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Research paper

The Strength Index of Short and Slender Circular Concrete-Filled Steel Tube Columns

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Abstract

The factors affecting the sectional capacity, also known as strength index (*SI*) of concrete-filled steel tube columns (CFSTC) are, among others, type of cross-section and slenderness ratio (L/D). This study is to determine the effects of slenderness ratio of short ($L/D \leq 3.4$) and slender ($L/D \leq 10$) circular CFSTC on the *SI*. Concentric load tests were conducted to determine the ultimate strength (N_{ue}) of ten circular sections of short and slender CFSTC with ordinary Portland cement concrete (OPCC) and pozzolan concrete (PC) infills. The *SI* are determined using several design codes. Results show that the *SI* for short CFSTC is higher than the slender for circular section. This is because of the effect of the L/D of short and slender CFSTC circular section. It shows that the composite action between steel tube and core concrete for short is more efficient than slender circular columns. The results also show that similar compressive strength concrete (f_{cu}) infills, either comprises of OPCC or PC do not affect the the *SI* values. Different design codes provide different concrete confinement safety coefficients thus the difference in the *SI* values. AISC (LRFD) provides the highest *SI* for both short and slender CFSTC. Whereas, EC4 and AS5100.6 provide the lowest *SI* for short and AIJ provides lowest *SI* for slender circular sections. The lowest calculated values of *SI* show the most efficient design of composite column.

Keywords: *Concentric load, high strength concrete, stress-strain, structural behaviours, ultimate strengths.*

1. Introduction

Concrete filled steel tube columns (CFSTC) are valuable structural members compared to separate reinforced concrete columns or hollow steel columns. CFSTC combine the best characteristics of both steel and concrete materials, that is, CFSTC have high strength, high ductility, and high stiffness. The advantage of CFSTC is that the steel tube serves as a form for casting the concrete, which reduces construction cost. Also, no other reinforcement is needed since the tube acts as longitudinal and lateral reinforcement for the concrete core. In addition, the placement of longitudinal steel at the perimeter of the section is the most efficient use of the material since it provides the highest contribution of the steel to the section moment of inertia and flexural capacity. The continuous confinement provided to the concrete core by the steel tube enhances the core's strength and ductility. The concrete core delays local buckling of the steel tube by preventing inward buckling, while the steel tube prevents the concrete from spalling.
A strength index (*SI*) is to quantify the section strength:

$$SI = N_{ue}/N_{uo} \quad (1)$$

where, N_{ue} is experimental ultimate strength, while, $N_{uo} = A_s f_y + 0.85 A_c f_{cu}$, giving the sectional capacity in ACI [1] or the N_{uo} values are calculated using formulas provided by design codes such as EC4 [2], AIJ [3], AISC (LRFD) [4], BS5400 [5], AS3600 [6], AS (AS4100, AS3600, ACI2005) [7] and AS5100.6 [7]. Table 1 shows the N_{uo} provided by those codes. It is important to investigate the differences in *SI* values when different codes are used, as well as to analyze *SI* values for short and slender CFSTC of circular and rectangular cross-sections when filled with different types of concrete.

Table 1: Load capacity formulas provided by design codes

Codes	Load Capacity Formulas
EC4	$N_u = \eta_a A_a f_y + A_c f_c \left(1 + \eta_c \frac{t}{D}\frac{f_y}{f_c}\right)$
ACI	$N_u = 0.85 A_c f_c + A_a f_y$ $N_u = 1.3 A_c f_c + A_a f_y$ (modified)
AISC (LRFD)	$N_u = A_a F_{cr}$
DBJ13-15	$N_u = A_{sc} f_{scy}$
AIJ	$N_{u1} = N_{cu,c} + (1+\eta) N_{cu,s}, \left(\frac{l}{D} \leq 4\right)$

	$N_{u2} = N_{u1} - 0.125\left(N_{u1} - N_{u3}\left(\frac{l}{D} - 12\right)\right)\left(\frac{l}{D} - 4\right), \left(4 < \frac{l}{D} \leq 12\right)$
	$N_{u3} = N_{cr,c} + N_{cr,s}, \left(\frac{l}{D} > 12\right)$
AS 5100.6	$N_u = \alpha_c\left(\eta_2 A_s f_y + \left(1 + \frac{\eta_1 + f_y}{d_o f'_c}\right) A_c f'_c\right)$
AS	$N_u = A_s f_y + 0.85 A_c f'_c$
CECS28:90	$N_u = \rho_1 \rho_e N_o$
	$N_o = A_c f'_{c,pr}\left(1 + \sqrt{\xi} + \xi\right)$
HONG KONG	$N_u = \eta_a A p_y + 0.53 A_c f_{cu}\left(1 + \eta_c \frac{t}{d}\frac{p_y}{0.8 f_{cu}}\right)$
BS5400	$N_u = A_s f_y + 0.675 A_c f_{cu}$

Previous researchers [8], [9] and [10] had investigated the *SI* for CFSTC specimens and reported that the *SI* of circular sections are significantly higher than that of the columns with square or rectangular sections. This is due to the composite action between steel tube and core concrete where constraining factor (ξ) as defined by $A_s f_y / A_c f_{cu}$ for circular columns is more efficient than columns with square or rectangular sections. Their results had shown that different types of concrete with different concrete fillings such as self-compacting concrete (SCC) and dune sand concrete do not affect the *SI* values of the composite columns. Their studies also had shown that the *SI* values of circular sections are higher than the square or rectangular sections of CFSTC.The reason is because of the composite action between steel tube and core concrete for circular columns is more efficient than columns with square or rectangular sections. It was due to the good confinement of the circular steel tube to the core concrete.

The current research is to study the effect of slenderness ratio of short ($L/D \leq 3.4$) and slender ($L/D \leq 10$) circular CFSTC infilled with high strength concrete (HSC) using activated alum sludge ash (AASA), a type N pozzolan, which is a waste by-product material from drinking water treatment plant, as replacement of ordinary Portland cement (OPC), named as pozzolan concrete (PC) and compared with OPC concrete (OPCC). Then, this study analyzes the value of *SI* and the factors affecting it. The *SI* values are analysed using several codes namely ACI [1], EC4 [2], AIJ [3], AISC (LRFD) [4], BS5400 [5], AS3600 [6], AS (AS4100, AS3600, ACI2005) [7] and AS5100.6 [7] to observe the difference in *SI* values using these different codes.

2. Methodology

There are two mix designs for each OPCC and PC i.e. OPCC-1 and OPCC-2, and, PC-1 and PC-2 where for each, the differences are in the percentages dosage of chemical additives ie superplasticizer (SP), 1.5%, 1.0%, 5.0% and 7.0%, respectively. Ten samples of short and slender circular CFSTC sections were tested. All the samples were tested to obtain the N_{ue} for each sample containing different concrete strengths (f_{cu}). Axial concentric load tests were done on the hollow steel tube and the CFSTC.

2.1. Material properties

The material properties to calculate the N_{uo} are based on experimental values of the coupon tensile test of steel tube and compressive strength test of the HSC.

2.1.1. Tensile coupon test

Table 2 shows the properties of four coupon samples of mild steel sheet from the circular (C1, C2, C3, C4) tube. They were tested to determine the yield strength (f_y) of steel tube according to the ASTM E8 [11]. It was important to determine the actual f_y of the steel tubes because f_y affects the ultimate strength (N_{ue}) of the columns as the part of steel confinement that are provided in each code. The stress-strain diagrams of circular steel tubes are shown in Fig. 1. The average f_y and the modulus of elasticity (E_s) of circular steel tube are recorded as 304.0 MPa and 79.4 GPa, respectively. These values are used in the calculation to determine the N_{uo} of the composite columns.

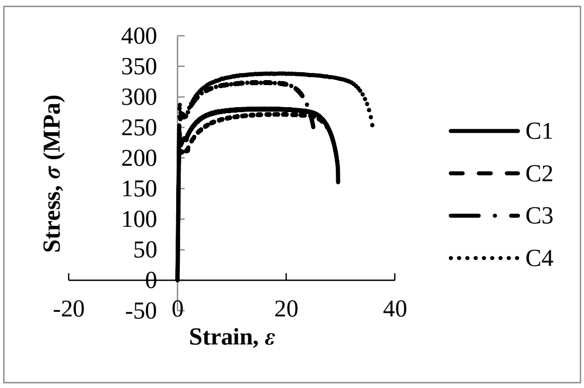

Fig. 1: Stress-strain relationship of circular steel tube

Table 2: Steel properties of circular section

Samples	f_y (MPa)	E_s (GPa)
C1	280.9	77.9

C2	272.0	75.8
C3	324.2	82.3
C4	338.9	81.7

2.1.2. Compressive strength test of HSC

There are four mixes of concrete (OPCC I and II and PCI and II) considered as the concrete-infilled in the composite columns. The PC includes waste materials, i.e. thermally activated alum sludge ash (AASA) and silica fume (SF) [12]. The HSC is designed based on ACI 211.4R standards [13, 14], with physical properties of aggregates (following ASTM C 127 [15] and ASTM C 128 [16]: maximum diameter (mm) ≤ 4.75 and 10 mm; specific gravity 2.68 and 2.51; absorption 1.63 and 0.53 for fine and coarse, respectively. The Fineness Modulus of sand is 2.48. The mixed proportions and the properties of concrete (f_{cu} and the modulus of elasticity (E_c) of OPCC and PC) mixes are shown in Table 3 and Table 4. For each concrete batch, at least three concrete cube specimens (150 mm× 150 mm× 150 mm) were tested to obtain the f_{cu} and the E_c.

Table 3: Mix proportions of concrete

Mix Description	OPCC-1	OPCC-2	PC-1	PC-2
w/b ratio	0.3		0.3	
Water (kg/m^3)	169.0		168.3	
Fine Aggregate (kg/m^3)	688.0		662.5	
Coarse Aggregate (kg/m^3)	990.0		989.5	
Cement (kg/m3)	529.0		365.1	
AASA (kg/m^3)	-		132.3	
SF (kg/m^3)	-		31.7	
SP (%)	1.5	1.0	7.0	5.0

Table 4: Properties of concretes

Types of concrete	Compressive Strength (f_{cu})	Elastic Modulus (E_c)
OPCC-1	62.5	40.5
OPCC-2	60.8	39.9
PC-1	51.2	36.6
PC-2	68.1	42.2

3. Axial concentric load test of CFST

The dimensions of the circular cross-sections tested in axial concentric load are 165 mm (D) and 2.5 mm (t). The h of columns are 500 mm and 510 mm for short columns and 1500 mm for slender columns. The total number of samples are 10 altogether. Table 5 shows the code designation of each sample.

Table 5: Code designation of samples

Code	Cross section	Type of column	Type of Infilled
C(S)I	Circular	Short	Hollow
C(L)I	Circular	Slender	Hollow
C(S)II- HSC(OPCC-1)	Circular	Short	OPCC-1
C(L)II- HSC(OPCC-1)	Circular	Slender	OPCC-1
C(S)II- HSC(OPCC-2)	Circular	Short	OPCC-2
C(L)II- HSC(OPCC-2)	Circular	Slender	OPCC-2
C(S)III- HSC(PC-1)	Circular	Short	PC-1
C(L)III- HSC(PC-1)	Circular	Slender	PC-1
C(S)III- HSC(PC-2)	Circular	Short	PC-2
C(L)III- HSC(PC-2)	Circular	Slender	PC-2

Fig. 2 and Fig. 3 show the test setup of the samples during the experiment. The tests were performed using a 2500 kN capacity universal testing machine. The specimen was placed in the testing machine and the load was applied on the specimen directly. The loading ram is a solid steel plate, which acts like an end stiffener. Twenty-six strain gauges are used for each CFST, while twelve strain gauges are for hollow steel tubes. Six linear voltage-displacement transducers (LVDTs) were used to measure the axial deformation. A load interval of less than one tenth of the estimated carrying load capacity was applied. Each load interval was maintained for about 2 min.

Fig. 2: Test setup of short circular CFSTC (h = 500, 510 mm)

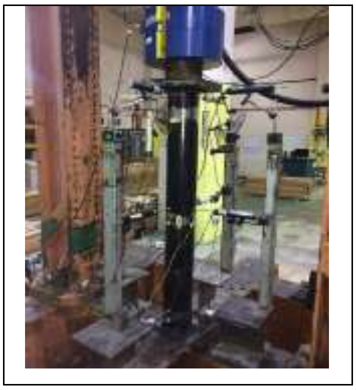

Fig. 3: Test set up of slender circular CFSTC (h = 1500 mm)

4. Results and discussion

The *SI* values of short and slender circular sections are influenced by the L/D and N_{ue} of the composite columns. Also, different design codes provide different concrete confinement safety coefficients thus the difference in the *SI* values. The following subsections discuss further on these factors.

4.1 Slenderness ratio

Table 6 and Table 7 show the N_{ue} for each sample and the *SI* values of the short and slender CFSTC circular sections with two concrete-infilled types (OPCC-1, OPCC-2, PC-1 and PC-2) calculated using different codes (Eq. 1 and Table 1). C(S)I are control samples to compare the *SI* between hollow steel tube columns and composite columns. Table 6 (short columns) shows higher values of *SI* for most of the infilled mixes compared to the same mixes in Table 7 (slender columns). The difference in the *SI* values between the short and slender columns are due to the low slenderness ratio (L/D) of short circular ($L/D \leq 3.4$) compared to the high slender circular section ($L/D \leq 10$). The lower value of L/D will give a higher *SI* value for CFSTC. Table 6 also shows that C(S)III-HSC(PC-1) having the highest *SI* values in the range between 1.10 to 1.66 for all codes. Meanwhile, Table 7 shows C(L)III-HSC(PC-2) having the highest *SI* values of 0.77 to 1.50 calculated using all codes. From both results, it can be seen that the *SI* values for the short circular is higher than the slender circular section and the differences is about 32%. This indicates that L/D is significantly affecting the value of *SI* composite columns. Results show that short circular sections are more efficient compared with slender circular sections.

4.2 Ultimate experimental capacity of CFSTC

In addition, N_{ue} also affects the value of *SI*. Table 6 shows, for short columns, when the value of N_{ue} is low (N_{ue} = 1568 kN for C(S)III-HSC(PC-1)), it provides high *SI* values compared to other concrete infills. Table 7 shows, for slender columns, at high N_{ue} value (N_{ue} = 1747 kN), it provides high *SI* for C(L)III-HSC(PC-2). This is due to the higher constraining factor (ξ) for short circular ($\xi = 0.38$) compared to the slender circular section ($\xi = 0.28$). It has been shown that L/D and N_{ue} affect the *SI* values of composite columns.

4.2 Type of CFSTC infilled

Table 4 shoes the properties of concrete infilled. The f_{cu} of OPCC-1, OPCC-2, PC-1, and PC-2 are 62.5, 60.8, 51.2 and 68.1 MPa, respectively. It can be seen that the PC attained nearly the same f_{cu} eventhough waste material (AASA) was used as concrete component replacing OPC. These results show that, if other type of concrete is used, instead of OPCC, if the design strength is at par with OPCC, it can be used as equivalent infilled. Thus, AASA is a potential OPC replacement in concrete and can be included as concrete materials for infilled.

4.2 Provisions of different codes

Table 6 and 7 indicate that the *SI* provided by AISC (LRFD) is the highest for circular short and slender sections because AISC (LRFD) provides the lowest concrete confinement safety coefficient value in N_{uo} calculation compared to other codes. Also, it is found that EC4 and AS5100.6 provide the lowest *SI* values for the circular section, compared to other codes for all concrete-infilled types. This is because of the high concrete confinement safety coeficient values provided in the calculation of N_{uo} values by EC4 and AS5100.6 compared to other codes. The lowest calculated values of *SI* show the most efficient design of composite column. Consequently, this results have shown that the values of the concrete confinement safety coefficient are very important and must be taken into consideration in structural design to differentiate between analytical calculation and simulation.

Table 6: Strength index of short columns

Spec.	N_{ue} (kN)	$SI_{(ACI)}$	$SI_{(EC4)}$	$SI_{(AIJ)}$	$SI_{(AISC(LRFD))}$
C(S)I	316	0.82	0.82	0.64	1.09
C(S)II- HSC(OPCC-1)	1644	1.13	1.00	1.05	1.51
C(S)II- HSC(OPCC-2)	1575	1.10	0.98	1.03	1.47
C(S)III- HSC(PC-1)	1568	1.24	1.11	1.15	1.66
C(S)III- HSC(PC-2)	1606	1.03	0.91	0.97	1.38

Spec.	N_{ue} (kN)	$SI_{(BS5400)}$	$SI_{(AS3600)}$	$SI_{(AS)}$	$SI_{(AS5100.6)}$
C(S)I	316	0.82	0.78	0.82	0.82
C(S)II- HSC(OPCC-1)	1644	1.33	1.13	1.13	1.00
C(S)II- HSC(OPCC-2)	1575	1.30	1.10	1.10	0.98
C(S)III- HSC(PC-1)	1568	1.45	1.24	1.24	1.11

C(S)III- HSC(PC-2)	1606	1.22	1.03	1.03	0.91

Table 7: Strength index of slender columns

Spec.	N_{ue} (kN)	$SI_{(ACI)}$	$SI_{(EC4)}$	$SI_{(AIJ)}$	$SI_{(AISC(LRFD))}$
C(L)I	398	1.03	1.03	0.74	1.37
C(L)II- HSC(OPCC-1)	1561	1.07	0.95	0.73	1.43
C(L)II- HSC(OPCC-2)	1591	1.12	0.99	0.76	1.49
C(L)III- HSC(PC-1)	1387	1.10	0.98	0.75	1.46
C(L)III- HSC(PC-2)	1747	1.13	0.99	0.77	1.50

Spec.	N_{ue} (kN)	$SI_{(BS5400)}$	$SI_{(AS3600)}$	$SI_{(AS)}$	$SI_{(AS5100.6)}$
C(L)I	398	1.03	0.98	1.03	1.03
C(L)II- HSC(OPCC-1)	1561	1.26	1.07	1.07	0.95
C(L)II- HSC(OPCC-2)	1591	1.31	1.12	1.12	0.99
C(L)III- HSC(PC-1)	1387	1.28	1.10	1.10	0.98
C(L)III- HSC(PC-2)	1747	1.33	1.13	1.13	0.99

5. Conclusion

This study has shown that the values of *SI* indicates that the constraining factor (ξ) of the slender circular CFST are lower than short section. Results also show that the experimental ultimate strength (N_{ue}) affects the *SI* values. For short column, when the N_{ue} is low, the resulting *SI* value is high. Meanwhile, for slender column, the *SI* value is high when the value of N_{ue} is high due to the higher constraining factor (ξ) for short circular ($\xi = 0.38$) compared to the slender circular section ($\xi = 0.28$). Results also show that different codes provide different concrete confinement safety coefficient value in N_{uo} calculation, thus affecting the *SI* values. The AISC (LRFD) provides the highest *SI* values for short and slender circular section. Whereas, EC4 and AS5100.6 provides the lowest *SI* values for short circular section, while, AIJ provides the lowest *SI* for slender circular CFSTC section. The highest *SI* value provided by AISC (LRFD) compared to other codes is due to the low concrete confinement safety coefficient provided by the code. On the other hand, the *SI* values provided by EC4, AIJ and AS5100.6 are the lowest because of the high concrete confinement safety coefficient provided by them compared to other codes. The values of the concrete confinement safety coefficient are very important and must be taken into consideration in structural design. It also can be concluded that waste material AASA shows good potential as OPC replacement in HSC as concrete infilled in steel tube column.

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