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Behaviour of small-diameter self-compacting concrete-filled steel tubes

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Abstract

This study explores the effect of length to diameter (L/D) ratio on the axial load capacity of small-diameter self-compacting concrete-filled steel tube (SCFT) specimens. The SCFT specimens with L/D ratio of 2 to 14 were tested. Two different cold-formed steel tubes with diameters of 26.9 and 33.7 mm were used in the construction of the SCFT specimens. The behaviour of the SCFT specimens was compared with the unfilled steel tube (UT) specimens. The axial load capacity of SCFT specimens was found to be higher than the axial load capacity of UT specimens. The compressive failure of SCFT and UT specimens with a ratio of 2 and 4 occurred due to local buckling, and with L/D ratio ≥ 6 failure occurred due to global buckling. However, the self-compacting concrete inside the steel tubes improved the ductility and the post-peak axial load-axial deformation response of SCFT specimens compared to the UT specimens.

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Behaviour of small-diameter self-compacting concrete-filled steel tubes

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This study explores the effect of length to diameter (L/D) ratio on the axial load capacity of small-diameter self-compacting concrete-filled steel tube (SCFT) specimens. The SCFT specimens with L/D ratio of 2 to 14 were tested. Two different cold-formed steel tubes with diameters of 26.9 and 33.7 mm were used in the construction of the SCFT specimens. The behaviour of the SCFT specimens was compared with the unfilled steel tube (UT) specimens. The axial load capacity of SCFT specimens was found to be higher than the axial load capacity of UT specimens. The compressive failure of SCFT and UT specimens with a ratio of 2 and 4 occurred due to local buckling, and with L/D ratio ≥ 6 failure occurred due to global buckling. However, the self-compacting concrete inside the steel tubes improved the ductility and the post-peak axial load–axial deformation response of SCFT specimens compared to the UT specimens.

Notation

A_c	cross-section area of the concrete
A_s	cross-section area of the steel tube
C_3	coefficient of concrete effective stiffness
D	outside diameter of steel tube
E_c	modulus of elasticity of the concrete
E_s	modulus of elasticity of the steel tube
EI_e	effective flexural stiffness
f'_c	concrete compressive strength
f_y	steel yield stress
I_c	second moment of area of the concrete
I_s	second moment of area of the steel tube
k_e	member effective length factor
L	column length
N_c	nominal member capacity
N_{cd}	design member capacity
N_e	Euler elastic buckling capacity
N_{exp}	average ultimate load capacity of two self-compacting concrete-filled steel tube specimens tested under axial compression
N_o	squashing capacity of the cross-section
t	wall thickness of the steel tube
α_1	reduction factor for the filling concrete
ϕ_{co}	partial safety factor for a composite column capacity

In addition, the change of buckling mode is not only evident in the cross-section but is also evident along the length of the member (AISC, 2010). CFTs have the following advantages.

- Yield load carrying capacity of a CFT is higher owing to the delay in the buckling of the steel tube in the elastic range (Lai and Ho, 2016).
- CFTs provide excellent resistance to seismic and impact loads (Shanmugam and Lakshmi, 2001).
- The strain concentrations of CFTs are reduced by spreading the localised buckling over the length of the CFT (Elchalakani *et al.*, 2001).
- The failure of CFTs is not as rapid as UTs because the inward buckling failure mechanism is eliminated by the infill concrete (AISC, 2010; Zeghiche and Chaoui, 2005).
- The post-buckling behaviour of CFTs is more ductile than UTs owing to an increase in the wavelength of the bulking response (Ellobody *et al.*, 2006).
- The fire resistance of CFTs is greater than that of UTs (Huo *et al.*, 2014).
- In CFTs, the steel tube acts as permanent formwork.
- The circular steel tube section significantly increases the confinement of the concrete core owing to uniform membrane pressure (Schneider, 1998).

Introduction

Concrete-filled steel tubes (CFTs), constructed by filling steel tubes with concrete, are widely used as structural members. The behaviour of CFTs is fundamentally different from the behaviour of unfilled steel tubes (UTs). The presence of the concrete infill changes the buckling mode of steel tube specimens from inward buckling to outward buckling (AISC, 2010).

Due to the above mentioned advantages, CFTs have been widely used as columns for bridges and high-rise buildings (Fam *et al.*, 2004; Giakoumelis and Lam, 2004; Lai and Ho, 2015). The CFT is also used as chords in truss bridges (Han *et al.*, 2011) and as ribs in transmission towers (Han *et al.*, 2012). Han and An (2014) used composite columns consisting of an inner CFT and an outer layer of reinforced concrete. Recently, Hadi *et al.* (2017) proposed to use small-diameter

CFTs for reinforcing concrete columns. The innovative use of the CFTs for reinforcing concrete columns was found to be equally effective, especially considering the axial load capacity and the ductility of the columns (Hadi *et al.*, 2017). However, the axial load carrying capacity and the ductility of the CFT-reinforced concrete columns depend significantly on the behaviour of the CFTs under axial compression. The CFTs can be effectively used as structural members where small-diameter steel tubes are required. The concrete-filled small-diameter steel tubes can also be used in the construction of garage sheds, covered walkways and pedestrian bridges to increase the axial load capacity and to reduce the vibration of the total structure.

In a CFT, the confinement provided by the steel tube is initiated by the expansion of concrete due to microcracking under axial load. The increase in load-resisting capacity is mostly observed in circular short CFT columns. However, when the length to outside diameter (L/D) ratio is high, the CFT columns tend to buckle before providing any confinement to the expanding concrete core. Knowles and Park (1969) reported that the CFT columns with L/D ratio ≥ 12 did not exhibit any significant confinement effect. Gupta *et al.* (2007) tested 72 CFT specimens (340 mm in length) with two different grades of concrete (nominal concrete compressive strength of 30 and 40 MPa) in steel tubes with outside diameters of 47.28, 89.32 and 112.56 mm and thicknesses of 1.87, 2.74 and 2.89 mm, respectively. Normal vibrated concrete (NVC) and self-compacting concrete (SCC) were used to fill the steel tubes. The SCC mix was produced by using three different percentages of fly ash (15, 20 and 25%). Gupta *et al.* (2007) reported that CFT specimens with 47.28 mm outside diameter failed by Euler buckling (global buckling) and CFT specimens with outside diameters of 89.32 mm and 112.56 mm failed by local buckling. However, Gupta *et al.* (2007) did not investigate the influence of different L/D ratios on the axial load capacity of the CFT specimens under axial compression. It was reported that the confinement effect decreased with an increase in the concrete strength for smaller L/D ratios. De Oliveira *et al.* (2009) tested 16 CFT columns (114.3 mm outside diameter and 3.35 mm wall thickness) with different grades of concrete (nominal concrete compressive strength of 32.7, 58.7, 88.8 and 105.5 MPa) and different L/D ratios (3, 5, 7 and 10). It was reported that the axial load capacity of CFT columns increased with the increase in the compressive strength of the concrete core and decreased with the increase in the L/D ratio of the specimen. Muciaccia *et al.* (2011) tested 24 CFT columns (139.6 mm outside diameter and 4 mm wall thickness) with different types of concrete (NVC, SCC and expansive SCC) and L/D ratios ranging from 9 to 33 under 25 mm eccentric axial load. It was found that the influence of the L/D ratio and the failure mode of tested specimens were similar to previous findings of the CFT columns filled with NVC. Additionally, the use of SCC instead of NVC did not affect the design of CFT.

The behaviour of steel tubes filled with concrete has been extensively studied and included in major design standards, such as the American Standard ANSI/AISC 360-10 (AISC, 2010), Eurocode 4 (BSI, 2005) and the Canadian Standard CAN/CSA-S16-09 (CSA, 2009). A large number of studies were carried out on medium-scale specimens with an outside diameter between 100 mm and 200 mm using concrete of varying compressive strengths. However, only a limited number of research studies were conducted on the behaviour of small-diameter CFTs. In this paper, steel tubes with small diameters were used as CFTs. Since the diameter of the steel tubes is very small, the ability of concrete to flow and consolidate without segregation is highly critical. Therefore, concrete with high flowability is required to completely fill the tube without segregation. SCC is considered to be a suitable option; it is able to compact under its own weight without requiring any vibration. Besides the requirement for no vibration, the SCC is chosen due to its good rheological performance, constructional enhancement, environmental advantage and economic benefit (Aslani, 2015; Badry *et al.*, 2016; Chamani *et al.*, 2014; EFNARC, 2005). The present study investigates the influence of L/D ratio on the axial load capacity of small-diameter SCC-filled steel tube (SCFT) specimens under axial compression. For specimens with L/D ratio of 2 to 14, the compressive failure of SCFT specimens was compared with the compressive failure of the UT specimens. The influence of outside diameter to thickness (D/t) ratio of steel tubes on the behaviour of SCFT specimens was also investigated. Moreover, experimental axial load capacities of SCFT specimens with different L/D ratios were compared with the estimates from American Standard ANSI/AISC 360-10 (AISC, 2010).

Experimental program

Two different types of cold-formed steel tubes were used to construct SCFT specimens. The first cold-formed steel tube had an outside diameter of 26.9 mm, wall thickness of 2.6 mm and a nominal tensile strength of 250 MPa. The second cold-formed steel tube had an outside diameter of 33.7 mm, a wall thickness of 2 mm and a nominal tensile strength of 350 MPa. The cold-formed steel tube specimens were divided into two groups: SCFT specimens and UT specimens. The behavior of specimens under axial compression depends largely on the unsupported length to outside diameter (L/D) ratio. In the experimental program, two specimens of each L/D ratio of 2, 4, 6, 8, 10, 12 and 14 were tested under axial compression. Three specimens of each type of UT were also tested under axial tension. A total of 62 specimens were tested, which included 56 specimens under axial compression and six specimens under axial tension.

A SCC mix with a maximum aggregate size of 10 mm was used in casting the SCFT specimens. The SCC was prepared according to EFNARC (2002). Several concrete mixes were

investigated to achieve SCC. The mix proportion of the SCC used in this study is shown in Table 1. The properties of fresh concrete were tested according to ASTM C 1610/C 1610M-14 (ASTM, 2014b), ASTM C 1611/C 1611M-14 (ASTM, 2014c) and ASTM C 1621/C 1621M-14 (ASTM, 2014d). For the water/powder ratio of 0.4, column segregation test (ASTM, 2014b), slump flow test (ASTM, 2014c) and J-ring test (ASTM, 2014d) results were found to be satisfactory. The compressive strength of the SCC was determined by testing three cylinders of 100 mm diameter and 200 mm height according to AS 1012.9-14 (SA, 2014). The average 28 d compressive strength of the SCC was 57 MPa. The formwork was constructed to keep both the top and bottom of the steel tube specimens in a fixed plumb position, as shown in Figure 1. Steel tube specimens were fixed to a non-absorbing plywood base plate. The SCC mix was poured into the steel tube specimens without any vibration or compaction.

The label for the specimen groups consist of one part and the labels for the specimens consist of three parts; these are listed in Tables 2–5. There are four groups of specimens. The groups UT26.9 and UT33.7 refer to UTs with 26.9 mm and 33.7 mm outside diameters, respectively. The groups SCFT26.9 and SCFT33.7 refer to SCFTs with 26.9 mm and 33.7 mm outside diameters, respectively. The first part of the specimen label represents the group name. In the second part of the specimen label, the letter ‘T’ refers to the specimens tested under axial tension, and the letter ‘C’ refers to the specimens tested under axial compression. The number associated with letter ‘C’ represents L/D ratio. The third part of the specimen label refers to the test specimen number. Two specimens from each group were tested under axial compression and three specimens from each group were tested under axial tension. For example, specimen SCFT26.9-C10-1 refers to a SCFT specimen (with 26.9 mm outside diameter) tested under axial compression, with L/D ratio of 10, and the specimen is the first of the two tested specimens.

Instrumentation and testing

A 500 kN universal testing machine in the High Bay laboratory at the University of Wollongong, Australia, was used to conduct the tests for all specimens. For tension tests, different wedge grips of the machine jaw were used based on the

Figure 1. Construction of formwork

outside diameters of steel tube specimens. Tensile testing of steel tubes was conducted according to ASTM A370-14 (ASTM, 2014a). Full-size tubular sections were used to conduct the tensile test. To avoid the crushing at the ends of the tube due to gripping, two metal plugs fabricated from solid steel were inserted in both ends of the tube. The metal plugs were designed based on the inside diameters of the steel tubes to suit the 21.7 and 29.7 mm steel tubes. Figure 2 shows the schematic of the metal plugs for the steel tubes. Flat grips were used for the axial compression test. The SCFT specimens were tested with the axial load applied on the entire section. The ends of steel tube specimens were milled for a flat surface. The specimens were tested under displacement controlled load applications at 1 mm/min.

Test results of UT specimens

UTs under axial tension

Test results of cold-formed UT specimens under axial tension are reported in Table 2. Figure 3 shows the stress–strain behaviour of cold-formed UT specimens under axial tension. It was observed from the stress–strain behaviour of the tested specimens that the UT specimens did not show clearly defined yield points. Hence, yield stresses were calculated based on 0.2% proof stress (AISI, 1996). The average ultimate strength to

Table 1. Mix proportion of the SCC used in this study

Material	Quantity
Cement	280 kg/m ³
Fly ash	120 kg/m ³
Slag	50 kg/m ³
Fine aggregate	950 kg/m ³
Coarse aggregate	780 kg/m ³
Water	182 kg/m ³
High range water reducer	3.375 l/m ³
Water/powder ratio	0.4

Table 2. Test results of UT specimens under axial tension

Group	Specimen	Yield stress ^a : MPa	Yield strain ^a : %	Ultimate strength: MPa	Corresponding strain: %	Modulus of elasticity: GPa
UT26-9	UT26-9-T-1	360	0.55	399	2.53	193
	UT26-9-T-2	355	0.51	389	2.50	192
	UT26-9-T-3	350	0.52	385	2.57	191
	Avg. UT26-9-T	355	0.53	391	2.53	192
UT33-7	UT33-7-T-1	455	0.53	491	4.47	195
	UT33-7-T-2	447	0.65	500	6.69	197
	UT33-7-T-3	448	0.57	495	4.52	196
	Avg. UT33-7-T	450	0.58	495	5.23	196

^aYield stress and yield strain of specimens were calculated based on 0.2% proof stress

Table 3. Test results of UT specimens under axial compression

Group UT26-9			Group UT33-7		
Specimen	Ultimate load: kN	Corresponding deformation: mm	Specimen	Ultimate load: kN	Corresponding deformation: mm
UT26-9-C2-1	83.8	4.88	UT33-7-C2-1	102.0	3.67
UT26-9-C2-2	83.7	4.53	UT33-7-C2-2	101.0	3.61
Avg. UT26-9-C2	83.8	4.71	Avg. UT33-7-C2	101.5	3.64
UT26-9-C4-1	81.8	3.97	UT33-7-C4-1	100.0	5.86
UT26-9-C4-2	80.8	3.88	UT33-7-C4-2	100.4	5.83
Avg. UT26-9-C4	81.3	3.93	Avg. UT33-7-C4	100.2	5.85
UT26-9-C6-1	78.4	3.42	UT33-7-C6-1	94.2	5.97
UT26-9-C6-2	79.4	3.40	UT33-7-C6-2	93.4	5.84
Avg. UT26-9-C6	78.9	3.41	Avg. UT33-7-C6	93.8	5.91
UT26-9-C8-1	73.6	2.52	UT33-7-C8-1	88.3	4.61
UT26-9-C8-2	73.3	2.33	UT33-7-C8-2	88.9	5.00
Avg. UT26-9-C8	73.5	2.40	Avg. UT33-7-C8	88.6	4.81
UT26-9-C10-1	71.3	1.70	UT33-7-C10-1	83.7	3.82
UT26-9-C10-2	71.9	1.82	UT33-7-C10-2	83.8	4.00
Avg. UT26-9-C10	71.6	1.76	Avg. UT33-7-C10	83.8	3.91
UT26-9-C12-1	70.4	1.69	UT33-7-C12-1	81.4	3.53
UT26-9-C12-2	71.2	1.70	UT33-7-C12-2	81.6	3.65
Avg. UT26-9-C12	70.8	1.70	Avg. UT33-7-C12	81.5	3.59
UT26-9-C14-1	69.2	1.57	UT33-7-C14-1	78.7	3.36
UT26-9-C14-2	69.7	1.71	UT33-7-C14-2	78.5	3.13
Avg. UT26-9-C14	69.5	1.64	Avg. UT33-7-C14	78.6	3.25

yield stress ratio for UT specimens was greater than 1.08 (Table 2), which satisfies the ductility requirement specified in *Specification for the Design of Cold-Formed Steel Structural Members* (AIS, 1996).

UTs under axial compression

Test results of UT specimens under axial compression are reported in Table 3. The axial load–axial deformation behaviours of the specimens in the groups UT26-9 and UT33-7 under axial compression are shown in Figure 4. For each group of steel tubes, two specimens were tested for each L/D ratio. It was observed that the two tested specimens for each L/D ratio experienced similar axial load–axial deformation behaviour. Consequently, the axial load–axial deformation behaviour of one of the two tested specimens (the first specimen)

for each L/D ratio is shown in Figure 4 for ease of comparison. The behaviour of UT specimens under axial compression is significantly influenced by the L/D ratio. Two failure modes were observed for UT specimens depending on the L/D ratio of the specimen. The first type of failure mode was due to local buckling (elephant's foot buckling), which occurred in a ring shape at one end of the steel tube. The second type of failure mode was due to global buckling, which occurred along the entire length of the tube. Global buckling of the UT specimens occurred with insignificant local buckling at the ends of the UT specimen. After the ultimate load, global buckling failure was observed to occur as a bend in a sharp angle near the mid-height of the tube (inward buckling). For the L/D ratio of 2 and 4, the compressive failure in the UT specimens occurred due to local elephant's foot buckling. For the L/D ratio ≥ 6 , the compressive failure modes of UT specimens changed from

Table 4. Test results of SCFT specimens under axial compression

Group SCFT26-9				Group SCFT33-7			
Specimen	Ultimate load ^a : kN	Corresponding deformation: mm	Concrete enhancement factor	Specimen	Ultimate load ^a : kN	Corresponding deformation: mm	Concrete enhancement factor
SCFT26-9-C2-1	117.6	3.67	1.603	SCFT33-7-C2-1	161.7	8.85	1.512
SCFT26-9-C2-2	116.4	3.41	1.551	SCFT33-7-C2-2	166.3	9.51	1.654
Avg. SCFT26-9-C2	117.0	3.54	1.577	Avg. SCFT33-7-C2	164.0	9.18	1.583
SCFT26-9-C4-1	104.6	3.36	1.082	SCFT33-7-C4-1	145.1	8.93	1.142
SCFT26-9-C4-2	103.8	3.12	1.091	SCFT33-7-C4-2	141.1	8.81	1.031
Avg. SCFT26-9-C4	104.2	3.24	1.086	Avg. SCFT33-7-C4	143.1	8.87	1.086
SCFT26-9-C6-1	104.0	3.27	1.214	SCFT33-7-C6-1	137.7	6.49	1.102
SCFT26-9-C6-2	102.7	2.98	1.105	SCFT33-7-C6-2	136.7	6.40	1.097
Avg. SCFT26-9-C6	103.4	3.14	1.160	Avg. SCFT33-7-C6	137.2	6.45	1.099
SCFT26-9-C8-1	97.9	3.16	1.153	SCFT33-7-C8-1	132.0	4.66	1.107
SCFT26-9-C8-2	97.8	2.96	1.162	SCFT26-9-C8-2	133.7	4.50	1.134
Avg. SCFT26-9-C8	97.9	3.06	1.157	Avg. SCFT33-7-C8	132.9	4.58	1.121
SCFT26-9-C10-1	92.7	2.31	1.015	SCFT33-7-C10-1	124.5	3.94	1.033
SCFT26-9-C10-2	93.3	2.35	1.015	SCFT33-7-C10-2	127.3	3.92	1.102
Avg. SCFT26-9-C10	93.0	2.33	1.015	Avg. SCFT33-7-C10	125.9	3.93	1.067
SCFT26-9-C12-1	90.7	2.14	0.963	SCFT33-7-C12-1	117.5	3.75	0.914
SCFT26-9-C12-2	91.0	1.93	0.939	SCFT33-7-C12-2	118.0	3.62	0.922
Avg. SCFT26-9-C12	90.9	2.04	0.951	Avg. SCFT33-7-C12	117.8	3.69	0.918
SCFT26-9-C14-1	83.7	1.94	0.688	SCFT33-7-C14-1	115.4	3.04	0.929
SCFT26-9-C14-2	87.9	2.24	0.863	SCFT33-7-C14-2	115.2	3.12	0.929
Avg. SCFT26-9-C14	85.8	2.09	0.776	Avg. SCFT33-7-C14	115.3	3.08	0.929

^aThe ultimate load of the SCFT specimens with $L/D = 2$ and 4 represents the load at the first peak axial load

Table 5. Comparison of experimental results with design provision in code for SCFT specimens

Group	Specimen	N_{exp} : kN	N_c : kN ^a	N_{exp}/N_c
SCFT26-9	SCFT26-9-C2	117.0	90.2	1.297
	SCFT26-9-C4	104.2	89.2	1.168
	SCFT26-9-C6	103.4	87.7	1.179
	SCFT26-9-C8	97.9	85.6	1.144
	SCFT26-9-C10	93.0	83.0	1.121
	SCFT26-9-C12	90.9	79.8	1.139
SCFT33-7	SCFT26-9-C14	85.8	76.3	1.124
	SCFT33-7-C2	164.0	126.6	1.295
	SCFT33-7-C4	143.1	125.1	1.144
	SCFT33-7-C6	137.2	122.7	1.119
	SCFT33-7-C8	132.9	119.3	1.114
	SCFT33-7-C10	125.9	115.1	1.094
	SCFT33-7-C12	117.8	110.1	1.070
	SCFT33-7-C14	115.3	104.6	1.103

^a N_c is the nominal member capacity of SCFT specimens calculated from the design standard

local elephant's foot buckling to global buckling. Figure 5 shows the typical failure modes of specimens in the groups UT26-9 and UT33-7.

Increasing the L/D ratio of specimens in the group UT26-9 from 2 to 14 decreased the ultimate load and corresponding axial deformation by 17% and 65.2%, respectively. For

Figure 2. Metal plugs: (a) UT26-9 steel tube plug and (b) UT33-7 steel tube plug (all dimensions are in mm)

Figure 3. Stress-strain behaviour of cold-formed UT specimens under axial tension

(a)

(b)

Figure 4. Load-deformation behaviour of UT specimens under axial compression: (a) group UT26-9 and (b) group UT33-7

specimens in the group UT33-7, increasing the L/D ratio from 2 to 14 decreased the ultimate load by 22.6%. However, for specimens in the group UT33-7 with L/D ratio of 2 and 4, the axial deformation corresponding to the ultimate axial load was less than that for specimens with L/D ratio of 6. The lower axial deformation of the specimens in the group UT33-7 with L/D ratio of 2 and 4 may be attributed to the larger D/t ratio compared to the specimens in group UT26-9. The formation of elephant's foot buckling in the one end of the specimen with the larger D/t ratio was faster than other specimens with smaller D/t ratios and hence the thinner tubes were less ductile (O'Shea and Bridge, 1997). For specimens in group UT33-7, the axial deformation corresponding to the ultimate load synchronised with elephant's foot buckling was less than the axial deformation corresponding to the ultimate axial load synchronised with global buckling. However, for specimens in group UT33-7, increasing the L/D ratio from 6 to 14 decreased the axial deformation corresponding to the ultimate load by 45%. The D/t ratio of specimens in group UT33-7 was 38.6% higher than the D/t ratio of specimens in group UT26-9. For UT specimens with a high D/t ratio, the influence of elephant's foot buckling on the axial deformation and ductility with L/D ratio of 2 and 4 was more significant than the influence of global buckling on the axial deformation and ductility of UT specimens with L/D ratio of 6.

Test results of SCFTs

Test results of SCFT specimens under axial compression are reported in Table 4. The axial load-axial deformation behaviours of the specimens in the groups SCFT26-9 and SCFT33-7 that were tested under axial compression are shown in Figure 6. For each group of steel tubes, two specimens were tested for each L/D ratio. It was observed that the two tested specimens for each L/D ratio experienced similar axial load-axial deformation behaviour. Consequently, the axial load-axial deformation of one of the two tested specimens (the first specimen) for each L/D ratio is shown in Figure 6. It was also observed from axial load-axial deformation behaviour of the tested specimens with L/D ratio of 2 and 4 that the load capacity continued to increase after yielding of the steel. This increase of axial load after peak load occurred because the length of the specimen was short and hence global buckling of the specimen did not occur. In the present study, however, the increasing axial load after the first peak of the specimens with L/D ratio of 2 and 4 was ignored and the first peak load was used for comparison. For specimens with L/D ratio ≥ 6 there was no load increase after the first peak load. Increase in the L/D ratio of the SCFT specimens decreased the ultimate axial load and corresponding axial deformation. For specimens in group SCFT26-9, increasing the L/D ratio from 2 to 14 decreased the ultimate axial load and the corresponding axial deformation by 26.7% and 41%, respectively. For specimens in group SCFT33-7, increasing the L/D ratio from 2 to 14 decreased the ultimate axial load and the corresponding axial

Figure 5. Typical failure modes of UT specimens: (a) group UT26·9 and (b) group UT33·7

deformation by 29·7% and 66%, respectively. For specimens with L/D ratio of 2 and 4, the influence of the D/t ratio on specimens in group SCFT33·7 was less than the influence of the D/t ratio on specimens in group UT33·7. In the SCFT

specimens with L/D ratio of 2 and 4, the elephant's foot buckling did not show any significant influence on the axial deformation and ductility because the infill concrete prevented the elephant's foot buckling.

Figure 6. Load-deformation behaviour of concrete-filled steel tube specimens under axial compression: (a) group SCFT26-9 and (b) group SCFT33-7

The failure modes of the specimens in groups SCFT26-9 and SCFT33-7 were similar. The failure mode of the SCFT specimens was significantly influenced by the L/D ratio. For SCFT specimens with L/D ratio of 2 and 4, the first peak load occurred with small bulges along the steel tube specimen. The small bulges extended due to an expansion of the infill concrete after the yielding of the steel tube. Afterwards, the specimens with L/D ratio of 2 showed a significant increase in the axial load capacity and the specimens with L/D ratio of 4 showed a slight increase in the axial load without any sudden loss of the axial load capacity and with significant ductility. The higher axial load capacity experienced by the SCFT specimens with L/D ratio of 2 and 4 was because the length of steel tubes was very short and the concrete inside the steel tubes prevented the elephant's foot buckling. The axial strain of SCFT

specimens with L/D ratio of 2 and 4 caused microcracking within the infill concrete of SCFT specimens and activated the confinement effect in the concrete. Finally, the specimens with L/D ratio of 2 and 4 failed due to crushing of the concrete core. The concrete crushing was caused by the increase in the outward local buckling of the steel tube. For specimens with L/D ratio ≥ 6 , the failure occurred due to global buckling of the specimens. The global buckling occurred after the yielding of the steel tube. The specimens with L/D ratio ≥ 6 gradually lost the axial load capacity due to the formation of small bulges in the middle of the steel tube. The gradual loss of the axial load capacity experienced by the SCFT specimens with L/D ratio ≥ 6 was because the concrete inside the steel tubes prevented the inward buckling of the UT specimens. The small bulges prevented the occurrence of sudden failure owing to global buckling of the specimen. Figure 7 shows the typical failure modes of the SCFT specimens.

The SCFT specimens showed higher axial load capacities compared to the UT specimens owing to the influence of the infill concrete. The average axial load capacity of the specimens in group SCFT26-9 was 30% higher than the average axial load capacity of the specimens in group UT26-9. Also, the average axial load capacity of the specimens in the group SCFT33-7 was 49% higher than the average axial load capacity of the specimens in group UT33-7. In addition, unlike the UT specimens, the axial load of the SCFT specimens with L/D ratio of 2 and 4 showed higher axial load capacity after yielding of the steel tube. The higher axial load capacity of the SCFT specimens with L/D ratio of 2 and 4 was a result of the concrete inside the steel tubes preventing the elephant's foot buckling. This led to an increase in the axial deformation of SCFT specimens with L/D ratio of 2 and 4 owing to activation of the confinement effect in the concrete. The concrete confinement significantly increased the axial load capacity of the SCFT specimens with L/D ratio of 2 and 4.

From the experimental results obtained for SCFT and UT specimens, the concrete enhancement factor (O'Shea and Bridge, 1996) was calculated, given in Table 4. The experimental concrete enhancement factor was calculated by dividing the confined concrete strength with the unconfined compressive strength of the SCC. The confined concrete strength was calculated by subtracting the contribution of UT from the load carrying capacity of the SCFT and dividing the remainder by the area of concrete infill. The average experimental concrete enhancement factor of specimens in group SCFT26-9 decreased from 1.577 to 1.015 when the L/D ratio increased from 2 to 10. The average experimental concrete enhancement factor of specimens in group SCFT33-7 decreased from 1.583 to 1.067 when the L/D ratio increased from 2 to 10. However, for specimens with L/D ratio ≥ 12 , the experimental concrete enhancement factor decreased to a value less than 1. The reduction of the experimental concrete enhancement factor to

Figure 7. Typical failure modes of concrete-filled steel tube specimens: (a) group SCFT26-9 and (b) group SCFT33-7

a value less than 1 was due to the effect of column slenderness (L/D). The SCFT specimens with L/D ratio ≥ 12 buckled before providing any confinement effect in the infill concrete. The global buckling of the SCFT specimens with L/D ratio ≥ 12 occurred at a strain in the infill concrete, which was lower than the strain necessary to induce microcracking in the infill concrete. Hence, the steel tube did not provide a confinement effect in the concrete. Rather, the steel tube buckled before reaching the unconfined compressive strength of the concrete. Hence, the concrete enhancement factor of the SCFT specimens with L/D ratio ≥ 12 was less than 1.

Analytical considerations

The American Standard ANSI/AISC 360-10 (AISC, 2010) was used to calculate the axial load capacity of the SCFT specimens under concentric axial load. The calculated results were compared with the experimental results. ANSI/AISC 360-10 (AISC, 2010) covers three components in the composite columns: steel tube, concrete infill and reinforcing steel bars. The design standard was briefly reviewed for composite

columns constructed with only two components: steel tube and concrete infill. The limits of the material parameters in ANSI/AISC 360-10 (AISC, 2010) for the design of CFT columns are: (a) the concrete compressive strength is ranged from 21 MPa to 70 MPa; (b) the yield tensile stress of the steel tube is less than 525 MPa; and (c) the amount of steel is more than 1% of the total cross-section. The limits for the minimum diameter of steel tubes are not explicitly described in ANSI/AISC 360-10 (AISC, 2010). However, to classify the local buckling effect, ANSI/AISC 360-10 (AISC, 2010) specifies limits for compact, non-compact and slenderness composite members based on the maximum D/t ratio of the steel tube. In the present study, only the limits of compact sections were reviewed to evaluate the applicability of code recommendations for SCFT specimens.

In ANSI/AISC 360-10 (AISC, 2010), design member capacity N_{cd} of a composite column is calculated by Equation 1.

$$1. \quad N_{cd} = \phi_{co} N_c$$

where ϕ_{co} is the partial safety factor for a composite column capacity that is equal to 0.75, and the nominal member capacity N_c is calculated by Equations 2 and 3.

$$2. \quad N_c = N_o \left[0.658^{(N_o/N_c)} \right], \quad \text{if } \frac{N_o}{N_c} \leq 2.25$$

$$3. \quad N_c = 0.877 N_o, \quad \text{if } \frac{N_o}{N_c} > 2.25$$

$$4. \quad N_o = f_y A_s + \alpha_1 f'_c A_c$$

$$5. \quad N_e = \frac{\pi^2 EI_c}{(k_e L)^2}$$

where N_o is the squashing capacity of the cross-section, N_e is the Euler elastic buckling capacity, f_y is the steel yield stress, f'_c is the concrete compressive strength, A_s and A_c are the steel and concrete cross-section areas, respectively, α_1 is the reduction factor for the filling concrete which is equal to 0.95 for circular section, k_e is the member effective length factor and L is the column length. The effective flexural stiffness EI_c of a cross-section of a composite column is calculated by Equation 6.

$$6. \quad EI_c = E_s I_s + C_3 E_c I_c$$

$$7. \quad C_3 = 0.6 + 2 \left(\frac{A_s}{A_s + A_c} \right) \leq 0.9$$

$$8. \quad E_c = 4700 \sqrt{f'_c} \text{ (MPa)}$$

where E_s and E_c are the modulus of elasticity of the steel and concrete, respectively, I_s and I_c are the second moment of area of the steel and concrete, respectively, and C_3 is the coefficient of concrete effective stiffness.

In order to compare the experimental results with prediction results based on the recommendations in ANSI/AISC 360-10 (AISC, 2010), the partial safety factor (ϕ_{co}) was taken as 1 in this study. The ratios of experimental results to the estimate from the design standard (N_{exp}/N_c) for SCFT specimens is reported in Table 5. The values of average nominal member capacity N_c predicted by the design standard were found to be conservative. The average N_{exp}/N_c ratios for the specimens in groups SCFT26.9 and SCFT33.7 were 1.167 and 1.134, respectively, with standard deviations of 0.061 and 0.075,

respectively. It is noted here that the above comment does not constitute a criticism of the recommendations in ANSI/AISC 360-10 (AISC, 2010), as the design recommendations in ANSI/AISC 360-10 (AISC, 2010) are not intended for SCFT specimens.

Conclusions

Based on the experimental investigation presented in this study, the following conclusions can be drawn.

- The axial load capacity of SCFT specimens was found to be higher than the axial load capacity of corresponding UT specimens owing to the effect of the concrete infill. The average axial load capacity of the specimens in groups SCFT26.9 and SCFT33.7 were 30% and 49% higher than the average axial load capacity of the specimens in groups UT26.9 and UT33.7, respectively. The greater effect of the infill concrete was observed for specimens tested with L/D ratio of 2 and 4.
- For L/D ratios of 2 and 4, the compressive failure in the UT specimens occurred as a result of local elephant's foot buckling. However, the compressive failure in the SCFT specimens was different to the compressive failure in the UT specimens. For SCFT specimens with L/D ratio of 2 and 4, the first peak axial load occurred with small bulges along the steel tube specimen. Then, the axial load continued to increase due to extension of small bulges during the compression test. The small bulges were extended as an expansion of the concrete core after the steel yielding. Finally, the specimens failed by crushing the concrete core owing to an increase in outward local buckling of the steel tube.
- For L/D ratio ≥ 6 , the compressive failure modes of UT specimens changed from local elephant's foot buckling to global buckling. Global buckling failure was observed to occur as a bend in a sharp angle near the mid-height of the tube (inward buckling). For SCFT specimens, the failure also occurred because of global buckling of the specimens. However, the SCFT specimens with L/D ratio ≥ 6 gradually lost the axial load capacity due to the formation of small bulges in the middle of the steel tube. The small bulges prevented the occurrence of sudden failure as a result of global buckling of the specimen.
- The design recommendations in ANSI/AISC 360-10 (AISC, 2010) for CFT columns conservatively predicted the experimental axial load capacity of the SCFT.

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