Ultimate Capacity Estimate of Self-Compacting Concrete-Filled Small Diameter Steel Tubes under Axial Load

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Abstract

This study explores the effect of length to diameter (L/D) ratio on the axial load capacity of self-compacting concrete-filled small diameter steel tube (SCFT) specimens. The SCFT specimens with L/D ratio of 2, 4, 6, 8, 10, 12 and 14 were tested. Two different cold-formed steel tubes were used in the construction of the SCFT specimens. For each L/D ratio, two specimens were tested. For tension tests, three specimens were tested for each type of unfilled steel tube. A total of 62 steel tube specimens were tested which included 6 specimens under axial tension and 56 specimens under axial compression. The experimental results of the SCFT specimens were compared with the estimates from three design standards: American Standard, Canadian Standard and European Standard (Eurocode 4). It was found that Eurocode 4 provided the best estimate, whereas American Standard provided the most conservative estimate. Also, when the L/D ratio of SCFT specimens increased from 2 to 8, the parameter related to the effect of confinement concrete (η_c) which is calculated from Eurocode 4 decreased. Therefore, the decrease in η_c resulted in a decrease in the concrete enhancement factor. For SCFT specimens with L/D ratio $\geq$ 10 the parameter η_c was negligible and resulted in the concrete enhancement factor =1.

***Keywords**: Concrete-filled steel tube, Self-compacting concrete, Axial load, Length to diameter ratio.*

1. INTRODUCTION

In recent years cold-formed steel tubes have become more popular as a structural member due to its high yield stress (Alhussainy et al. 2017). One of the main applications of cold-formed steel tubes is concrete-filled steel tube (CFT). The CFT is constructed by filling steel tubes with concrete. The advantages of the CFT are high ultimate capacity, ductility, seismic resistance and fire resistance (Shanmugam and Lakshmi 2001; Huang et al. 2015). Due to the above mentioned advantages, CFTs have been widely used as columns for bridges and high-rise buildings (Abed et al. 2013). The CFT is also used in composite column that consists of inner CFT and outer reinforced concrete (Han and An 2014). Recently, Hadi et al. (2017) proposed using small diameter CFTs in lieu of longitudinal steel bars for reinforcing concrete columns. The innovative use of CFTs was found to be efficient due to the increase in the axial capacity and ductility (Hadi et al. 2017). In addition, CFT members can be effectively adopted for structural components where small cross-sections are required.

Li et al. (2015) compared experimental data of CFT columns with three design standards (American Standard ANSI/AISC 360-10 2010; European Standard Eurocode 4 2004 and Chinese Standard CECS 28-12 2012). Li et al. (2015) reported that all three design standards provided conservative estimates for both short and long CFT columns. Aslani et al. (2015) developed simplified relationships to predict the section capacity and ultimate buckling capacity of normal and high-strength concrete filled short and long CFTs. Aslani et al. (2015) considered that the slenderness reduction factor was modified based on the adjusted formula of section capacity.

The behaviour of steel tubes filled with concrete has been extensively studied and included in major design standards (American Standard ANSI/AISC 360-10 2010; Canadian Standard CAN/CSA S16-09 2009; and European Standard Eurocode 4 2004). A large number of studies were carried out on medium scale specimens with outside diameter between 100 mm and 200 mm using concrete of varying compressive strengths. However, research studies have seldom been conducted on small diameter concrete filled steel tubes. In this study, steel tubes with small diameters were used as CFT. The results of the axial load capacity of SCFT with different L/D ratios were compared to the estimates from three design standards. Also, experimental concrete enhancement factors of the SCFT specimens were calculated and compared with the estimates from the Eurocode 4.

2. EXPERIMENTAL PROGRAM

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

Self-compacting concrete (SCC) mix with a maximum aggregate size of 10 mm was used in casting the SCFT specimens. The average 28-day compressive strength of the SCC was 57 MPa.

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. 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.

Three samples of each UT26.9 and UT33.7 steel tubes were tested according to ASTM A370 (2014). Yield stresses of both unfiled steel tubes were determined using the 0.2% offset method, as clearly defined yield stress was not observed. The average yield stress and modulus of elasticity of UT26.9 steel tube were found as 355 MPa and 192 GPa, respectively. The average yield stress and modulus of elasticity of UT33.7 steel tube were found as 450 MPa and 196 GPa, respectively.

3. COMPARISON OF EXPERIMENTAL RESULTS WITH DESIGN STANDARDS

Three different design standards were used to calculate the axial load capacity of the self-compacting concrete-filled steel tube (SCFT) specimens under concentric axial load. The calculated results were compared with the experimental results. The design standards included in this study were the American Standard (ANSI/AISC 360-10 2010), Canadian Standard (CAN/CSA S16-09 2009) and European Standard (Eurocode 4 2004). The design standards for composite columns constructed with only two components: steel tube and concrete infill are briefly reviewed below.

In the American Standard (ANSI/AISC 360-10 2010), the nominal member capacity N_c is calculated by Eqs. (1) and (2).

$$N_c = N_o \left[0.658^{\left(\frac{N_o}{N_e}\right)}\right], \qquad \text{If } \frac{N_o}{N_e} \leq 2.25 \tag{1}$$

$$N_c = 0.877\, N_e, \qquad \text{If } \frac{N_o}{N_e} > 2.25 \tag{2}$$

$$N_o = f_y\, A_s + \alpha_1\, f_c'\, A_c \tag{3}$$

$$N_e = \frac{\pi^2\, EI_e}{(k_e\, L)^2} \tag{4}$$

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_e of a cross section of a composite column is calculated by Eq. (5).

$$EI_e = E_s\, I_s + C_3\, E_c\, I_c \tag{5}$$

$$C_3 = 0.6 + 2\left(\frac{A_s}{A_s + A_c}\right) \le 0.9 \tag{6}$$

where E_s and E_c are the elastic moduli 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 the Canadian Standard (CAN/CSA S16-09 2009), the nominal member capacity is calculated by Eq. (7).

$$N_c = (\tau\ f_y\ A_s + \tau'\, \alpha_1\, f_c'\, A_c)\,(1 + \lambda^{2n})^{-1/n} \tag{7}$$

$$\alpha_1 = 0.85 - 0.0015\, f_c' \quad \ge 0.67 \tag{8}$$

where n =1.8 for a composite concrete filled steel tube, τ is the parameter of reducing steel capacity, τ' is the parameter of increasing concrete capacity due to confinement by steel tube.

τ = τ'= 1.0, except for circular steel tube sections with a length to outside diameter (L/D) ratio less than 25 for which:

$$\tau = \frac{1}{\sqrt{1+\rho+\rho^2}} \tag{9}$$

$$\rho = 0.02(25 - L/D) \tag{10}$$

$$\tau' = \left(\frac{25\ \rho^2\ \tau}{D/t}\right)\left(\frac{f_y}{\alpha_1\, f_c'}\right) + 1 \tag{11}$$

$$\lambda = \sqrt{\frac{N_o}{N_e}} \tag{12}$$

where t is the wall thickness of steel tube, λ is the relative slenderness, $N_o = N_c$ (computed with $\lambda = 0$), the Euler elastic buckling capacity N_e is calculated by Eq. (4). The effective flexural stiffness EI_e is calculated by Eq. (5) and the coefficient C_3 is calculated by Eq. (13).

$$C_3 = \frac{0.6}{1 + C_{fs}/C_f} \tag{13}$$

where C_{fs} and C_f are sustained and total axial load on the column, respectively.

The European Standard (Eurocode 4 2004) provides more detailed expression to estimate the effect of the confinement concrete due to steel circular tube. The nominal member capacity N_c is calculated by Eq. (14).

$$N_c = x\left[\eta_a\, f_y\ A_s + f_c'\, A_c\left(1 + \eta_c\, \frac{t}{D}\, \frac{f_y}{f_c'}\right)\right] \tag{14}$$

where η_a is a reduction factor for the steel strength and η_c is a factor related to the effect of confinement concrete. The factors η_a and η_c are functions of the relative slenderness λ which is calculated by Eq. (15). The squashing capacity of the cross-section N_o is calculated by Eq. (4) and by using the reduction factor for the filling concrete α_1 which is equal to 1. The Euler elastic buckling capacity N_e is calculated by Eq. (4). The effective flexural stiffness EI_e of a cross section of a composite column is calculated by Eq. (5) and by using the coefficient C_3 which is equal to 0.6.

For columns having slenderness λ > 0.5, there is no gain from confinement effect and η_a =1 and η_c =0. For columns having no eccentricity (e = 0), the coefficients η_a and η_c are calculated as:

$\eta_a = \eta_{ao} = 0.25(3 + 2\lambda)$, (but ≤ 1) (15)

$\eta_c = \eta_{co} = 4.9 - 18.5\lambda + 17\lambda^2$, (but ≥ 0) (16)

The function x provides the resistance reduction for slender columns, in terms of the relative slenderness λ, as shown in Eq. (12). For columns having relative slenderness $\lambda \leq 0.2$, the resistance reduction x =1.

$$x = \frac{1}{\varphi + \sqrt{\varphi^2 - \lambda^2}} \quad \text{(but} \leq 1\text{)} \quad (17)$$

$$\varphi = 0.5[1 + 0.21(\lambda - 0.2) + \lambda^2] \quad (18)$$

In order to compare the experimental results with prediction results based on the recommendations in the design standards, the partial safety factors for the design standards were taken equal to 1 in this study. The ratios of experimental results to the estimates from design standards (N_{SCFT}/N_c) for SCFT specimens are reported in Table 1. The values of average nominal member capacity N_c predicted by the design standards were found to be not very different from the experimental average ultimate load capacity N_{SCFT} for the SCFT specimens. The average N_{SCFT}/N_c ratios were close to 1 for the Eurocode 4 (2004), less than 1 for the CAN/CSA S16-09 (2009) and higher than 1 for ANSI/AISC 360-10 (2010). For the ANSI/AISC 360-10 (2010), the average N_{SCFT}/N_c ratios for the specimens in Group SCFT26.9 and Group SCFT33.7 were 1.167 and 1.134, respectively, with standard deviations of 0.061 and 0.075, respectively. For the CAN/CSA S16-09 (2009), the average N_{SCFT}/N_c ratios for the specimens in Group SCFT26.9 and Group SCFT33.7 were 0.933 and 0.888, respectively, with standard deviations of 0.018 and 0.024, respectively. For the Eurocode 4 (2004), the average N_{SCFT}/N_c ratios for the specimens in Group SCFT26.9 and Group SCFT33.7 were 1.060 and 1.018, respectively, with standard deviations of 0.057 and 0.048, respectively.

Table 1. Comparison of experimental results with design provisions in codes for SCFT specimens

L/D	N_{SCFT} (kN)[a]	N_c (kN)[b]			N_{SCFT}/N_c		
		ANSI/AISC	**CAN/CSA**	**EC4[c]**	**ANSI/AISC**	**CAN/CSA**	**EC4[c]**
Specimens constructed by using steel tube ST26.9							
2	117	90.2	122.5	119.4	1.297	0.955	0.98
4	104.2	89.2	116.2	106.4	1.168	0.897	0.979
6	103.4	87.7	110.3	95.5	1.179	0.937	1.083
8	97.9	85.6	104.9	88.0	1.144	0.933	1.112
10	93	83	100.1	84.4	1.121	0.929	1.101
12	90.9	79.8	95.9	82.8	1.139	0.948	1.098
14	85.8	76.3	92.3	80.3	1.124	0.929	1.068
Specimens constructed by using steel tube ST33.7							
2	164	126.6	175.2	170.5	1.295	0.936	0.962
4	143.1	125.1	165.7	150	1.144	0.864	0.954
6	137.2	122.7	156.9	132.9	1.119	0.875	1.032
8	132.9	119.3	148.8	122.3	1.114	0.893	1.087
10	125.9	115.1	141.5	119.1	1.094	0.890	1.057
12	117.8	110.1	135.1	114.6	1.070	0.872	1.028
14	115.3	104.6	129.6	114.0	1.103	0.889	1.011

[a] N_{SCFT} is the average ultimate load capacity of two SCFT specimens tested under axial compression.
[b] N_c is the nominal member capacity of SCFT specimens calculated from three design standards.
[c] EC4 is the Eurocode 4 (2004).

The experimental value for the concrete enhancement factor (O'Shea and Bridge 1996) was calculated by dividing the confinement concrete strength (f_{cc}) on the compressive strength of SCC. The confinement concrete strength f_{cc} was calculated by subtracting the unfilled steel tube capacity (N_{UT}) from the concrete-filled steel tube capacity (N_{SCFT}) and dividing the remainder by the infill concrete area (A_c). Also, Eurocode 4 was used to calculate theoretically the concrete enhancement factor of the SCFT specimens with different L/D ratios (Shanmugam and Lakshmi 2001; O'Shea and Bridge

1996). The theoretically concrete enhancement factor was calculated based on the term $\left(1 + \eta_c \frac{t}{D} \frac{f_y}{f'_c}\right)$ in the Equation 14 (Eurocode 4 2004). Table 2 presents the experimental and theoretical values for the concrete enhancement factor of the SCFT specimens. When the L/D ratio of SCFT specimens increased from 2 to 8, the parameter η_c calculated from Eurocode 4 (2004) decreased and resulted in decreasing the concrete enhancement factor. For SCFT specimens with L/D ratio ≥ 10 the parameter η_c was negligible and resulted in the concrete enhancement factor =1. Also, the experimental concrete enhancement factor of SCFT specimens decreased when the L/D ratio increased from 2 to 10. However, for specimens with L/D ratio ≥ 12 the experimental concrete enhancement factor continued to decrease to a value less than 1, unlike the theoretical concrete enhancement factor which remained constant at 1. The concrete enhancement factor from Eurocode 4 (2004) is only valid for a relative slenderness lower than 0.5. Therefore, specimens with L/D ratio ≥ 12 tested in this study are considered out of scope.

Table 2. Experimental and theoretical values for the concrete enhancement factor of SCFT specimens

L/D	N_{UT} (kN)[a]	N_{SCFT} (kN)[b]	f_{cc} (MPa)[c]	f_{cc}/f'_c Concrete enhancement factor (Exp.)	Parameter η_c Eurocode 4 (2004)	Concrete enhancement factor (Theo.) $\left(1 + \eta_c \frac{t}{D} \frac{f_y}{f'_c}\right)$
Specimens constructed by using steel tube ST26.9						
2	83.8	117	89.8	1.575	3.325	3
4	81.3	104.2	61.9	1.086	2.045	2.231
6	78.9	103.4	66.2	1.161	1.059	1.637
8	73.5	97.9	66	1.158	0.368	1.222
10	71.6	93	57.9	1.016	0	1
12	70.8	90.9	54.3	0.953	0	1
14	69.5	85.8	44.1	0.774	0	1
Specimens constructed by using steel tube ST33.7						
2	101.5	164	90.2	1.582	3.202	2.5
4	100.2	143.1	61.9	1.086	1.853	1.868
6	93.8	137.2	62.6	1.098	0.851	1.399
8	88.6	132.9	63.9	1.121	0.198	1.093
10	83.8	125.9	60.8	1.067	0	1
12	81.5	117.8	52.4	0.919	0	1
14	78.6	115.3	53	0.930	0	1

[a] N_{UT} is the average ultimate load capacity of two unfilled steel tube specimens tested under axial compression.
[b] N_{SCFT} is the average ultimate load capacity of two concrete-filled steel tube specimens tested under axial compression.
[c] f_{cc} is the confinement concrete strength.

4. CONCLUSIONS

Based on the experimental and analytical results presented in this study, the following conclusions can be drawn:

1. Based on the experimental results of self-compacting concrete-filled small diameter steel tubes (SCFT) and unfilled small diameter steel tube (UT) specimens, the SCFT specimens showed a higher increase of axial load capacity compared to the UT specimens due to the effect of the concrete infill.

2. The ratio of experimental results to the estimates from design standards (N_{SCFT}/N_c) for SCFT specimen was found to be close to 1 for Eurocode 4 (2004), less than 1 for CAN/CSA S16-09 (2009) and higher than 1 for ANSI/AISC 360-10 (2010).

3. When the L/D ratio of SCFT specimens increased from 2 to 8, the parameter related to the effect of confinement concrete (η_c) which was calculated from Eurocode 4 decreased. Therefore, the decrease in η_c resulted in a decrease in the concrete enhancement factor. For SCFT specimens with L/D ratio ≥ 10 the parameter η_c was negligible and resulted in the concrete enhancement factor =1.

4. The experimental concrete enhancement factor of SCFT specimens decreased when the L/D ratio increased from 2 to 10. However, for specimens with L/D ratio $\geq$ 12 the experimental concrete enhancement factor continued to decrease to a value less than 1, unlike the theoretical concrete enhancement factor which remained constant at 1.

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