Journal of Engineering Science and Technology
Special Issue on 5th International Technical Conference 2016, June (2020) 1 - 8

EFFECT OF CONFINEMENTS ON THE LOAD CAPACITY OF SHORT CIRCULAR HIGH-STRENGTH CONCRETE-FILLED STEEL TUBE COLUMNS

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Abstract

This paper is to investigate the influence of confinement of composite columns on the ultimate load capacity (N_u) of concrete-filled steel tube columns (CFSTC) calculated using different codes (EC4, ACI, AISC (LRFD), DBJ13-15, AIJ, AS5100.6, AS (AS4100, AS3600, ACI), CECS28:90, HONG KONG and BS5400). The strength predictions are focused on a single section. The materials properties to calculate the N_u are obtained from experimental values, such as the yield strength (f_y) and the modulus of elasticity (E_s) of steel tube. The properties of two types of high-strength concrete (HSC)-infilled i.e., ordinary Portland cement concrete (OPCC) and pozzolan concrete (PC) are also obtained from compressive strength test of concrete. The results show that there is no significant variation in N_u of the CFSTC either infilled with OPCC or PC due to the nearly similar values of compressive strength (f'_c) of both. The N_u of CFSTC with OPCC and PC-infilled calculated using different codes varies between 2176.1 kN and 2111.9 kN (CECS28:90) (highest) and 1150.4 kN and 1115.8 kN (BS5400) (lowest) with nearly 90% difference. This is due to the influence of the confinement values provided for each code. The concrete-infilled types do not influence the N_u of CFSTC composite, so different types of pozzolanic materials can be included in the concrete infill if the strength is maintained. Different codes provide different formulas of confinement, which result in different predicted load capacity values.

Keywords: Concrete-filled steel columns, Confinement, High-strength concrete, High-strength steel, Ultimate load capacity.

1. Introduction

Concrete-filled steel tube columns (CFSTC) are finding increasing usage in modern construction practice throughout the world. The structural behaviours of CFSTC are influenced by many factors such as the cross-section of steel, steel and concrete strengths, concrete types, and height of columns [1-3]. When high-strength steel (HSS) tube column is filled with high-strength concrete (HSC), the ductility of CFSTC decreases compared to when HSS tube column is filled with normal-strength concrete (NSC). It shows that the relationship between steel and concrete is very important to obtain high ductility of composite column. If the strength of steel column and concrete filling are too high, the ductility of composite column reduced.

The predicted load capacity (N_u) is influenced by three main factors; (1) the slenderness ratio; (2) the partial safety coefficient; and (3) the compressive strength of concrete (f'_c). Although, the tensile yield strength of steel, f_y is also among the main factors that influence the N_u of CFSTC but in this paper all the values calculated are the same, hence, the effects could not be shown.

The concrete confinement depends mainly on the ratio of the external diameter of the steel tube to the plate thickness (D/t), f_y and f'_c. Good confinement between steel and concrete will give a higher ductility of composite column. Each design code presents different expression to predict the N_u of the CFSTC under concentric load. However, these expressions are all based on the sum of the contributions of concrete and steel for column resistance to load. The confinement introduced by the steel tube to the concrete core is an important aspect of the structural behaviour of CFSTC composite. The increase of N_u due to the concrete confinement provided by the steel tube depends on cross-sectional area and shape, material properties (f_y and f'_c), D/t, length-to-diameter ratio (l/D), partial safety coefficient provided in codes and eccentricity of the load (e/D). All these parameters contribute to defining the degree of confinement of the concrete.

During testing, since the Poisson coefficient of the steel is larger than the concrete's coefficient, the confinement effect in the initial stages of loading can been neglected [4-7]. Hence, the steel tube does not restrain the concrete core and the steel tube expands faster than the concrete core in the radial direction. However, when the applied load reaches the level of the uniaxial strength of the concrete, the micro cracking of concrete increases. At this point, the lateral expansion of the concrete reaches its maximum, mobilizing the steel tube to efficiently confine the concrete core. In this way, the N_u of the CFSTC composite is higher than the sum of the resistance of their components, which are the steel tube and the concrete core. The lateral stress introduced by the steel tube is responsible for the additional resistance of the concentrically loaded CFSTC composite. In this situation, the concrete core is subjected to a triaxial stress state, while the steel tube is in a biaxial stress state [1].

Therefore, it is very important to make calculations in detail in accordance with the codes' specifications in order to meet the conditions permitted. This initial calculation is necessary to ensure the security features of each building or bridge designed.

Previous results had shown that one of the factors for the large decrease of concrete confinement is when the D/t ratio is small ($D/t \leq 60$), and it tends to be moderate when the D/t ratio ≥ 60. The concrete confinement increases linearly when the f_y of the steel tube increases, and it decreases as the unconfined f'_c of the concrete core increases, respectively [8]. The steel tube restrains the concrete core at failure, an internal pressure (σ_r) develops between the steel tube and concrete, creating a tensile hoop stress (σ_t) in the steel tube [9]. In CFSTC, the steel tube encloses the concrete core and is used as both longitudinal and lateral reinforcement. Thus, the steel section is subjected to biaxial stresses consisting of longitudinal compression and hoop tension, which interacts and affects the mechanical behaviour of the column. The composite action must be achieved by the natural bond in that the bond strength has a significant effect on the behaviour of the CFSTC. Previous studies have shown lack of information on the effectiveness of confinement in CFSTC filled with HSC [10], so this paper is to understand how the confinement contributes to the N_u and behaviour of CFSTC.

This paper is to investigate the influence of confinement on the N_u of CFSTC infilled with two different types of concrete and strengths calculated using different kind of codes CFSTC were the EC4, ACI, AISC (LRFD), DBJ13-15, AIJ, AS5100.6, AS (AS4100, AS3600, and ACI), CECS28:90, HONG KONG and BS5400. The strength predictions are focused on a single section. The predicted N_u can be used as base in running concentric axial test on CFSTC.

2. Methodology

2.1. Materials properties

The material properties used to calculate the N_u are based on experimental values of the coupon tensile tests of steel tube and compressive strength tests of HSC.

2.1.1. Tensile coupon test

Four coupon samples of mild steel sheet from the tube were tested to determine the f_y of steel tube as accordance with the ASTM E8 [11]. The resulting stress-strain diagrams are shown in Fig. 1. The average f_y and the modulus of elasticity of steel tube (E_s) are recorded as 242.3 MPa and 200,000 N/mm^2, respectively.

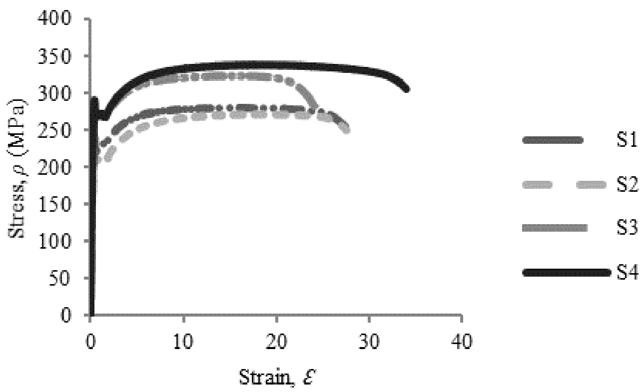

Fig. 1. Stress-strain relationship of steel tube.

2.1.2. Compressive strength of HSC

There are two types of concrete, ordinary Portland cement concrete (OPCC) and pozzolan concrete (PC), which f'_c and modulus of elasticity (E_c) of 62.0 MPa and 59.4 MPa; and 40,302 N/mm^2 and 39,464 N/mm^2, respectively are 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], with physical properties of aggregates (following ASTM C 127 [14] and ASTM C 128 [15]): maximum diameter (mm) ≤ 4.75 and 10; 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 mix design proportions of concrete are shown in Table 1. For each concrete batch, at least three concrete cube specimens (150 mm × 150 mm × 150 mm) were tested to obtain the f'_c and E_c of both types of concretes.

Table 1. Mix proportions of concrete.

Mix Description	OPCC	PC
w/b	0.30	0.30
Water (kg/m^3)	169	168.3
Fine Aggregate (kg/m^3)	688	662.5
Coarse Aggregate (kg/m^3)	990	989.5
Cement (kg/m^3)	529	365.1
AASA (kg/m^3)	-	132.3
SF (kg/m^3)	-	31.7
SP %	1.5	7.0

2.2. Predicted load capacity

The predicted N_u of CFSTC was calculated using different codes, i.e. EC4 [16], ACI [17, 18], AISC (LRFD) [19], DBJ13-15 [20], AIJ [21], AS5100.6 [22], AS (ACI, AS4100, AS3600) [17, 23, 24], CECS28:90 [25], HONG KONG [26] and BS5400 [27] as shown in Table 2. The dimension ($D \times t \times l$) of steel tube is $165 \times 2.5 \times 500$ mm^3. The steel tube slenderness, *D/t* and *L/D* are 66 and 3.03, respectively.

Table 2. Total load for different 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	$N_u = 0.85 A_c f_c + A_a f_y$ $N_u = 1.3 A_c f_c + A_a f_y$ [18]
AISC (LRFD)	$N_u = A_a F_{cr}$
DBJ13-15	$N_u = A_{sc} f_{scy}$
AIJ	$N_{u1} = N_{cu,c} + (1+\eta) N_{cu,s}, \left(\frac{l}{D} \le 4\right)$ $N_{u2} = N_{u1} - 0.125\left(N_{u1} - N_{u3}\left(\frac{l}{D} - 12\right)\right)\left(\frac{l}{D} - 4\right), \left(4 < \frac{l}{D} \le 12\right)$ $N_{u3} = N_{cr,c} + N_{cr,s}, \left(\frac{l}{D} > 12\right)$
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	$N_u = \rho_1 \rho_e N_o$ $N_o = A_c f'_{c,pr}\left(1 + \sqrt{\xi} + \xi\right)$
HONGKONG	$N_u = \eta_a A p_y + 0.53 A_c f_{cu}\left(1 + \eta_c \frac{t}{d}\frac{p_y}{0.8 f_{cu}}\right)$
BS5400	$N_u = A_s f_y + 0.675 A_c f_{cu}$

3. Results and Discussion

3.1. Comparison of load capacity with different HSC-infilled

Table 3 shows the N_u as calculated by different codes for two different types of concrete infills, OPCC and PC. It can be seen that the modified ACI code [18] gives the highest percentage values difference, which is 3.5% between OPCC and PC-infilled, and HONG KONG code shows the lowest percentage values difference of load capacity, which is only 0.2%. The percentage differences between OPCC and PC is insignificant due to the nearly the same f'_c of both concrete, which is at 62.0 MPa and 59.4 MPa. This shows that the type of concrete-infills does not influence the N_u, if they maintained the same strength. This suggests that usage of many other supplementary materials (SCM) such as waste materials AASA, slag, palm oil fuel ash (POFA), fly ash (FA) and SF can be included in the HSC-infilled as long as the design strength maintains the same.

3.2. Load capacity of CFSTC from different codes

Referring to Table 3, the CECS 28:90 code provides the highest N_u values of CFSTC infilled with OPCC and PC, which are at 2176.1 kN and 2111.9 kN respectively, followed by ACI modified codes, which are at 1929.2 kN and 1862.5 kN. AIJ code provides the N_u of CFSTC composite for both types of concretes as 1451.9 kN and 1408.3 kN, respectively. Meanwhile, AS (AS4100, AS3600, ACI) and ACI codes had provided the same N_u values, which are 1368.44 kN (OPCC) and 1324.85 kN (PC) because they provide similar equations. Likewise, the EC4 and AS5100.6 codes give same N_u values of 1555.36 kN (OPCC) and 1504.08 kN (PC) due to similar materials properties. BS5400 code shows the lowest N_u of CFSTC, which is 1150.36 kN and 1115.75 kN for both concretes, respectively, due to lower partial safety coefficient provided by the code. Based on the results, different codes give different load capacities of the composite columns. The results vary from one another because of the influence of the steel-concrete confinement values as provided by each code.

The N_u of CFSTC in Table 3 shows the OPCC and PC concrete fillings for ACI and AS codes are much lower than the N_u of the modified ACI [18] values for both these concretes. Even though the basic requirement of the codes, i.e., the limiting thickness of the steel tube to prevent local buckling is the same for both codes (ACI and AS) and both codes use the same formula for calculating the total load capacity but neither code takes into consideration the concrete confinement. Modified ACI [18] takes consideration on concrete confinement by increasing the coefficient of f'_c. The capacities given by the ACI code are too conservative whereas those calculated by using revised equation are more realistic, especially for circular columns [18]. The overestimate figures (modified ACI [18] and CECS28:90) are needed because concrete confinement factor condition is unpredictable at site due to changes in concrete properties.

The same condition applies to CECS28:90, where concrete confinement factor is included in the code. CECS28:90 includes the testing load factor, ρ_e and the slenderness of column (l_e/D). The ρ_1 reduction factors consider the slenderness influence. For concentric loading, $\rho_e = 1$ and $\rho_1 = \left\{1 - 0.115\sqrt{l_e/D - 4},\ [l_e/D > 4], 1[l_e/D \leq 4]\right\}$ where l_e is the effective length of the column, which is determined by the supports conditions.

Table 3 also shows the percentage difference between the highest calculated N_u of CFSTC (CECS28:90) and the lowest (BS5400). CESC28:90 is overestimated between 89.2% and 89.3% over the values provided by BS5400 for both types of concrete fillings, respectively. This is due to the partial safety coefficient factor for the calculation of the concrete confinement portion, which causes the highest percentage of N_u (CESC28: 90) compared to other codes. Table 3 also shows the lowest percentage difference between the calculated N_u of CFSTC (Hong Kong) and BS5400 of 9.8% (OPCC) and 13.0% (PC). This is also due to a partial safety coefficient factor for the calculation of the concrete confinement part, which results in near similarity between the two.

Table 3. Load capacity of CFSTC.

CODES	Total Load, N_u (kN)		% diff. of conc. infill	% diff. with lowest N_u	
	OPCC	PC		OPCC	PC
EC4	1555.4	1504.1	3.3	35.2	34.8
ACI Modified	1368.4	1324.9	3.2	19.0	18.7
ACI [18]	1929.2	1862.5	3.5	67.7	66.9
AISC(LRFD)	1367.8	1324.2	3.2	18.9	18.7
DBJ13-15	1347.6	1306.0	3.1	17.1	17.1
AIJ	1451.9	1408.3	3.0	26.2	26.2
AS5100.6	1555.4	1504.1	3.3	35.2	34.8
AS (AS4100, AS3600, ACI)	1368.4	1324.9	3.2	19.0	18.7
CECS28:90	2176.1	2111.9	2.9	89.2	89.3
HONG KONG	1263.4	1260.6	0.2	9.8	13.0
BS5400	1150.4	1115.8	3.0	-	-

3.3. Limitations of CFSTC from different codes

Each code provides different equation of slenderness ratio (λ) and different required minimum value for circular section. Therefore, each code has limitations for design D and t. Predicted N_u is important to ensure that the composite structure is safe and to prevent global or local buckling. The values of D/t and L/D for the calculation of N_u in this paper are 66 and 3.03. These values are less than the value required by all codes.

4. Conclusions

The load capacities vary depending on the different codes because of the confinement effect values provided by each code. Modified ACI code gives the highest percentage values difference of N_u between OPCC and PC-infilled, and HONG KONG code shows the lowest, at 3.5% and 0.2%, respectively. It can be concluded that he type of concretes-infilled does not influence the N_u, if they maintained the same strength, even though the components of concrete are different. The N_u of CFSTC with OPCC and PC fillings for ACI and AS codes are much lower than the N_u of the modified ACI because neither code takes into consideration the concrete confinement compared to modified ACI by increasing the coefficient of concrete strength. The same condition applies to CECS28:90, where concrete confinement factor is included in the code, which had resulted in the high value of N_u. CESC28:90 is overestimated between 89.2% and 89.3% over the values provided by BS5400 for both types of concrete fillings (OPCC and PC), respectively. The lowest percentage difference between the calculated N_u of CFSTC (Hong Kong) and the lowest (BS5400) is at 9.8% (OPCC) and 13.0% (PC), respectively due to a partial safety coefficient factor for the calculation of the concrete confinement. The predicted N_u values are important in design for safety and in testing for planning the experimental setup.

Acknowledgements

The authors acknowledge the Ministry of Higher Learning Malaysia for the financial supports under grant FRGS/1/2016/TK06/UKM/02/2 and Universiti Kebangsaan Malaysia under grant DIP-2014-019.

References

1. El-Heweity, M.M. (2012). On the performance of circular concrete-filled high strength steel columns under axial loading. *Alexandria Engineering Journal*, 51(2), 109-119.
2. Inai, E.; Mukai, A.; Kai, M.; Tokinoya, H.; Fukumoto, H.; and Mori, K. (2004). Behavior of concrete-filled steel tube beam columns. *Journal of Structural Engineering*, 130(2), 189-202.
3. Fujimoto, T.; Mukai, A.; Nishiyama, I.; and Sakino, K. (2004). Behavior of eccentrically loaded concrete-filled steel tubular columns. *Journal of Structural Engineering*, 120(2), 203-212.
4. Susantha, K.A.S.; Ge, H.; and Usami, T. (2001). Uniaxial stress-strain relationship of concrete confined by various shaped steel tubes. *Engineering Structures*, 23(10), 1331-1347.
5. Shanmugam, N.E.; and Lakshmi, B. (2001). State of the art report on steel–concrete composite columns. *Journal of Constructional Steel Research*, 57(10), 1041-1080.
6. Johansson, M. (2002). The efficiency of passive confinement in CFT columns. *Steel and Composite Structures Int. J.*, 2(5), 379-396.
7. Sakino, K.; Nakahara, H.; Morino, H.; and Nishiyama, I. (2004). Behavior of centrally loaded concrete-filled steel-tube short columns. *Journal of Structural Engineering*, 130(2), 180-188.
8. Lu, Z.H.; and Zhao, Y.G. (2008). Mechanical behavior and ultimate strength of circular CFT columns subjected to axial compression loads. *The 14th World Conference on Earthquake Engineering, Beijing, China*, 12-17.
9. Gardner, N.J.; and Jacobson, E.R. (1967). Structural behavior of concrete-filled steel tubes. *ACI Journal Proceeding*, 64(7), 404-412.
10. De Oliveira, W.L.A.; De Nardin, S.; De Cresce El Debs, A.L.H.; and Khalil El Debs M. (2009). Influence of concrete strength and length/diameter on the axial capacity of CFT columns. *Journal of Constructional Steel Research*, 65(12), 2103-2110.
11. ASTME8/E8M-09 (2009). Standard Test methods for tension testing of metallic materials.

12. Owaid, H.M.; Hamid, R.; and Taha, R.M.R. (2014). Influence of thermally activated alum sludge ash on the engineering properties of multiple-blended binders concretes. *Construction and Building Materials*, 61, 216-229.
13. ACI211.4R-93 (1998). Guide for selecting proportions for high-strength concrete with portland cement and fly ash.
14. ASTMC127-88 (1988). Standard test method for specific gravity and absorption of coarse aggregate.
15. ASTMC128-97 (1997). Standard test method for specific gravity and absorption of fine aggregate.
16. EUROCODE 4 (2004). EN 1994-1-1 (2004): Design of composite steel and concrete structures - Part 1-1: General rules and rules for buildings.
17. ACI318-05 (2005). Building code requirements for structural concrete and commentary. *American Concrete Institue*.
18. Giakoumelis, G.; and Lam, D. (2004). Axial capacity of circular concrete-filled tube columns. *Journal of Constructional Steel Research*, 60(7), 1049-1068.
19. AISC (LRFD) (1999). Load and resistance factor design specification for structural steel buildings.
20. DBJ13-15-2003 (2003). Technical specification for concrete-filled steel tubular structures. *The Construction Department of Fujian Province*.
21. AIJ (2001). Recommendations for design and construction of concrete-filled steel tubular structures.
22. AS5100.6-2004 (2004). Bridge design. Part 6: Steel and composite construction. *Standard Australia*.
23. AS4100-1998 (2012). Steel structures, *Standard Australia*.
24. AS3600-2001 (2001). Concrete strutures. *Standard Australia*.
25. CECS28:90 (1992). Specification for design and construction of concrete-filled steel tubular structures. *China Planning Press*.
26. HONG KONG (2011). Code of practice for the structural use of steel.
27. BS5400 (1979). Part 5: Steel, concrete and composite bridges. *Code of Practice for Design of Composite Bridges*.