4 groups: (1) Four CFDST columns with external steel rings at different spacing ($5t_o$, $10t_o$, $15t_o$ and $20t_o$, where t_o is the thickness of the outer steel tube) with hollow section ratio χ (defined as $\chi = \frac{D_i}{D_o - 2t_o}$)of 0.56; (2) One CFDST columns without external confinement with hollow section ratio χ of 0.56; (3) Four CFDST columns with external steel rings at different spacing ($5t_o$, $10t_o$, $15t_o$ and $20t_o$, where t_o is the thickness of the outer steel tube) with hollow section ratio χ of 0.72; (4) One CFDST columns without external confinement with hollow section ratio χ of 0.72 for comparison purpose. The concrete cube and cylinder strength were about 60 MPa and 50MPa respectively on testing day. The grade of both inner and outer steel tube is S355 produced as per BS

EN 10210-2:2006. The thickness of all the steel tubes of CFDST specimens was 5 mm and the diameter of the outer steel tube was 168.3 mm. For CFDST columns with hollow ratio of 0.56 and 0.72, the diameter of inner steel tube was 88.9 mm and 114.3 mm respectively. The height of the CFDST columns was 330 mm, which gives an aspect ratio of about 2. Fig 1(a) shows the photo of the CFDST column with hollow ratio of 0.56 with various spacing of steel rings as external confinement. Fig 1(b) shows the photo of CFDST column with hollow ratio of 0.56 with no external confinement. Fig 1(c) shows the photo of the CFDST column with hollow ratio of 0.72 with various spacing of steel rings as external confinement. Fig 1(d) shows the photo of CFDST column with hollow ratio of 0.72 with no external confinement.

(a) CFDST columns with external steel rings (s=5t_o, 10t_o, 15t_o and 20t_o) with hollow ratio of 0.56

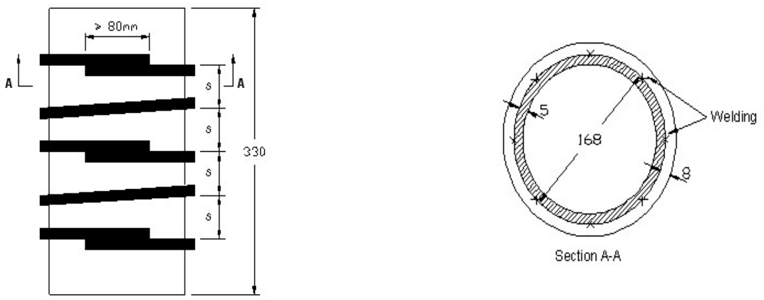
(b) CFDST columns without external steel ring with hollow ratio of 0.56

(c) CFDST columns with external steel rings (s=5t_o, 10t_o, 15t_o and 20t_o) with hollow ratio of 0.72

(d) CFDST columns without external steel ring with hollow ratio of 0.72

Fig 1 Photos of tested columns

The external steel rings were made of mild steel round bars of 8mm diameter. The yield strength of the steel bars is f_R = 300 MPa. The rings were welded to the outer tubes at different spacing and the lap length was designed to be ten times the diameter of the steel bar, which was 80 mm. Each ring was welded to the outer tube at eight locations with a central angle of 45° separated from each other.Fig 2 shows the details of the steel rings (welding locations and overlapping length).



s	mm	No. of rings
5t	25	13
10t	50	7
15t	75	5
20t	100	3

Fig 2 Steel rings arrangement

A naming system consisting of two letters and two numbers has been used to represent the specimens. For instance, 'D-L-50-5' represents a CFDST column (indicated by the first letter "D"), a lower hollow ratio of 0.56 (indicated by the second letter "L"), a concrete cylinder strength of about 50 MPa on the testing day (indicated by the first number) and lastly five times the thickness of the outer tube steel tube as the ring spacing (indicated by the last number). Alternatively, 'D-H-50-0' represents a CFDST column (indicated by the first letter "D") with a higher hollow ratio of 0.72 (indicated by the second letter "H"), a concrete cylinder strength of about 50 MPa on the testing day (indicated by the first number), and lastly no external steel ring (i.e. zero spacing indicated by the last number). The section and material properties of the specimens are summarised in Table 1. All the tests were carried out by a 5000 kN compression testing machine (as shown in Fig 3). All the loading tests were displacement-controlled. The loading rate is 0.3 mm/min. This rate would be increased incrementally by 0.05 mm/min for every 10 mm axial deformation after the specimens had reached the yielding stage. The test was ended when the load dropped to 80% of the maximum load. For the plain concrete cylinders, the loading rate was set constant at 0.3 mm/min.

Fig 3 Test setup

Table 1 Details of specimens and materials

Specimen Label	D_i (mm)	t_i (mm)	$f_{y,i}$ (MPa)	D_o (mm)	t_o (mm)	$f_{y,o}$ (MPa)	f'_c (MPa)	f_R (MPa)
D-L-50-5	88.9	5	450	168.3	5	360	50	300
D-L-50-10	88.9	5	450	168.3	5	360	50	300
D-L-50-15	88.9	5	450	168.3	5	360	50	300
D-L-50-20	88.9	5	450	168.3	5	360	50	300
D-L-50-0	88.9	5	450	168.3	5	360	50	-
D-H-50-5	114.3	5	430	168.3	5	360	50	300
D-H-50-10	114.3	5	430	168.3	5	360	50	300
D-H-50-15	114.3	5	430	168.3	5	360	50	300
D-H-50-20	114.3	5	430	168.3	5	360	50	300
D-H-50-0	114.3	5	430	168.3	5	360	50	-

3. Instrumentation

a) Strain gauges – Two-dimensional strain gauges of type FCA-5-11-3L produced by Tokyo Sokki Kenkyujo Co., Ltd were adopted to measure the strain of the longitudinal and transverse strains of the specimens. Three strain gauges were installed at the mid-level of the outer tube with 120° separated from each other from the centre of the specimen. Fig 4(a) shows the details of the strain gauges.
b) Linear variable differential transducers (LVDTs) – Three LVDTs with 100 mm stroke were used to measure the axial shortening of the specimen during the test. They were installed to measure the movement of the bottom plate relative to the top plate, which were separated from each other with an angle of 120° at the centre of the specimen. The average value of the readings obtained from these LVDTs would be taken as the measured axial shortening of the specimen. Fig 4(b) shows the details of the LVDTs.
c) Circumferential Extensometer – Circumferential extensometers were used to measure the lateral expansion of the specimens within the elastic stage. The circumferential extensometers were removed when the measured lateral expansion was about to reach 6 mm, which is the maximum limit of the range of measurement. For unconfined and ring-confined CFDST and CFST specimens, two circumferential extensometers were installed at the locations which are 1/3 and 2/3 of the total height of the specimens to avoid clashing with the external steel rings. The installation details of the circumferential extensometers are also shown in Fig 4(b).

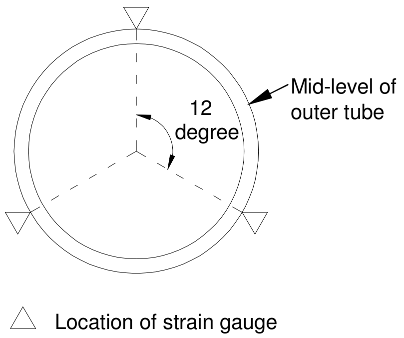


Fig 4(a) Details of strain gauges

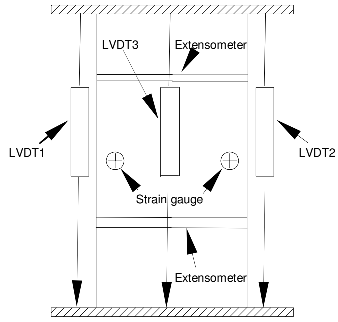
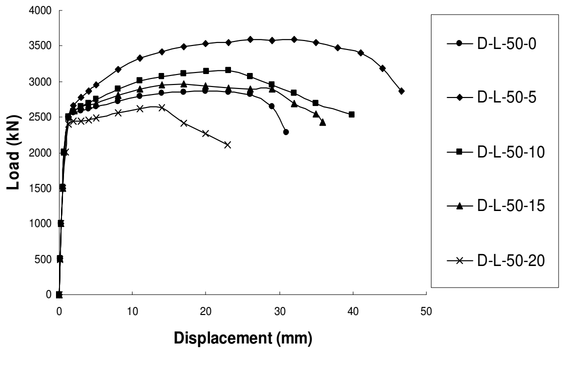


Fig 4(b) Details of LVDT and circumferential extensometers

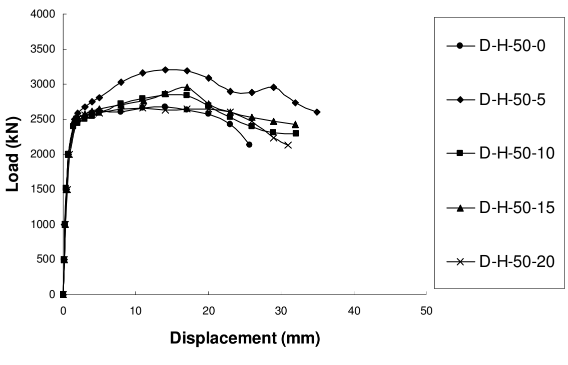
4. Experimental results

4.1 Axial load – displacement curves

The axial load is plotted against the displacement for unconfined and ring-confined concrete-filled double-skin tubular columns (CDFST) with χ = 0.56 and χ = 0.72 with external steel rings of various spacing ($5t_o$, $10t_o$, $15t_o$ and $20t_o$) as shown in Fig 5(a) and Fig 5(b). The *y*-axis represents the axial load measured during the test while *x*-axis represents the axial displacement measured by the LVDTs, which was taken as the average reading measured. It can be found from the figure that the stiffness, load-carrying capacity and ductility of confined CFDST columns is noticeably larger than the unconfined CFDST columns (except for D-L-50-20 which had an exceptionally low strength and ductility caused by the poor compaction of concrete). From the figure, it can be observed that the CFDST specimens with external confinement performed better in terms of strength, stiffness and ductility than that without confinement. The reasons are that the external steel rings restricted the lateral dilation of the steel tube under uni-axial compression. Therefore, larger confining pressure was provided to confine the steel tube as well as the concrete core.



(a) Load-displacement curves of CFDST columns with χ = 0.56



(b) Load-displacement curves of CFDST columns with χ = 0.72

Fig 5 Axial load – shortening curves

(a) Failure modes of CFDST columns with $\chi = 0.56$ with external steel rings

(b) Failure modes of CFDST columns with $\chi = 0.72$ with external steel rings

(c) Failure modes of CFDST columns with $\chi = 0.56$(left) and 0.72 (right) without external steel rings

(d) Inward buckling of inner steel tube

Fig 6 Failure modes

Comparing Figures 5(a) and 5(b), it is found that the maximum load-carrying capacity of the CFDST specimens with a lower hollow ratio was larger than those with a higher hollow ratio. This is because specimens with a lower hollow ratio had a larger concrete cross-sectional area, which increases the loading carrying capacity. With respect to ductility indicated by the slope of the descending branch of the load-displacement curve, it is seen that specimens with a lower hollow ratio will have larger ductility. From Fig 6, it is observed that the failure modes of these unconfined CFDST columns were the fracture of the outer tube and inward buckling of the inner tube at large axial strain. The inward buckling of the inner tube would also reduce considerably the confining pressure provided to the concrete and hence decrease the load-carrying capacity of the in-filled concrete. The failure modes of ring-confined specimens were the fracture of the outer steel tube and/or steel rings. However, it can be seen from the figures that the fracture of the outer steel tube mostly occurred only between the external steel rings except for some CFDST columns with large ring spacing and small hollow ratio.

4.2 Poisson's ratio

Because of the different Poisson's ratios of steel (~0.3) and concrete (~0.2), the steel tube is not fully effective to confine the concrete core during initial elastic stage. Therefore, external steel ring is adopted to restrict the dilation of the steel tube and hence improve the steel-concrete interface bonding and the confining pressure provided to the concrete core. The effectiveness of the external confinement could be studied by the Poisson's ratios of the specimens calculated by the slope of the initial straight line portion of the lateral strain against longitudinal strain. The results are listed in Table 2. The lateral strain is obtained by the circumferential strain. The axial strain is obtained by dividing the axial shortening of the CFDST columns by the overall height of the specimen. From the table, it can be seen that the Poisson's ratios of all ring-confined CFDST columns are about or smaller than 0.2, which is regarded as the average Poisson's ratio of NSC. Hence, it indicates that external steel rings can effectively restrict the lateral dilation of steel tube and maintain an intact steel-concrete interface bonding.

4.3 Improvement on axial strength, elastic stiffness and ductility due to external steel rings

Table 3 summarises the axial strength and elastic stiffness (i.e. the tangent stiffness of the initial elastic portion) of the CFDST columns. The relative strength and elastic stiffness increase due to the installation of external steel rings is studied by the axial strength and elastic stiffness enhancement ratio. The values are listed in Table 3. From the table, it is found that the average axial strength (elastic stiffness) enhancement ratios are about 11.5% (24.7%) and 9.5% (31.2%) for CFDST columns confined by steel rings with hollow ratio of 0.56 and 0.72 respectively.

Table 2 Poisson's ratios

Specimen Label	Poisson's ratio
χ=0.56	
D-L-50-5	---^
D-L-50-10	0.14
D-L-50-15	0.22
D-L-50-20	0.21
D-L-50-0	0.15
χ=0.72	
D-H-50-5	---^
D-H-50-10	0.16
D-H-50-15	0.18
D-H-50-20	0.11
D-H-50-0	0.17

^ Result is NOT included because there is not enough room for the installation of extensometers for D-L-50-5 and D-H-50-5.

^^ Result is NOT included because there is no external steel ring for D-L-50-0 and D-H-50-0.

Table 3(a) Load-carrying capacity enhancement ratio

Specimen Label	Load-carrying capacity (kN)	Enhancement ratio (%)	Specimen Label	Load-carrying capacity (kN)	Enhancement ratio (%)
D-L-50-5	3464	21.5	D-H-50-5	3209	20.0
D-L-50-10	3107	8.9	D-H-50-10	2873	7.4
D-L-50-15	2971	4.2	D-H-50-15	2946	10.2
D-L-50-20	---*	---*	D-H-50-20	2688	0.5
Average		11.5			9.5
D-L-50-0	2865	0.0	D-H-50-0	2674	0.0

* Result is NOT included because of poor concrete compaction

Table 3(b) Elastic Stiffness enhancement

Specimen Label	Stiffness (kN/mm)	Enhancement ratio (%)	Specimen Label	Stiffness (kN/mm)	Enhancement ratio (%)
D-L-50-5	4437	32.9	D-H-50-5	5150	46.9
D-L-50-10	4072	22.0	D-H-50-10	4308	22.9
D-L-50-15	3979	19.2	D-H-50-15	4864	38.7
D-L-50-20	---*	---*	D-H-50-20	4076	16.3
Average		24.7			31.2
D-L-50-0	3339	0.0	D-H-50-0	3506	0.0

Conclusions

The following conclusions are drawn from the test results:

(1)CFDST columns with external confinement were effective in restricting the lateral dilation of the columns and maintain an intact steel-concrete interface bonding.

(2)The performance of ring-confined CFDST columns is better than the unconfined CFDST columns in terms of strength, stiffness and ductility. It is because the steel rings provide a more effective, uniform and continuous confining pressure to the concrete core.

(3)The external ring confinement can effectively improve the axial strength of CFDST columns by an average value of 11.5% (9.5%) for CFDST columns with $\chi = 0.56$ ($\chi = 0.72$).

(4)The external ring can effectively improve the stiffness of CFDST columns by an average value of 24.7% (31.2%) for CFDST with $\chi = 0.56$ ($\chi = 0.72$) respectively.

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