Experimental study of square and rectangular concrete filled stainless steel tube stub columns under partial compression

AN HE[1], YATING LIANG[2] and OU ZHAO[3]

[1]*School of Civil and Environmental Engineering, Nanyang Technological University, Singapore*
E-mail: he.an@ntu.edu.sg
[2]*School of Engineering, University of Glasgow, Glasgow, UK*
E-mail: Yating.Liang@glasgow.ac.uk
[3]*School of Civil and Environmental Engineering, Nanyang Technological University, Singapore*
E-mail: ou.zhao@ntu.edu.sg

The partial compression behavior and bearing strengths of square and rectangular concrete filled stainless steel tube (CFSST) stub columns were experimentally investigated in this paper. The experimental study was conducted on five series of CFSST stub column specimens, with each series involving five geometrically identical specimens, including one fully loaded specimen and four partially loaded specimens, which allows a series of material and geometric parameters, including the stainless steel hollow section size, concrete infill grade and partial compression area on the partial compression behavior of CFSST stub column to be studied. The test setup, experimental procedures and key test results are reported in detail. The derived bearing strengths of CFSST stub columns were then utilized to assess the suitability of the existing international codes, as specified in the European code EN 1994-1-1 and American specification AISC 360-16, to the design of bearing strengths of partially loaded CFSST stub columns. It was found that both selected design codes generally yield inaccurate (unsafe and scattered) predictions for the bearing strengths of CFSST stub column.

Keywords: Concrete-filled stainless steel tube, Partial compression tests, Stub columns, Design standards.

1 Introduction

Concrete-filled steel tube (CFST) columns have been increasingly used in high-rise buildings and bridges, as they uniquely combine the material advantages of both steel and concrete, where the outer steel tube enhances the compressive strength of inner concrete core by providing effective lateral confinement to the concrete core, while the concrete core improves the local buckling resistance of the outer steel tube by preventing its inward buckling mode from happening. The past decade has witnessed an increasing trend of using concrete-filled stainless steel tube (CFSST) composite columns to replace concrete filled normal carbon steel tube composite columns, as the stainless steel possesses more advantageous material properties, including high strength, superior ductility and excellent durability. To date, extensive experimental investigations have been conducted on various type of CFSST stub columns at room and elevated temperatures (Young and Ellobody 2006, Lam and Gardner 2008, Uy et al. 2011, Ellobody and Ghazy 2012, Han et al. 2013, Yang and Ma 2013, Li et al. 2016, Li et al. 2016, Tao et al. 2016, Chen et al. 2018, He et al. 2019). Nevertheless, research into the partial

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compression behavior of CFSST stub columns remains unexplored, despite the fact that partial compression is a common loading case existing in the bridges and long-span structures. For example, piers supporting beam girders of bridges through bearings and columns holding up arch structures through bearings are subjected to partial compression load.

The partial compression performance and bearing capacities of square and rectangular CFSST stub columns were investigated in this paper. A testing program was firstly carried out on five series of CFSST stub column specimens, with each series involving five geometrically identical specimens, including one fully loaded specimen and four partially loaded specimens. Given that there have been no existing codified provisions for the design of bearing strengths of partially loaded CFSST stub columns, the corresponding design rules for the bearing strengths of concrete-filled carbon steel tube stub columns, as specified in the European code EN 1994-1-1 (CEN (2004)) and American specification AISC 360-16 (AISC (2016)), were assessed for their suitability to the design of partially loaded CFSST stub columns, based on the acquired experimental data.

2 Experiment

2.1 *Test specimens*

The experimental study was conducted on 25 CFSST stub column specimens, which were designed to cover a broad range of geometric and material parameters, enabling the effects of stainless steel hollow section size, concrete infill grade and partial compression area on the partial compression behavior of CFSST stub column to be studied. Specifically, four cold-formed EN 1.4420 austenitic stainless steel square and rectangular hollow section tubes (i.e. SHS 100×100×3, SHS 120×120×5, SHS 150×150×5 and RHS 150×100×5) and one concrete infill grade of C50 were employed to fabricate four series of CFSST stub column specimens, namely S100-C50, S120-C50, S150-C50 and R150-C50. Note that the identifier of each specimen series starts with the nominal cross-sectional width of the hollow tubes, where the letter 'S' and 'R' respectively represent square and rectangular hollow section, and ends with the nominal concrete grade. Moreover, an additional specimen series S100-C80 was fabricated with the SHS 100×100×3 tube and C80 concrete. Each specimen series involves a fully loaded (reference) CFSST stub column specimen and four partially loaded CFSST stub column specimens, and the labelling system of each specimen consists of the specimen series name and a number indicating the level of partial compression area. The measured geometric dimensions of the fully and partially loaded CFSST stub column specimens as well as their corresponding bearing plate adopted for applying partial compressive loads are summarized in Table 1, including the overall depth h, width b, thickness t and inner corner radius r_i of the outer stainless steel tube, the member length L, the diameter d_b and thickness t_b of the circular bearing plate and the partial compression ratio $\beta = A_c/A_b$, in which A_c and A_b are respectively the cross-sectional areas of the concrete core and the bearing plate.

2.2 *Material testing*

Tensile coupon tests and standard cylinder tests were respectively conducted to derive the material properties of stainless steel tube and concrete infill. The key material properties for the flat and curved coupons, including the Young's modulus E, the 0.2% proof stress $\sigma_{0.2}$, the ultimate stress σ_u and its corresponding strain ε_u, are reported in Table 2. Two concrete grades,

Table 1. Geometric and material properties of partially and fully loaded CFSST stub column specimens.

Specimen	h (mm)	b (mm)	t (mm)	r_i (mm)	L (mm)	d_b (mm)	t_b (mm)	β	f_c (MPa)
S100-C50	100.3	100.5	3.03	4.5	300	–	–	–	53.8
S100-C50-C-1	100.0	100.5	3.13	4.5	302	89.0	46.5	1.4	53.8
S100-C50-C-2	99.7	101.3	3.18	4.5	303	51.0	62.0	4.3	53.8
S100-C50-C-3	100.0	100.7	3.03	4.5	303	35.0	33.0	9.2	53.8
S100-C50-C-4	100.3	100.4	3.00	4.5	300	30.1	48.5	12.5	53.8
S100-C80	99.8	100.7	3.08	4.5	301	–	–	–	84.4
S100-C80-C-1	99.8	100.7	3.02	4.5	302	89.0	46.5	1.4	84.4
S100-C80-C-2	99.8	100.8	3.02	4.5	300	51.0	62.0	4.3	84.4
S100-C80-C-3	100.6	100.8	3.02	4.5	304	35.0	33.0	9.3	84.4
S100-C80-C-4	100.1	100.4	3.09	4.5	301	30.1	48.5	12.4	84.4
S120-C50	119.4	120.6	4.97	6.5	322	–	–	–	60.8
S120-C50-C-1	120.0	120.4	5.06	6.5	325	101.7	46.6	1.5	60.8
S120-C50-C-2	119.3	120.5	4.98	6.5	324	63.5	46.7	3.8	60.8
S120-C50-C-3	119.9	120.2	5.08	6.5	324	41.0	58.0	9.1	60.8
S120-C50-C-4	119.4	120.9	4.98	6.5	323	30.1	48.5	17.0	60.8
S150-C50	149.7	150.3	4.95	6.5	400	–	–	–	62.6
S150-C50-C-1	149.4	150.2	5.00	6.5	400	127.2	47.4	1.5	62.6
S150-C50-C-2	149.8	150.3	4.96	6.5	400	79.8	45.1	3.9	62.6
S150-C50-C-3	149.6	150.3	4.97	6.5	400	51.0	62.0	9.6	62.6
S150-C50-C-4	149.2	149.7	4.99	6.5	401	41.0	58.0	14.7	62.6
R150-C50	101.0	149.1	5.00	6.0	367	–	–	–	66.4
R150-C50-C-1	100.7	149.6	4.98	6.0	364	89.0	46.5	2.0	66.4
R150-C50-C-2	101.0	149.7	5.13	6.0	367	63.5	46.7	4.0	66.4
R150-C50-C-3	100.9	149.2	4.94	6.0	365	41.0	58.0	9.6	66.4
R150-C50-C-4	100.1	150.2	5.00	6.0	367	30.1	48.5	17.7	66.4

namely C50 and C80, were adopted to fabricate the CFSST stub column specimens. The average measured compressive cylinder strengths f_c for each specimen series are listed in Table 1.

2.3 *Stub column tests under partial and full compression*

A 2000 kN hydraulic compression machine was employed to apply axial concentric loads onto the CFSST stub column specimens. The setup for full compression tests is shown in Fig. 1(a), which included a pair of rigid platens that completely covered the entire end section of the CFSST stub column, hence ensuring the application of uniform loads to both outer stainless steel tube and inner concrete core. The same setup is also used for partial compression tests except

Table 2 Key material properties from tensile coupon tests.
(a) Flat coupons

Cross section	E (GPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ε_u (%)
SHS 100×100×3	217	365	707	39
SHS 120×120×5	201	317	665	44
SHS 150×150×5	210	324	673	44
RHS 150×100×5	201	321	669	42

(b) Curved coupons

Cross section	E (GPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ε_u (%)
SHS 100×100×3	208	503	781	27
SHS 120×120×5	195	560	795	26
SHS 150×150×5	203	548	805	25
RHS 150×100×5	195	554	759	24

that the top rigid platen adopted in the full compression test was replaced by a circular bearing plate, allowing the application of compression loads onto the concrete surface directly in contact with the bearing plate only, as shown in Fig. 1(b).

The test rigs for both fully and partially loaded CFSST stub columns are depicted in Figs 1(a) and 1(b), respectively, where four LVDTs are vertically arranged at the top end of the rigid platen to record the end shortening of the specimen. For each fully loaded CFSST stub column specimen, two strain gauges were orthogonally affixed at the mid-height of the specimen to monitor the longitudinal and transverse strains; while for each partially loaded CFSST stub column specimen, four pairs of strain gauges were orthogonally adhered on the outer stainless steel tube at distances of 20 mm, $0.25L$, $0.5L$ and $0.75L$ (L is the member length) from the top end of the CFSST stub column, allowing the longitudinal and transverse strains at these positions to be monitored.

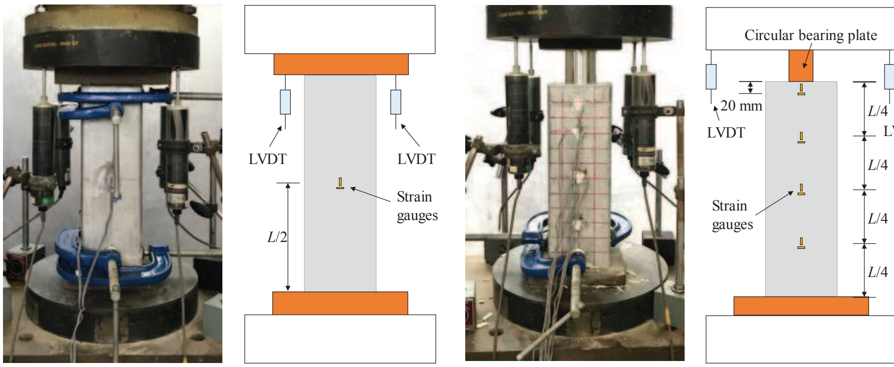
The experimental load–end shortening curves for the five series of partially loaded CFSST stub columns, along with their respective fully loaded counterparts, are depicted in Figs 2(a)–2(e), while the ultimate loads for the specimens subjected to partial and full compression (denoted as $N_{u,p}$ and $N_{u,f}$, respectively) are summarized in Table 3. In order to quantify the reduction of cross-section resistances of CFSST stub columns resulting from the partial compression effect, the relative capacity index (RCI) for each specimen series, as defined in Eq. (1), was calculated and presented in Table 3. Typical failure modes of a specimen series S100-C50, including the partially and fully loaded specimens, are displayed in Fig. 3.

$$\mathrm{RCI} = \frac{N_{u,p}}{N_{u,f}} \tag{1}$$

3 Evaluation of existing design methods

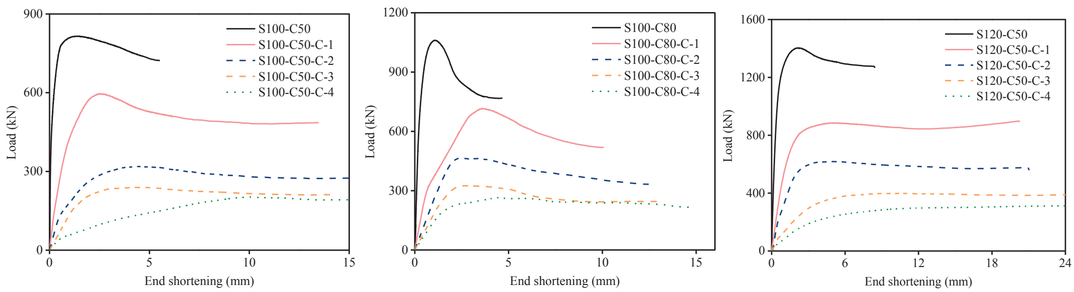
3.1 *General*

Due to the absence of established standards for the design of bearing strengths of CFSST stub columns subjected to partial compression, the corresponding design rules for partially loaded concrete filled normal carbon steel tube stub columns, as specified in EN 1994-1-1 (CEN (2014)) and AISC 360-16 (AISC (2016)), were evaluated herein for their suitability to CFSST stub columns subjected to partial compression loads. Table 3 presents the mean ratios of the test failure loads to the predicted ultimate loads of the two considered design standards.

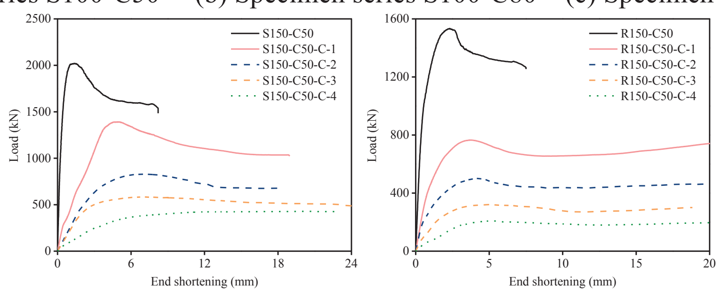


(a) Full compression tests (b) Partial compression tests

Figure 1. Test setup for full and partial compression tests.



(a) Specimen series S100-C50 (b) Specimen series S100-C80 (c) Specimen series S120-C50



(d) Specimen series S150-C50 (e) Specimen series S150-C50

Figure 2. Load–end shortening curves for partially and fully loaded CFSST stub column specimens.

3.2 *EN 1994-1-1*

The design formula for concrete-filled carbon steel tube members under partial compression, as set out in the existing European code EN 1994-1-1 (CEN (2014)), is expressed as the product of the design concrete compression resistance within the bearing area N_b and an factor reflecting the advantageous partial compression effect k, as given in Eq. (2), in which the enhancement factor k is determined by $\sqrt{A_c / A_b}$. Note that the beneficial confinement effect provided by the

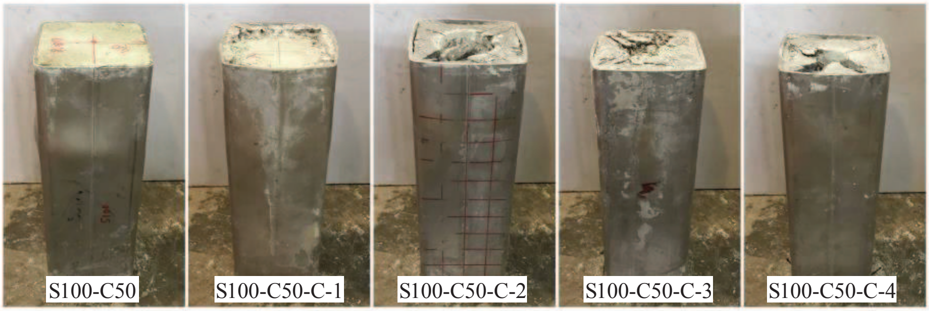


Figure 3. Typical failure modes of a specimen series S100-C50.

outer steel tube on the enhancement of concrete compressive strength was considered in the calculation of N_b, leading to the resultant EC4 design formula for bearing strengths of concrete-filled carbon steel tube members given in Eq. (3), where A_b is the bearing area of concrete, A_c is the gross area of the concrete, η is a coefficient to take into account the beneficial confinement effect of concrete, and is taken as 3.5 for square steel tube, f_y is the yield stress of the steel tube and f_c is the cylinder strength of the concrete. The EC4 design bearing strength of CFSST stub columns were then calculated herein using Eq. (3), but with f_y=$\sigma_{0.2}$, and then compared against the experimentally acquired failure loads. As reported in Table 3, the mean ratio of $N_{u,EC4}/N_{u,p}$ and the corresponding COV are equal to 1.11 and 0.15, respectively, revealing that the EC4 design strengths for partially loaded CFSST stub columns generally yields inaccurate (unsafe and scattered) predictions.

$$N_{u,pred} = N_b k \tag{2}$$

$$N_{u,EC4} = (1+\eta \frac{t}{d}\frac{f_y}{f_c}) f_c A_b \sqrt{\frac{A_c}{A_b}} \le f_c A_c \tag{3}$$

3.3 *AISC 360-16*

In terms of the calculation of the design bearing strengths of concrete-filled carbon steel tube members, the American specification AISC 360-16 (AISC (2016)) utilises the same approach as that employed in EN 1994-1-1 (CEN (2014)), as given by Eq. (2), except for the use of a different method in determining the concrete compression resistance within the bearing area, which only allows the use of unconfined concrete cylinder strength, resulting in the AISC design formula for bearing strengths of concrete-filled carbon steel tube members given in Eq. (4). The AISC design bearing strengths of CFSST stub columns were then calculated and compared with the corresponding experimental failure loads. As tabulated in Table 3, it was generally found that AISC results in rather inaccurate and scattered bearing strength predictions when used for the design of CFSST stub columns under partial compression.

$$N_{u,AISC} = 0.85 f_c A_b \sqrt{\frac{A_c}{A_b}} \le 1.7 f_c A_b \tag{4}$$

Table 3 Experimental and predicted failure loads for partially loaded CFSST stub columns.

Specimen	$N_{u,f}$ (kN)	$N_{u,p}$ (kN)	RCI	$N_{u,EC4}$ (kN)	$N_{u,EC4}/N_{u,p}$	$N_{u,AISC}$ (kN)	$N_{u,AISC}/N_{u,p}$
S100-C50	816	–	–	–	–	–	–
S100-C50-C-1	–	597	0.73	475	0.80	669	1.12
S100-C50-C-2	–	319	0.39	399	1.25	220	0.69
S100-C50-C-3	–	240	0.29	269	1.12	103	0.43
S100-C50-C-4	–	202	0.25	231	1.14	76	0.38
S100-C80	1061	–	–	–	–	–	–
S100-C80-C-1	–	716	0.67	747	1.04	1050	1.47
S100-C80-C-2	–	466	0.44	522	1.12	345	0.74
S100-C80-C-3	–	326	0.31	360	1.10	162	0.50
S100-C80-C-4	–	265	0.25	310	1.17	120	0.45
S120-C50	1404	–	–	–	–	–	–
S120-C50-C-1	–	886	0.63	734	0.83	986	1.11
S120-C50-C-2	–	619	0.44	659	1.06	385	0.62
S120-C50-C-3	–	399	0.28	429	1.08	160	0.40
S120-C50-C-4	–	311	0.22	312	1.00	86	0.28
S150-C50	2021	–	–	–	–	–	–
S150-C50-C-1	–	1391	0.69	1222	0.88	1590	1.14
S150-C50-C-2	–	829	0.41	990	1.19	626	0.76
S150-C50-C-3	–	584	0.29	632	1.08	256	0.44
S150-C50-C-4	–	429	0.21	508	1.19	165	0.39
R150-C50	1534	–	–	–	–	–	–
R150-C50-C-1	–	765	0.50	839	1.10	826	1.08
R150-C50-C-2	–	501	0.33	663	1.32	420	0.84
R150-C50-C-3	–	321	0.21	423	1.32	175	0.55
R150-C50-C-4	–	208	0.14	310	1.49	94	0.45
				Mean	1.11	Mean	0.69
				COV	0.15	COV	0.48

4 Conclusions

This paper presents a thorough experimental investigation on the partial compression behavior and bearing strengths of square and rectangular concrete-filled stainless steel tube (CFSST) stub columns. The experimental study was conducted on five series of CFSST stub column specimens, with each series involving five geometrically identical specimens, including one fully loaded specimen and four partially loaded specimens. Given that there have been no existing national codes for the design of bearing strengths of partially loaded CFSST stub columns, the corresponding design rules for the bearing strengths of concrete-filled normal carbon steel tube stub columns, as specified in the European code EN 1994-1-1 (CEN (2014)) and American specification AISC 360-16 (AISC (2016)), were assessed for their suitability to the design of bearing strengths of CFSST stub columns, based on the acquired experimental data. It was found that both selected design codes generally yield inaccurate (unsafe and scattered) predictions for the bearing strengths of CFSST stub column. Therefore, it is suggested that a more accurate and efficient design method for the prediction of bearing strength of CFSST stub columns under partial compression is required, and hence further research is underway in this area.

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