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Statistical-based evaluation of design codes for circular concrete-filled steel tube columns

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Abstract. This study addresses the load capacity prediction of circular concrete-filled steel tube (CFST) columns under axial compression using current design codes. Design methods given in the Chinese code CECS 28:2012 (2012), American code AISC 360-10 (2010) and EC4 (2004) are presented and described briefly. A wide range of experimental data of 353 CFST columns is used to evaluate the applicability of CECS 28:2012 in calculating the strength of circular CFST columns. AISC 360-10 and EC4 (2004) are also compared with the test results. The comparisons indicate that all three codes give conservative predictions for both short and long CFST columns. The effects of concrete strength, steel strength and diameter-to-thickness ratio on the accuracy of prediction according to CECS 28:2012 are discussed, which indicate a possibility of extending the limitations on the material strengths and diameter-to-thickness ratio to higher values. A revised equation for slenderness reduction factor in CECS 28:2012 is given.

Keywords: concrete-filled steel tube columns; axial compression; load capacity; CECS 28:2012

1. Introduction

Concrete-filled steel tube (CFST) column system offers advantages over either pure steel or reinforced concrete members for the interaction between the concrete infill and external steel tube. The steel tube effectively confines the concrete, thus providing an increased strength and a highly ductile response under compression. The presence of concrete infill modifies the local buckling mode and delays the failure by forcing it to buckle outward only. Besides the mechanical advantages, a more economic and faster construction can be achieved because the steel tube acts as the formwork and the load resisting system during the construction phase when the concrete filling is unable to contribute.

The confinement of steel tube in concrete core plays a critical role in the structural behavior of CFST columns. In the early stage of loading, Poisson's ratio of the concrete core is lower than that of the steel tube, and the steel tube has no confinement pressure on the concrete core (Shanmugam and Lakshmi 2001, Susantha *et al*. 2001). As the longitudinal strain increases and the cracks

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propagate, Poisson's ratio of the concrete gradually catches up with that of the steel tube. Therefore, the lateral expansion of uncontained concrete gradually becomes greater than that of steel. A radial pressure develops at the steel-concrete interface thereby confining the concrete core and setting up a hoop tension in the tube. At this stage, the concrete core is stressed tri-axially and the steel tube bi-axially, and a load transfer from the steel tube to the concrete core occurs, because the tube cannot sustains the yield stress longitudinally in the presence of a hoop tension (Hajjar and Gourley 1996).

Extensive research on CFST columns has been on going worldwide for several decades. The results show that the increased load capacity due to the synergistic interaction between concrete core and steel tube depends on many parameters, such as the columns slenderness ratio (length-to-diameter ratio), section slenderness (diameter-to-thickness ratio), load eccentricity, shape of cross section and strength and deformability of materials (Hu *et al*. 2005, Portolés *et al*. 2011a, Uy *et al*. 2011, Giakoumelis and Lam 2004, Beck *et al*. 2009, Yu *et al*. 2007, Bradford *et al*. 2002). Several codes have been issued to support the applications of CFST constructions. Research and practice of CFST structures, in turn, has led to the development of these design codes. The aim of this study is to verify the applicability and provide useful information for a possible revision of CECS 28:2012 for the application of high strength materials and thin-walled steel tube. For this purpose, a wide range of experimental data of 353 tested circular CFST columns under axial load was compared with the code pre1ictions. Effects of concrete strength, steel strength and diameter-to-thickness ratios on the accuracy of predicting the axial compressive strength according to CECS 28:2012 are discussed. The codes AISC 360-10, EC4 are also compared with the test results.

2. Previous research on the circular CFST columns under axial compression

A number of studies on CFST columns under axial compression have been carried out. The parameters of circular CFST column closely related to its behaviour include: diameter (Probst *et al*. 2010, Ellobody *et al*. 2006), diameter-to-thickness ratio (Abdalla *et al*. 2013, Lee *et al*. 2011, Fujimoto *et al*. 2004, Han and Yao 2004, Yu *et al*. 2008), length-to-diameter ratio (Kato 1996, Tan and Pu 2000, Han 2000a, Oliveira *et al*. 2009, Liang and Fragomeni 2009), concrete strength (Oliveira *et al*. 2010, Sakino *et al*. 2004, Schneider 1998) and steel strength (Gupta *et al*. 2007, Ellobody *et al*. 2006). The use of CFST columns has provided significant economic benefit, and further economies can be obtained using high-strength concrete with thin-walled steel tubes (Pu 2004). The concrete confinement is not as effective as the normal strength concrete due to reduced circumferential expansion (Zhang and Wang 2004). However, using high strength concrete as concrete infill can achieve structural ductile behavior (Zeghiche and Chaoui 2005, O'Shea and Bridge 2000).

Increasing the slenderness ratio decreases the load capacity of CFST column, and slender CFST columns exhibit few beneficial effects of composite behavior in terms of strength enhancement due to the confinement (Tan and Pu 2000, Han 2000b). Dundu (2012), Gupta *et al*. (2007) concluded that both the confinement degree and load capacity decreases as the length-to-diameter ratio increases. For column with a high length-to-diameter ratio, the failure is characterized by lateral instability with low deformation and before the mobilization of the confinement.

Oliveira *et al*. (2009) investigated the influence of column slenderness ratio and concrete strength on the confinement concrete. The columns had length-to-diameter ratios from 3 to 10, and filled with concrete with compressive strengths from 30 MPa to 100 MPa. Increasing in the concrete strength resulted in load capacity enhancing and confinement improving in the columns filled with normal strength concrete. The increase of concrete strength can achieve a higher increase of load capacity for the columns with relatively small slenderness ratios. As expected, the load capacity decreased with the increased slenderness ratio of the column. Before the concrete core could develop its full capacity, slender columns failed due to global buckling. This reduces the radial deformation of the concrete core and avoids the mobilization of the confinement effect of the tube.

Zeghiche and Chaoui (2005) also studied the influence of column slenderness and concrete strength on the capacity and behavior of CFST columns, but the columns had length-to-diameter ratios ranging between 12.5 and 25. All columns failed due to overall instability. They also stated that the increase of concrete core strength is only effective for shorter columns and decreases with length-to-diameter ratio. Increasing the concrete strength from 40 MPa to 100 MPa improved the load capacity slightly for the columns with a slenderness ratio of 25. For the CFST column filled with higher strength concrete, its load capacity decreases more significantly with the increasing of length-to-diameter ratios.

The infill concrete has significant influence on the local buckling of steel tube, especially thin-walled steel tube. Cross-section slenderness limits for CFST columns can benefit from the effects of the concrete restraint in increasing the local buckling stress. Bradford *et al*. (2002) showed that the elastic local buckling stress for filled round sections is 1.73 times that for hollow round sections. A modified slenderness limitation which is larger than the value proposed for hollow circular steel tubes was also proposed.

Abed *et al*. (2013) conducted tests to study the effects of diameter-to-thickness ratio and concrete strength on the behavior of axially loaded short CFST columns. The diameter-to-thickness ratio ranged from 20 to 54. The concrete strengths were 44 MPa and 60 MPa. It was concluded that the diameter-to-thickness ratio had a greater influence on the compressive behavior than other factors. The increase in the diameter-to-thickness ratio reduced not only the CFST column's stiffness but also its axial load due to the decrease in the confinement. Comparisons between experimental results and current codes showed that those currents underestimate the load capacity of CFST columns, but the underestimation reduced as the diameter-to-thickness ratio increased.

O'Shea and Bridge (2000) examined the diameter-to-thickness ratio and concrete strengths as well, but their focus was on thin-walled CFST columns with a diameter-to-thickness ratio between 60 and 120 and high strength concrete with a compressive strength of 50, 80 and 120 MPa. The effects of different axially loading were investigated. The results showed that the degree of confinement offered by a thin-walled circular steel tube to the concrete core is dependent upon the loading condition. The buckling strength of circular column was not improved by providing internal lateral restraint. For steel tubes with a diameter-to-thickness ratio in excess of 50, and filled with concrete with strength of 80-120 MPa, the steel tube provided insignificant confinement to the concrete when both steel and concrete were loaded simultaneously.

Han (2000b) and An *et al*. (2012) studied the behavior of very slender CFST columns. The results showed that the confinement effect does not exist until very slender columns reach the ultimate strength, and the contact stress decreased as the slenderness ratio increases. The predicted ultimate strengths for very slender CFST columns by DBJ/T 13-51-2010, AISC 360-05 and EC4 are generally conservative (An *et al*. 2012).

Roeder *et al*. (1999) stated that stress transfer between the steel and the concrete is required in order to ensure the composite action. O'Shea and Bridge (2000) reported that the bond between the infill concrete and steel is critical in determining the formation of a local buckling. Giakoumelis and Lam (2004) affirmed that as the concrete strength increased, the effects of the bond of the concrete and the steel tube became increasingly critical. For normal concrete strength, the reduction on the axial capacity of the column due to bonding was negligible.

3. Strength provisions for CFST columns

Several design codes have been proposed to calculate the axial load capacity of CFST columns, and modified based on the research and practice of CFST structures. In general, the design of composite columns may be carried out by a superposition method or by treating the structural steel as a strong reinforcement and following the design procedure for reinforced concrete structures. Some of these design codes ignore the increase in the infill concrete strength (AS3600 2001, AS4100 1998), while others take account of the concrete strength increase (EC4 2004, AISC 360-05 2005, AISC 360-10 2010, CECS 28:90 1990, CECS 28:2012 2012). All these codes regulated different limitations about the material strength and diameter-to-thickness ratio. The provisions were revised for the application of high strength materials and thin-walled steel tube, as shown in Table 1. In Table 1, f_c' and f_{cu} are the cylinder strength, and cubic strength of concrete, respectively, f_y and E_s are the yield strength and of steel tube, and $(D/t)_{\max}$ is the maximum value of diameter-to-thickness ratio of steel tube. CECS (CECS 28:90 1990, CECS 28:2012 2012) deregulated from 60 MPa to 80 MPa for concrete cubic strength, 390 MPa to 420 MPa for steel strength and $85 \times 235/f_y$ to $135 \times 235/f_y$ for diameter-to-thickness ratio to allow the usage of high strength materials and thin-walled steel tube. It is clear that EC4 is most conservative in concrete strength, steel strength and section slenderness limit. Sections 3.1-3.3 present provisions from CECS 28:2012, AISC 360-10 and EC4 for predicting the compressive resistance of circular CFST columns under axial compression.

3.1 Chinese code CECS 28:2012

China Engineering Construction Standard CECS 28:2012 applies to the design and construction of not only industry and residential buildings but bridges and pylons using circular concrete-filled steel tubular members. The infill concrete can be normal concrete and self-compacting concrete. Longitudinally-welded pipe, helically welded tube, seamless steel tube can be used as external steel tube for CFST columns.

The theory of limit equilibrium is adopted by CECS 28:2012 to determine the composite section nominal strength based on the experiment results. The load capacity of concrete filled steel

Table 1 Provisions of codes for circular CFST column

Provisions	CECS 28:90	CECS 28:2012	AISC 360-05	AISC 360-10	EC4
f_c', f_{cu}* (MPa)	(30-60)*	(30-80)*	21-70	21-70	20-50
f_y (MPa)	235-390	235-420	525	525	235-460
$(D/t)_{\max}$	$85 \times \sqrt{235/f_y}$	$135 \times (235/f_y)$	$0.15\,E_s/f_y$	$0.31\,E_s/f_y$	$90 \times 235/f_y$

tube is based on the load capacity of concrete ($A_c f_c$), and strength enhancement due to the confinement provided by steel tube is taken into consideration. A confinement index (θ) takes account of the enhancement of load capacity. The expression of θ is given by (Cai 2007)

$$\theta = \frac{A_s f_y}{A_c f_c} \tag{1}$$

where A_s and A_c are the cross-sectional areas of steel tube and concrete, respectively, and f_c is the prism compressive strength of concrete.

The confinement index θ is the ratio between the maximum capacity of steel and concrete, and represents the mechanical slenderness of the section. For short column, it is directly relative to the confinement obtained. The higher the confinement index, the higher the compression strength of confined concrete and the more ductile the confined concrete (Han *et al*. 2005). The confinement index is specified in CECS 28:2012 with an allowed range from 0.5 to 2.5. The lower limit of 0.5 is introduced to prevent the failure with a brittle mode due to the insufficient confinement, while the upper limit of 2.5 is determined to prevent a plastic deformation due to the overly small concrete strength (Cai 2007) and a less concrete mechanical contribution to the composite action to enable an economic construction (Portolés *et al*. 2011b).

In CECS 28:2012, the slenderness effect is ignored when the length-to-diameter ratio is below 4, defined as short column. The load capacity of short CFST column under concentric axial load N_0 is calculated as follows

$$N_0 = 0.9 f_c A_c (1 + \alpha\theta), \quad \text{if} \quad 0.5 < \theta \le [\theta] \tag{2}$$

$$N_0 = 0.9 f_c A_c (1 + \sqrt{\theta} + \theta), \quad \text{if} \quad [\theta] < \theta < 2.5 \tag{3}$$

where A_c is the areas of the core concrete, θ is the confinement index reflecting the confinement effect of steel tube, $[\theta]$ and α are the factors mainly depend on the concrete strength, and the values are listed in Table 2.

The value of $[\theta]$ can be obtained by the equation $[\theta] = 1/(\alpha - 1)^2$. The value of 0.9 is introduced to increase the safety referring to the Code for design of concrete structural GB50010-2010 (2010). The expressions $(1 + \alpha\theta)$ and $(1 + \sqrt{\theta} + \theta)$ in CECS are named strength enhancement factor in this paper. This design method is not only applied to concrete and steel tube loaded CFST columns, but concrete loaded CFST columns and steel tube loaded CFST columns.

For CFST columns with a length-to-diameter ratio above 4 and/or under axial loads, the resistance is calculated by Eq. (4).

$$N_{CECS} = \varphi_1 \varphi_e N_0 \tag{4}$$

where φ_1 is the slenderness reduction factor, and φ_e is a reduction factor for eccentricity and set to

Table 2 Values of factors $[\theta]$ and α

Factor	≤ C50	C55-C80
α	2.00	1.80
$[\theta]$	1.00	1.56

1 for concentric axial load.

The slenderness reduction factor φ_1 is determined form the following expression

$$\varphi_1 = 1 - 0.115\sqrt{L_e / D - 4}, \quad \text{if} \quad 4 < L_e / D \leq 20 \tag{5}$$

where L_e is the effective length of columns, and D is the external diameter of steel tube.

CECS 28:2012 revised the previous specification CECS 28:90. By comparison, the provisions CECS 28:2012 not only relaxed the limitations on high-strength materials and thin-walled steel tubes (Table 1), but also modified the design expressions for the load capacity of short CFST columns. New provisions were added for the load capacity of short CFST columns. These provisions reduce the load capacity either for CFST columns with the normal strength or with high strength concrete when the confinement index is lower than a certain level, as shown in Fig. 1. This figure also demonstrates that for the same confinement index, the strength enhancement factor is higher for normal strength concrete than for high strength concrete. From Table 2, it also can be seen that the value of α, obtained from a large number of experimental results, for normal strength concrete (≤ C50) is higher than that for higher strength concrete. This can be explained by the fact that the confinement provided by steel tube for high strength concrete is less effective than that for normal strength concrete (Pu 2004, Zhang and Wang 2004, Tan *et al*. 1999).

3.2 European standard EC4

EC4 adopts a simplified method to estimate the axial capacity of CFST columns. In the simplified method, the European buckling curves for steel columns are introduced and the element's imperfections are implicitly taken into account. EC4 also omits the reduction factor of 0.85 for the filling concrete strength due to the protection against the environment and against splitting of concrete (Eq. (7)). Enhancement of the concrete from the confinement is included for some specific cases (Eq. (8)).

According to EC4, the plastic resistance of circular CFST column N_{pl} can be predicted as follows

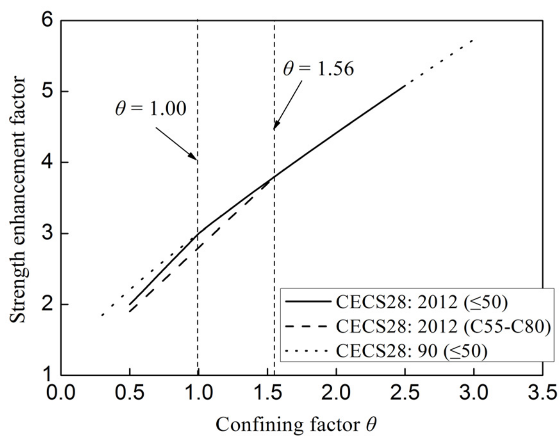


Fig. 1 Comparisons between CECS 28:90 and CECS 28:2012

$$N_{pl} = f_y A_s + f_c' A_c \tag{7}$$

where f_c' is the cylinder compressive strength of concrete.

For circular composite columns with relative slenderness ratios (λ) less than 0.5, confinement effects should be incorporated in the compressive strength of CFST column. The plastic compressive resistance of circular CFST columns is determined by

$$N_{pl} = \eta_a f_y A_s + \left(1 + \eta_c \frac{t}{D}\frac{f_y}{f_c'}\right) f_c' A_c \tag{8}$$

where t is the thickness of the steel tube, η_a is the steel reduction factor, η_c is concrete enhancement factor. η_a and η_c both are functions of the column relative slenderness and given by Eqs. (9)-(10), respectively.

$$\eta_{a0} = 0.25(3 + 2\overline{\lambda}) \leq 1 \tag{9}$$

$$\eta_{c0} = 4.9 - 18.5\overline{\lambda} + 17\overline{\lambda}^2) \geq 0 \tag{10}$$

When the column relative slenderness ratio is above 0.2, the effectiveness is taken into consideration by applying a reduction factor to the compressive resistance of CFST column. As given in Eq. (11)

$$N_{EC} = \chi N_{pl} \tag{11}$$

The reduction factor depends on relative slenderness $\overline{\lambda}$ and is calculated using European column curves (EC3 2003).

3.3 AISC 360-10 code

The plastic stress distribution method is adopted by the AISC (2010) to determine the composite sections' nominal strength. Local buckling of steel tube is considered for CFST columns when using this method. The AISC specifies that for the plastic stress distribution method, the steel tube reaches the yield stress (f_y) when the concrete infill strength is about 0.95 f_c'. Local buckling was accounted for by classifying the composite sections as: compact, non-compact or slender. The filled composite element is qualified as compact if the diameter-to-thickness (D/t) ratio of steel composite element does not exceed $\lambda_p = 0.15E/f_y$, and non-compact if the D/t ratio exceed λ_p but does not exceed $\lambda_r = 0.19\,E/f_y$. If the D/t ratio of steel compression element exceeds $\lambda_r = 0.19\,E/f_y$, the section is slender. In any case, the maximum D/t ratio should not exceed 0.31 E/f_y.

For the axially loaded CFST columns, the nominal compressive strength N_{AISC} can be calculated for limit state of flexural buckling based on member slenderness as follows

$$N_{AISC} = P_{n0} \times 0.658^{\frac{P_{n0}}{P_e}}, \quad \text{if} \quad P_{n0} < 2.25P_e \tag{10}$$

$$N_{AISC} = 0.877P_e, \quad \text{if} \quad P_{n0} > 2.25P_e \tag{11}$$

where P_e is the elastic critical buckling load and P_{n0} is the nominal axial strength and can be determined following:

For compact section ($D/t \le \lambda_p$)

$$P_{n0} = P_p \tag{12}$$

where

$$P_p = f_y A_s + 0.95 f_c' A_c \tag{13}$$

For non-compact section ($\lambda_p \le D/t \le \lambda_r$)

$$P_{no} = P_p - \frac{P_p - P_y}{\lambda_r - \lambda_p}\left(\lambda - \lambda_p\right)^2 \tag{14}$$

where

$$P_y = f_y A_s + 0.7 f_c' A_c \tag{15}$$

For slender section ($\lambda_r \le D/t \le \lambda_{\max}$)

$$N_0 = f_{cr} A_s + 0.7 f_c' A_c \tag{16}$$

$$f_{cr} = \frac{0.72 f_y}{\left(\frac{D}{t}\frac{f_y}{E_s}\right)^{0.2}} \tag{17}$$

where f_{cr} is critical stress.

4. Comparison between test and predicted capacity

In this paper, 353 circular CFST columns from 18 references (Abed *et al.* 2013, Chitawadagi *et al.* 2010, Dundu 2012, Han 2000b, Han and Yao 2004, Giakoumelis and Lam 2004, Gupta *et al.* 2007, Kato 1996, O'Shea and Bridge 2000, Oliveira *et al.* 2009, Sakino *et al.* 2004, Schneider 1998, Tan *et al.* 1999, Tan and Pu 2000, Uy *et al.* 2011, Yu *et al.* 2008, Zeghiche and Chaoui 2005, Zhang *et al.* 2005) are collected and used to perform the code comparisons. The variation of geometrical and material properties covered in these tested specimens are 44-360 mm in tube diameter (D), 20-220 in diameter-to-thickness ratio (D/t), 1.5-38.5 in length-to-diameter ratio (L/D), 0.01-1.88 in relative slenderness ratio ($\overline{\lambda}$), 185-838 MPa in yield strength of steel (f_y) and 20-111 MPa in cylinder compressive strength of concrete (f_c'), 20-122 MPa in concrete cubic compressive strength (f_{cu}). The details of the columns are shown in Appendix A.

As some references reported a compressive strength of 150 mm cube (f_{cu}) while others report a cylinder strength (f_c'), it is need to convert cubic strength (f_{cu}) to cylinder compressive strength (f_c') for the application of AISC 360-10 and EC4, and to convert cubic strength (f_{cu}) or cylinder strength (f_c') to the prism compressive strength (f_c) for the application of CECS 28:2012. The approximate relationships between three strength indexes are determined according to Chen *et al.* (1992), as shown in Table 3. A quadratic interpolation is used when reported concrete strengths are not equal to the values in this table.

Table 3 Approximate relationships of concrete cylinder strength, cube strength and prism strength

Concrete strength (MPa)	C30	C40	C50	C60	C70	C80	C90	C100	C110	C120
f_{cu}	30	40	50	60	70	80	90	100	110	120
f_c'	24	33	40	51	60	70	80	90	100	110
f_c	20	26.8	33.5	41	48	56	64	71	79	87

4.1 Strength comparison

In this section, all code limitations are ignored to verify the accuracy and applicability of those design codes in predicting the load capacity of the test specimens. For a direct comparison between the design models and the test results, all partial safety factors have been set equal to unity, and the material properties have been taken as the measured values. Considering the fact that the definition of short and long CFST columns in these codes are quite different, and some of them are very complex to follow, "short column" and "long column" are classified on the basis of length-to-diameter ratio (Cai 2007). "Short column" is defined as member with an L / D ratio below 4 to determine section capacity, while "long column" is defined as member with an L / D ratio above 4. When E_s and/or E_c are not provided in the literature, we set E_s as 205 GPa and determine E_c according to the corresponding code.

As CECS 28:2012 sets a limit on concrete strength of a maximum cubic strength of 80 MPa, and use different design equations for concrete lower than 50 MPa and 50-80 MPa, the load capacity of the CFST columns with concrete above 80MPa are predicted using the method for 50-80 MPa. In addition, for a CFST column with a confinement index lower than 0.5, axial capacity is calculated using Eq. (2), while for a CFST column with a confinement index above 2.5, axial capacity is calculated using Eq. (3). In order to reflect the deviations of code predictions from the tested results, the -15% and $+15\%$ error bounds are depicted in figures. It is worth noting that this is not a criterion used to evaluate the acceptability of prediction accuracy.

4.1.1 Section capacity under axial compression

Experimental results of 353 circular CFST columns are compared with the design codes. Table 4 shows both the mean values (μ) and the standard deviations (σ) of the experimental to calculated strength (N_e / N_c) ratios for all the strength predictions. As shown in Table 4, EC4 presents the values closest to the experimental results with a mean value of 1.055. The agreement of the experimental and calculated strengths using CECS 28:2012 is generally good with a mean value of 1.094 and a deviation of 0.157.

Fig. 2 shows the comparisons between experimental strengths N_e and calculated strengths N_c using CECS 28:2012 for short columns. It is apparent that some tests obtained experimental

Table 4 Comparison results of code predictions with test results

Member type	CECS 28:2012		AISC 360-10		EC4	
	μ	σ	μ	σ	μ	σ
Short column	1.094	0.157	1.185	0.152	1.055	0.134
Long column	1.355	0.241	1.184	0.206	1.134	0.180

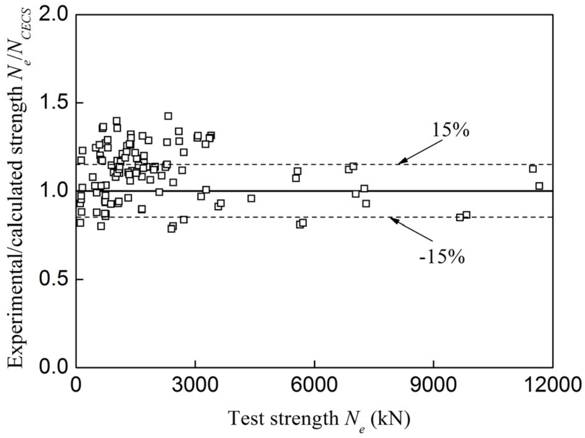


Fig. 2 Comparison between test results and predictions using CECS 28:2012 (short columns)

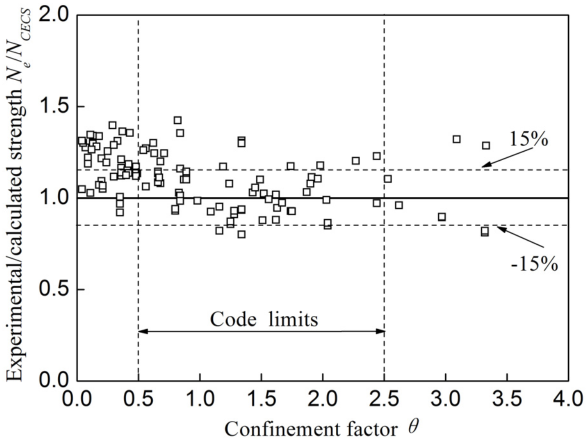
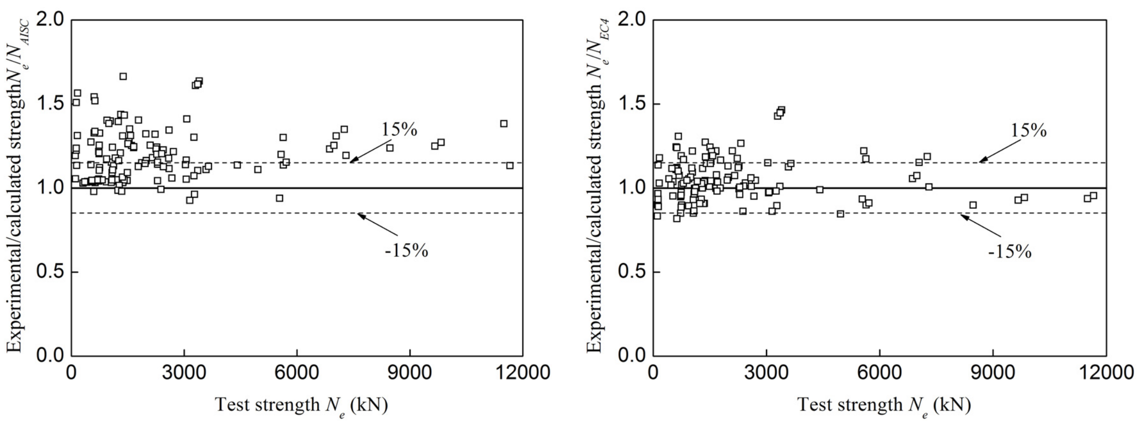


Fig. 3 Experimental to calculated strength ratio N_e/N_{CECS} for short CFST columns vs. confinement factor



(a) AISC 360-10 (b) EC4

Fig. 4 Comparison between test results and predictions using different codes (short columns)

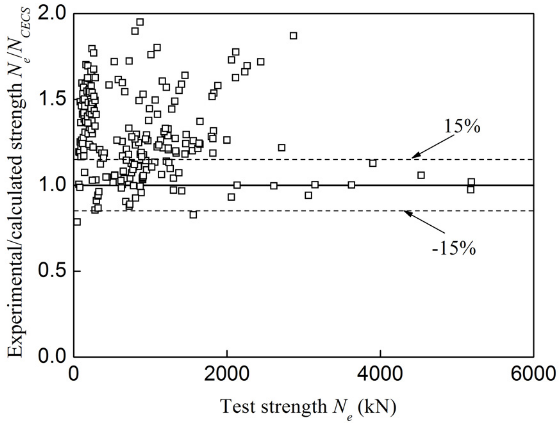


Fig. 5 Comparison between test results and predictions using CECS 28:2012 (long columns)

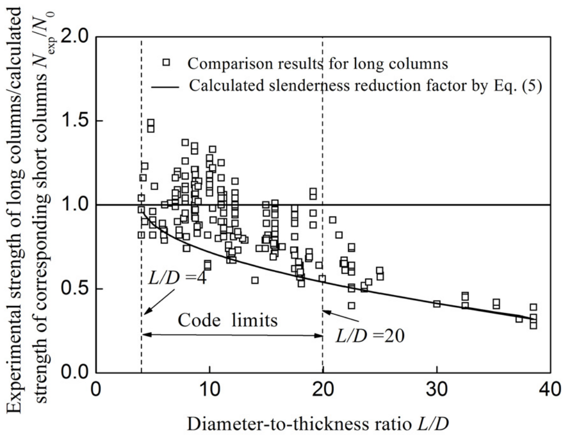


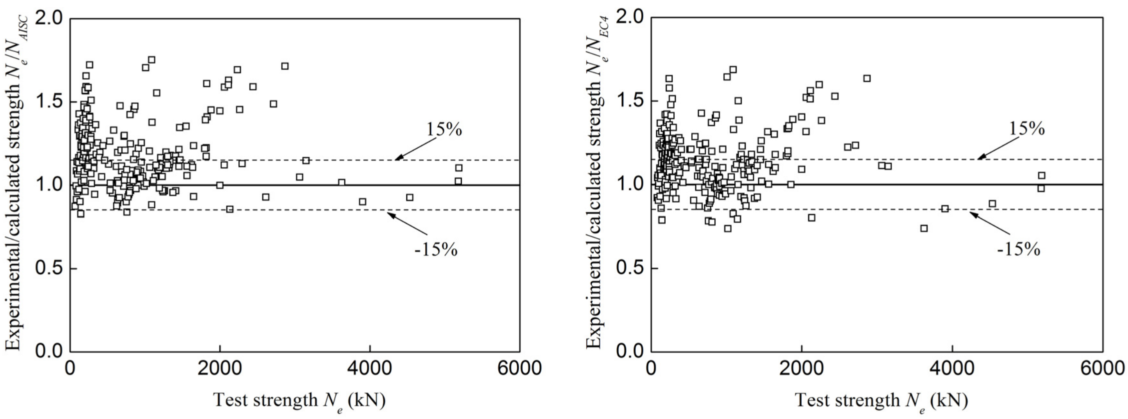
Fig. 6 Ratio N_e/N_0 for long CFST columns vs. length-to-diameter ratio

strength is lower than the calculated strength. These tests were mainly performed on the columns with a confinement index of 1.0-2.0, as shown in Fig. 3. For the columns with a confinement index lower than 0.5, the prediction strengths using CECS 28:2012 are on the safe side. The mean value and standard deviation for these predictions is 1.182 and 0.112, respectively. For the columns with a confinement index above 2.5, the mean value for N_e / N_{CECS} is slightly larger than 1.0, but the dispersion for N_e/N_{CECS} is much obvious. More research is needed to evaluate the application of CECS 28:2012 for these columns.

Comparison results from AISC 360-10 and EC4 are given in Fig. 4 and Table 4. The agreement of the experimental and calculated strengths is generally good. By comparison, AISC 360-10 is more conservative in its prediction than CECS 28:2012 and EC4, which can be rationalized by the fact that AISC ignored the concrete strength enhancement due to the steel confinement.

4.1.2 Long column capacity under axial compression

Fig. 5 shows the comparison between experimental results (N_e) and calculated value (N_c) using



(a) AISC 360-10 (b) EC4

Fig. 7 Comparison between test results and predictions using different codes (long columns)

CECS 28:2012 for long CFST columns. The mean values (μ) and standard deviations (σ) of the experimental to calculated strengths N_e / N_c for the long CFST columns are shown in Table 3. From Fig. 5 and Table 4, it is apparent that the calculated strengths compare conservatively with the experimental results with a relative large deviation, especially for the CFST columns with a relative small slenderness ratio. This is because that the slenderness reduction factor is determined by ignoring the effect of diameter-to-thickness ratio, steel type, concrete strength and confinement index on the load capacity. Although CECS 28:2012 regulates a maximum length-to- diameter ratio of 20 for the advantage of the composite columns under axial loads, the slender reduction factor equation can be safely extended to a length-to-diameter ratio of 38.5 (Fig. 6). The mean value and the standard deviation of the experimental to calculated strength ratio for the columns with a length-to-diameter ratio above 20 is 1.170 and 0.205, respectively.

Comparison results from AISC 360-10 and EC4 for the long CFST columns are shown in Fig. 7 and Table 4. It appears that AISC 360-10 and EC4 both give conservative predictions. As for EC4, the underestimation is attributed to the regulation that confinement effect should be ignored when the relative slenderness of CFST column is above 0.5. In fact, the apparent concrete confinement can still be expected for even very slender columns (O'Shea and Bridge 2000).

5. Discussion

All codes set some limitations on material strengths and diameter-to-thickness ratio for design purposes. On the other hand, many tests have been conducted to date beyond these limitations to relax these limitations. The following section discusses this possibility for CECS 28:2012.

5.1 Influence of parameters

5.1.1 Effect of concrete strength

The effect of concrete strength on the prediction accuracy of CECS 28:2012 is shown in Fig. 8. Table 5 presents the mean values and the standard deviations of the experimental to calculated

Table 5 Comparison results of CECS 28:2012 with test results

Parameters		Short column			Long column		
		No. of tests	μ	σ	No. of tests	μ	σ
Concrete strength	$f_{cu} \leq$ C80	83	1.077	0.172	209	1.293	0.250
	$f_{cu} >$ C80	38	1.141	0.116	23	1.363	0.135
Steel strength	$f_y \leq 420$ MPa	102	1.124	0.148	208	1.321	0.135
	$f_y > 420$ MPa	19	0.951	0.118	24	1.134	0.189
Diameter-to-thickness ratio	$(D/t)/(135 \times 235/f_y) \leq 1$	108	1.083	0.158	232	1.300	0.241
	$(D/t)/(135 \times 235/f_y) > 1$	13	1.186	0.138	0	---	---

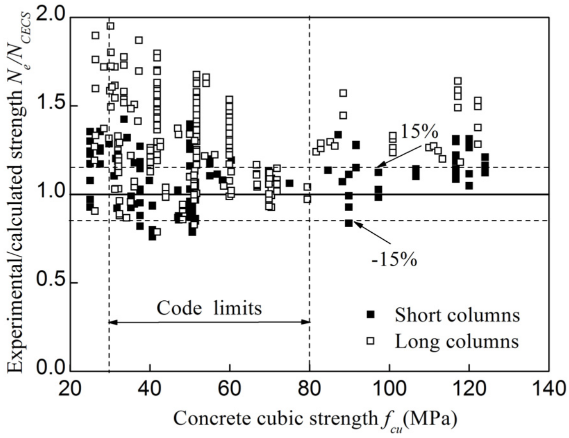


Fig. 8 Effect of concrete strength on the prediction accuracy of CECS 28:2012

strength N_e/N_{CECS} for all specimens. From the comparisons, it can be seen that for both short and long columns, the variability of the mean values of the experimental and calculated strength ratios is slight. Compared to the CFST columns with a concrete strength f_{cu} below 80 MPa, the mean values of the experimental and calculated strength ratios are increased by 6.7% and 7.0% for the short and long columns with a concrete strength f_{cu} above 80 MPa, respectively. All mean values are above unity. This demonstrates that there is a tendency to relax the limitation of concrete strength.

5.1.2 Effect of steel strength

Fig. 9 illustrates the effect of steel strength on the prediction accuracy of CECS 28:2012. The mean values and the standard deviations of the experimental to calculated strength (N_e / N_{CECS}) ratios for all specimens are listed in Table 5. From Fig. 9 and Table 5, as the steel strength is larger than 420 MPa, a decrease of 17.3% and 18.7% in mean values exists for the short columns and the long columns, respectively. All the mean values are above 1.0 except the short column with steel strength larger than 420 MPa. From Fig. 9, the N_e / N_{CECS} ratios show a decreasing trend with the increasing of the steel strength when the steel strength beyond 420 MPa. For the short columns with a steel strength between 420 MPa and 575 MPa, the mean value of the experimental to calculated strength is 1.008, while for the short columns with a steel strength above 800 MPa, all

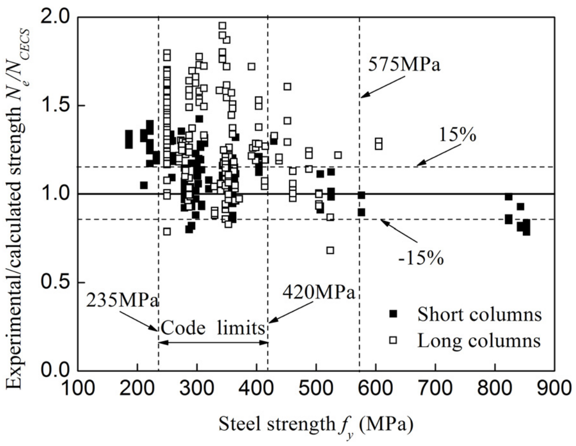


Fig. 9 Effect of steel strength on the prediction accuracy of CECS 28:2012

the calculated strength is lower than corresponding experimental results (Fig. 9). Thus, it can be concluded that there is a possibility of extending the steel strength to a higher value, though more tests are needed to verify this and determine the higher value.

5.1.3 Effect of diameter-to-thickness ratio

The effect of the diameter-to-thickness ratio on the prediction accuracy is presented in Fig. 10. The comparison results about the diameter-to-thickness ratio are shown in Table 5. As no long columns with a diameter-to-thickness ratio larger than $135 \times 235 / f_y$ were found in available literature, the comparison only carry out for short columns. It can be seen from Table 5 that there is an increase of 10.3% in the mean value when the diameter-to-thickness ratio is increased beyond the maximum diameter-to-thickness ratio regulated for the application of CECS 28:2012, which shows a tendency to relax the limitation of diameter-to-thickness ratio.

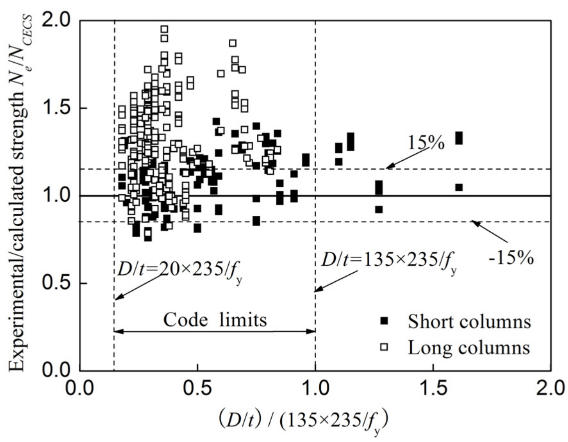


Fig. 10 Effect of diameter-to-thickness ratio on the prediction accuracy of CECS 28:2012

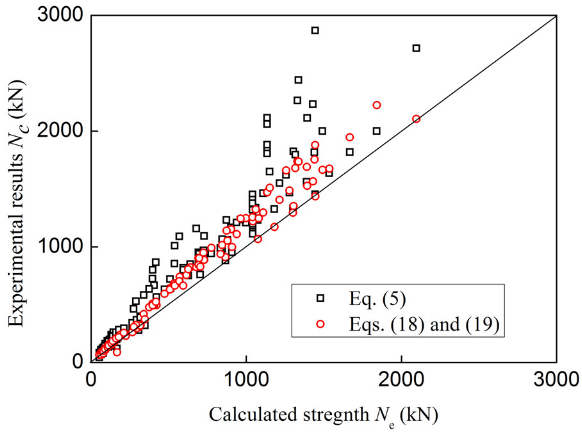


Fig. 11 Comparisons between experimental and calculated strength using Eqs. (18)-(19)

5.2 Revision of the slenderness reduction factor for CECS 28: 2012

CECS 28:2012 gives a slenderness reduction factor as shown in Eq. (5). It does not take the influence of diameter-to-thickness ratio, steel type, concrete strength and confinement index into consideration. This is unreasonable for the CFST column with a relative small slenderness ratio. Consideration of these parameters, the slenderness reduction factor can be given by

$$\varphi_1 = 0.5^{0.65\times\left(\frac{L_e}{D}\right)^2\times(1+\theta)\times\frac{f_c}{E_c}}, \quad \text{if} \quad 4 < L_e/D \le 20 \tag{18}$$

$$\varphi_1 = 1 - 0.115\sqrt{L_e/D - 4}, \quad \text{if} \quad L_e/D > 20 \tag{19}$$

When E_c is not provided in the literature, it is calculated according to GB 20010-2010 (2010). As is given as follows

$$E_c = \frac{10^5}{2.2 + \frac{34.7}{f_{cu}}} \tag{20}$$

Fig. 11 demonstrates the comparisons between experimental and calculated strengths. The calculated strengths according to Eqs. (18)-(19) (red circular dot) agree well with the experimental results. The mean value and standard deviation are 1.149 and 0.160, respectively. The comparisons between the test results and the calculated results according to Eq. (5) (black square dot) are also shown in Fig. 11. It is apparent that the proposed equation for slenderness reduction factor (see Eqs. (18)-(19)) give a more accurate prediction with smaller value of the dispersion for long CFST columns than the equation in Code (see Eq. (5)).

6. Conclusions

The following conclusions can be concluded within the present scope of investigation:

- All three codes give conservative predictions, but there are differences among different codes. CECS 28:2012 can be used with confidence for the design of short CFST columns with a mean measured to calculated ratio of 1.094. But CECS 28:2012 gives a most conservative prediction with a relative large deviation among three codes for long CFST columns.
- For long CFST columns, the equations for column slenderness reduction factor in CECS 28:2012 could be safely used to calculate the load capacity of the CFST columns with a length-to-thickness ratio beyond 20, even reaching a value of 38.5.
- As for the CFST columns with a confinement index beyond the limitation of 0.5-2.5, CECS 28:2012 also gives acceptable predictions, which is obtained from a mean value of 1.182 for the CFST columns with a confinement index below 0.5, and a mean value of 0.977 above 2.5.
- All three factors of concrete strength, steel strength and diameter-to-thickness ratio slightly affect the prediction accuracy using CECS 28:2012, the comparisons indicate a possibility to relax the limitations on the material strengths for CFST columns and a tendency to raise the maximum diameter-to-thickness ratio. The Code limitation on concrete cube strength could be safely extended to 120 MPa, while the limitation on steel strength could be safely extended to 575 MPa.
- A revised slenderness reduction factor is developed taking the influence of length-to-diameter ratio, the confinement index and the concrete strength into consideration. The calculated strengths using the revised slenderness reduction factor agree well with the experimental results.

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Appendix A. Database of circular concrete-filled steel tube (CFST) columns under axial load

Reference	No.	Dimensions of specimens				Properties of materials				Experimental results
		D (mm)	t (mm)	L (mm)	f_c' (MPa)	f_{cu} (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)	N_e (kN)
Abed *et al.* (2013)	1	167	3.1	350	60			300		1873
	2	114	3.6	250	60			301		1095
	3	114	5.6	250	60			302		1365
	4	167	3.1	350	44			303		1710
	5	114	3.6	250	44			304		1042
	6	114	5.6	250	44			305		1314
Chitawadagi *et al.* (2010)	7	44	1.3	1000		42		250		45
	8	44	1.6	1000		52		250		69
	9	44	2.0	1000		61		250		82
	10	44	1.3	1000		42		250		69
	11	44	1.6	1000		52		250		87
	12	44	2.0	1000		61		250		105
	13	44	1.3	1000		42		250		85
	14	44	1.6	1000		52		250		101
	15	44	2.0	1000		61		250		124
	16	44	1.3	700		42		250		82
	17	44	1.6	700		52		250		97
	18	44	2.0	700		61		250		127
	19	44	1.3	700		42		250		94
	20	44	1.6	700		52		250		117
	21	44	2.0	700		61		250		138
	22	44	1.3	700		42		250		110
	23	44	1.6	700		52		250		130
	24	44	2.0	700		61		250		145
	25	44	1.3	500		42		250		96
	26	44	1.6	500		52		250		117
	27	44	2.0	500		61		250		133
	28	44	1.3	500		42		250		115
	29	44	1.6	500		52		250		134
	30	44	2.0	500		61		250		148
	31	44	1.3	500		42		250		120
	32	44	1.6	500		52		250		142
	33	44	2.0	500		61		250		156
	34	57	1.3	1000		42		250		120

Reference	No.	Dimensions of specimens			Properties of materials					Experimental results
		D (mm)	t (mm)	L (mm)	f_c' (MPa)	f_{cu} (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)	N_e (kN)
Chitawadagi *et al.* (2010)	35	57	1.6	1000		52		250		135
	36	57	2.0	1000		61		250		144
	37	57	1.3	1000		42		250		152
	38	57	1.6	1000		52		250		173
	39	57	2.0	1000		61		250		188
	40	57	1.3	1000		42		250		162
	41	57	1.6	1000		52		250		182
	42	57	2.0	1000		61		250		206
	43	57	1.3	700		42		250		163
	44	57	1.6	700		52		250		182
	45	57	2.0	700		61		250		206
	46	57	1.3	700		42		250		177
	47	57	1.6	700		52		250		192
	48	57	2.0	700		61		250		222
	49	57	1.3	700		42		250		187
	50	57	1.6	700		52		250		202
	51	57	2.0	700		61		250		231
	52	57	1.3	500		42		250		172
	53	57	1.6	500		52		250		189
	54	57	2.0	500		61		250		214
	55	57	1.3	500		42		250		188
	56	57	1.6	500		52		250		206
	57	57	2.0	500		61		250		239
	58	57	1.3	500		42		250		200
	59	57	1.6	500		52		250		229
	60	57	2.0	500		61		250		256
	61	64	1.3	1000		42		250		151
	62	64	1.6	1000		52		250		186
	63	64	2.0	1000		61		250		202
	64	64	1.3	1000		42		250		169
	65	64	1.6	1000		52		250		211
	66	64	2.0	1000		61		250		231
	67	64	1.3	1000		42		250		181
	68	64	1.6	1000		52		250		227
	69	64	2.0	1000		61		250		241
	70	64	1.3	700		42		250		191

Reference	No.	Dimensions of specimens				Properties of materials				Experimental results
		D (mm)	t (mm)	L (mm)	f_c' (MPa)	f_{cu} (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)	N_e (kN)
Chitawadagi *et al.* (2010)	71	64	1.6	700		52		250		226
	72	64	2.0	700		61		250		244
	73	64	1.3	700		42		250		208
	74	64	1.6	700		52		250		241
	75	64	2.0	700		61		250		269
	76	64	1.3	700		42		250		239
	77	64	1.6	700		52		250		262
	78	64	2.0	700		61		250		280
	79	64	1.3	500		42		250		212
	80	64	1.6	500		52		250		231
	81	64	2.0	500		61		250		255
	82	64	1.3	500		42		250		242
	83	64	1.6	500		52		250		264
	84	64	2.0	500		61		250		281
	85	64	1.3	500		42		250		262
	86	64	1.6	500		52		250		283
	87	64	2.0	500		61		250		295
Dundu (2012)	88	115	3.0	1000	32	40	31.1	354	206.5	806
	89	115	3.0	1500	32	40	31.1	354	206.5	688
	90	115	3.0	2000	32	40	31.1	354	206.5	632
	91	115	3.0	2500	32	40	31.1	354	206.5	566
	92	127	3.0	1000	32	40	31.1	345	209.0	912
	93	127	3.0	1500	32	40	31.1	345	209.0	848
	94	127	3.0	2000	32	40	31.1	345	209.0	715
	95	127	3.0	2500	32	40	31.1	345	209.0	639
	96	139	3.0	1000	32	40	31.1	362	208.1	1060
	97	139	3.0	1500	32	40	31.1	362	208.1	942
	98	139	3.0	2000	32	40	31.1	362	208.1	868
	99	139	3.0	2500	32	40	31.1	362	208.1	751
	100	152	3.0	1000	26	31	28.3	488	206.7	1463
	101	152	3.0	1500	26	31	28.3	488	206.7	1209
	102	152	3.0	2000	26	31	28.3	488	206.7	1167
	103	152	3.0	2500	26	31	28.3	394	206.7	969
	104	165	3.0	1000	26	31	28.3	438	204.6	1550
	105	165	3.0	1500	26	31	28.3	438	204.6	1338

Reference	No.	Dimensions of specimens				Properties of materials				Experimental results
		D (mm)	t (mm)	L (mm)	f_c' (MPa)	f_{cu} (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)	N_e (kN)
Dundu (2012)	106	165	3.0	2000	26	31	28.3	438	204.6	1235
	106	165	3.0	2000	26	31	28.3	438	204.6	1235
	107	165	3.0	2500	26	31	28.3	430	201.6	1232
	108	194	3.0	1000	26	31	28.3	399	207.7	2000
	109	194	3.5	1500	26	31	28.3	399	207.7	1817
	110	194	3.5	2000	26	31	28.3	399	207.7	1796
	111	194	3.5	2500	26	31	28.3	392	206.8	1621
Han and Yao (2004)	112	100	3.0	300		40	37.4	304	206.5	708
	113	100	3.0	300		40	37.4	304	206.5	820
	114	100	3.0	300		40	37.4	304	206.5	766
	115	100	3.0	300		40	37.4	304	206.5	820
	116	100	3.0	300		40	37.4	304	206.5	780
	117	100	3.0	300		40	37.4	304	206.5	814
	118	200	3.0	600		40	37.4	304	206.5	2320
	119	200	3.0	600		40	37.4	304	206.5	2330
	120	200	3.0	600		40	37.4	304	206.5	2160
	121	200	3.0	600		40	37.4	304	206.5	2160
	122	200	3.0	600		40	37.4	304	206.5	2383
	123	200	3.0	600		40	37.4	304	206.5	2256
	124	200	3.0	2000		40	37.4	304	206.5	1830
	125	200	3.0	2000		40	37.4	304	206.5	1806
	126	200	3.0	2000		40	37.4	304	206.5	1882
	127	200	3.0	2000		40	37.4	304	206.5	2060
	128	200	3.0	2000		40	37.4	304	206.5	2115
Han (2004b)	129	108	4.5	4158		31.8	27.6	348	202	342
	130	108	4.5	4158		31.8	27.6	348	202	292
	131	108	4.5	4158		46.8	28.4	348	202	298
	132	108	4.5	4158		46.8	28.4	348	202	280
	133	108	4.5	4023		46.8	28.4	348	202	318
	134	108	4.5	4023		46.8	28.4	348	202	320
	135	108	4.5	3807		31.8	27.6	348	202	350
	136	108	4.5	3807		31.8	27.6	348	202	370
	137	108	4.5	3510		31.8	27.6	348	202	400
	138	108	4.5	3510		31.8	27.6	348	202	390
	139	108	4.5	3510		46.8	28.4	348	202	440

Reference	No.	Dimensions of specimens				Properties of materials				Experimental results
		D (mm)	t (mm)	L (mm)	f_c' (MPa)	f_{cu} (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)	N_e (kN)
Giakoumelis and Lam (2004)	140	114	4.0	300		31.4		343		948
	141	114	4.0	300		93.6		343		1308
	142	114	4.9	300		34.7		365		1380
	143	114	4.9	300		104.9		365		1787
	144	114	5.0	300		57.6		365		1413
	145	114	3.8	300		57.6		343		1067
	146	114	3.9	300		31.9		343		998
	147	114	3.8	300		98.9		343		1359
Gupta *et al*. (2007)	148	47	1.9	340		25.2		360		215
	149	47	1.9	340		28.9		360		215
	150	47	1.9	340		28.2		360		210
	151	89	2.7	340		25.2		360		610
	152	89	2.7	340		28.9		360		630
	153	89	2.7	340		28.2		360		524
	154	113	2.9	340		25.2		360		754
	155	113	2.9	340		28.9		360		730
	156	113	2.9	340		28.2		360		745
	157	47	1.9	340		37.6		360		215
	158	47	1.9	340		40.0		360		215
	159	47	1.9	340		37.8		360		210
	160	89	2.7	340		37.6		360		610
	161	89	2.7	340		40.0		360		630
	162	89	2.7	340		37.8		360		524
	163	113	2.9	340		37.6		360		754
	164	113	2.9	340		40.0		360		730
	165	113	2.9	340		37.8		360		745
Kato (1996)	166	95	3.1	861	25.0			350		667
	167	95	3.1	1420	25.0			350		583
	168	95	3.1	1981	25.0			350		529
	169	216	3.1	2220	22.8			292		1650
	170	216	3.1	2220	29.8			292		2264
	171	216	3.1	2220	22.8			392		2442
	172	216	3.1	2220	29.8			350		2869
	173	95	3.1	2032	24.0			338		463
	174	121	3.1	1049	21.1			312		721
	175	121	3.1	1049	24.2			312		854

Reference	No.	Dimensions of specimens				Properties of materials				Experimental results
		D (mm)	t (mm)	L (mm)	f_c' (MPa)	f_{cu} (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)	N_e (kN)
Kato (1996)	176	121	3.1	2311	21.1			312		636
	177	121	3.1	2311	24.2			312		725
	178	121	3.1	1049	21.1			343		1010
	179	121	3.1	1049	24.2			343		1090
	180	121	3.1	2311	21.1			343		801
	181	121	3.1	2311	24.1			343		867
	182	51	3.1	1067	27.9			524		121
	183	76	3.1	1067	27.3			524		320
	184	102	3.1	1524	34.1			605		818
	185	102	3.1	1524	34.1			605		801
	186	121	3.1	1049	24.4			452		1157
	187	121	3.1	1049	29.6			452		1094
	188	121	3.1	1049	25.9			452		952
	189	152	3.1	2271	20.9			415		939
	190	152	3.1	2271	20.9			415		881
	191	77	3.1	1524	25.0			364		245
	192	168	3.1	813	43.3			298		2233
	193	168	3.1	813	43.3			298		2113
	194	160	5.2	2500	71.0			281		1562
	195	160	5.1	3000	73.0			276		1468
	196	160	5.0	3500	74.0			276		1326
	197	160	5.0	4000	71.0			281		1231
	198	160	5.0	2000	99.0			281		2000
	199	160	5.0	2500	100.0			275		1818
	200	160	5.0	3000	101.0			275		1636
	201	160	5.0	3500	106.0			270		1454
	202	160	5.0	4000	102.0			270		1333
	203	100	1.9	900	110.0			404		1065
	204	100	1.9	900	110.0			404		980
O'Shea and Bridge (2000)	205	165	2.8	581	48.3		21.2	363	200.6	1662
	206	190	1.9	664	41.0		17.8	256	204.7	1678
	207	190	1.5	665	48.3		21.2	306	207.4	1695
	208	190	1.1	665	41.0		17.8	186	178.4	1377
	209	190	0.9	659	41.0		17.8	211	177.0	1350
	210	165	2.8	581	80.2		28.4	363	200.6	2295
	211	190	1.9	664	74.7		27.6	256	204.7	2592

Reference	No.	Dimensions of specimens				Properties of materials				Experimental results
		D (mm)	t (mm)	L (mm)	f'_c (MPa)	f_{cu} (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)	N_e (kN)
O'Shea and Bridge (2000)	212	190	1.5	665	80.2		28.5	306	207.4	2602
	213	190	1.1	665	80.2		28.5	186	178.4	2295
	214	190	0.9	659	108.0		27.6	211	177.0	2451
	215	165	2.8	581	108.0		29.8	363	200.6	2673
	216	190	1.9	664	108.0		29.8	256	204.7	3360
	217	190	1.5	665	108.0		29.8	306	207.4	3260
	218	190	1.1	665	108.0		29.8	186	178.4	3058
	219	190	0.9	659	108.0		29.8	211	177.0	3070
Oliveira *et al*. (2009)	220	114	3.4	343	32.5			287		737
	221	114	3.4	343	32.5			287		740
	222	114	3.4	343	32.5			287		632
	223	114	3.4	343	32.5			287		599
	224	114	3.4	572	58.7			287		952
	225	114	3.4	572	58.7			287		903
	226	114	3.4	572	58.7			287		869
	227	114	3.4	572	58.7			287		809
	228	114	3.4	800	88.8			287		1136
	229	114	3.4	800	88.8			287		1181
	230	114	3.4	800	88.8			287		1198
	231	114	3.4	800	88.8			287		1112
	232	114	3.4	1143	105.5			287		1453
	233	114	3.4	1143	105.5			287		1407
	234	114	3.4	1143	105.5			287		1376
	235	114	3.4	1143	105.5			287		1320
Sakino *et al*. (2004)	236	149	3.0		25.4			308		941
	237	149	3.0		40.5			308		1064
	238	149	3.0		40.5			308		1080
	239	149	3.0		77.0			308		1781
	240	300	3.0		25.4			279		2382
	241	300	3.0		41.1			279		3277
	242	300	3.0		41.1			279		3152
	243	300	3.0		80.3			279		5540
	244	450	3.0		25.4			279		4415
	245	450	3.0		41.1			279		6870
	246	450	3.0		41.1			279		6985
	247	450	3.0		85.1			279		11665

Reference	No.	Dimensions of specimens				Properties of materials				Experimental results
		D (mm)	t (mm)	L (mm)	f_c' (MPa)	f_{cu} (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)	N_e (kN)
Sakino *et al*. (2004)	248	122	4.5		25.4			576		1509
	249	122	4.5		40.5			576		1657
	250	122	4.5		40.5			576		1663
	251	122	4.5		77.0			576		2100
	252	238	4.5		25.4			507		3035
	253	238	4.5		40.0			507		3583
	254	238	4.5		40.0			507		3647
	255	238	4.5		77.0			507		5578
	256	360	4.5		25.4			525		5633
	257	360	4.5		41.1			525		7260
	258	360	4.5		41.1			525		7045
	259	360	4.5		85.1			525		11505
	260	108	6.5		25.4			853		2275
	261	108	6.5		40.5			853		2446
	262	108	6.5		40.5			853		2402
	263	108	6.5		77.0			853		2713
	264	222	6.5		25.4			843		4964
	265	222	6.5		40.5			843		5638
	266	222	6.5		40.5			843		5714
	267	222	6.5		77.0			843		7304
	268	337	6.5		25.4			823		8475
	269	337	6.5		41.1			823		9668
	270	337	6.5		41.1			823		9835
	271	337	6.5		85.1			823		13776
Schneider (1998)	272	140	3.0	602	28.2		25.6	285	189.5	881
	273	140	6.5	602	23.8		23.5	313	206.0	1825
	274	140	6.7	581	28.2		25.6	537	205.3	2715
Tan *et al*. (1999)	275	125	1.0	438		116.0		232		1275
	276	125	1.0	438		116.0		232		1239
	277	127	2.0	445		116.0		258		1491
	278	127	2.0	445		116.0		258		1339
	279	133	3.5	465		116.0		352		1995
	280	133	3.5	465		116.0		352		1991
	281	133	3.5	465		116.0		352		1962
	282	133	4.7	465		116.0		352		2273
	283	133	4.7	465		116.0		352		2158

Reference	No.	Dimensions of specimens				Properties of materials				Experimental results
		D (mm)	t (mm)	L (mm)	f_c' (MPa)	f_{cu} (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)	N_e (kN)
Tan *et al*. (1999)	284	133	4.7	465		116.0		352		2253
	285	127	7.0	445		116.0		429		3404
	286	127	7.0	445		116.0		429		3370
	287	127	7.0	445		116.0		429		3364
Tan and Pu (2000)	288	108	4.5	378		106		358		1535
	289	108	4.5	378		106		358		1578
	290	108	4.5	378		106		358		1518
	291	108	4.5	756		106		358		1286
	292	108	4.5	756		106		358		1280
	293	108	4.5	1188		106		358		1194
	294	108	4.5	1188		106		358		1232
	295	108	4.5	1620		106		358		974
	296	108	4.5	1620		106		358		1018
Uy *et al*. (2011)	297	51	1.2	150	20.0			291		106
	298	51	1.2	150	30.0			291		112
	299	51	1.2	150	20.0			291		134
	300	51	1.2	150	30.0			291		130
	301	51	1.6	150	20.0			298		132
	302	51	1.6	150	30.0			298		140
	303	51	1.6	150	20.0			298		167
	304	51	1.6	150	30.0			298		162
	305	102	1.6	300	20.0			320		421
	306	102	1.6	300	30.0			320		426
	307	102	1.6	300	20.0			320		477
	308	102	1.6	300	30.0			320		477
	309	127	1.6	400	20.0			274		664
	310	127	1.6	400	30.0			274		685
	311	127	1.6	400	20.0			274		743
	312	127	1.6	400	30.0			274		748
	313	152	1.6	450	20.0			279		816
	314	152	1.6	450	30.0			279		801
	315	152	1.6	450	20.0			279		904
	316	152	1.6	450	30.0			279		890
	317	203	2.0	500	20.0			259		390
	318	203	2.0	500	30.0			259		378
	319	203	2.0	500	20.0			259		522

Reference	No.	Dimensions of specimens				Properties of materials				Experimental results
		D (mm)	t (mm)	L (mm)	f_c' (MPa)	f_{cu} (MPa)	E_c (GPa)	f_y (MPa)	E_s (GPa)	N_e (kN)
Uy *et al*. (2011)	320	203	2.0	500	30.0			259		550
Yu *et al*. (2008)	321	100	1.9	300		121.6	42.6	404	207	1125
	322	100	1.9	300		121.6	42.6	404	207	1085
	323	100	1.9	300		121.6	42.6	404	207	1000
	324	100	1.9	300		121.6	42.6	404	207	1170
	325	100	1.9	900		121.6	42.6	404	207	1065
	326	100	1.9	900		121.6	42.6	404	207	980
	327	100	1.9	1500		121.6	42.6	404	207	907
	328	100	1.9	1500		121.6	42.6	404	207	760
	329	100	1.9	3000		121.6	42.6	404	207	288
	330	100	1.9	3000		121.6	42.6	404	207	318
Zeghiche and Chaoui (2005)	331	160	5.0	2000	40.0		32	280	212	1261
	332	160	5.0	2500	41.0		32	281	212	1244
	333	160	5.0	3000	43.0		32	270	212	1236
	334	160	5.0	3500	41.0		32	273	212	1193
	335	160	5.0	4000	45.0		32	281	212	1091
	336	160	5.0	2000	70.0		42	283	212	1650
	337	160	5.2	2500	71.0		42	281	212	1562
	338	160	5.1	3000	73.0		42	276	212	1468
	339	160	5.0	3500	74.0		42	276	212	1326
	340	160	5.0	4000	71.0		42	281	212	1231
	341	160	5.0	2000	99.0		45	281	212	2000
	342	160	5.0	2500	100.0		45	275	212	1818
	343	160	5.0	3000	101.0		45	275	212	1636
	344	160	5.0	3500	106.0		45	270	212	1454
	345	160	5.0	4000	102.0		45	270	212	1333
Zhang *et al*. (2005)	346	180	1.6	555		53.1		221	197	1287
	347	180	1.6	555		24.8		221	197	1040
	348	150	1.5	459		53.1		221	197	1024
	349	150	1.5	459		24.8		221	197	666
	350	135	1.5	417		53.1		221	197	800
	351	135	1.5	417		24.8		221	197	594
	352	120	1.5	369		53.1		221	197	690
	353	120	1.5	369		24.8		221	197	500