

*Article*

## Evaluation of AISC 360-16 and Eurocode 4 Compressive Strength Equations for Concrete-Filled Steel Tube Columns

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**Abstract.** This paper presents a review and evaluation of the AISC 360-16 and Eurocode 4 strength prediction equations for concrete-filled steel tube (CFST) columns subjected to axial compression. A new experimental database of CFST column test results is compiled from the published technical literature from year 1988 to present. The database includes up-to-date research data of which column properties are outside the specification or code limitations. A total of 335 and 257 columns of different properties regarding the material strength, column size and slenderness, confinement factor, and steel tube fabrication method (only for square CFST) are used to evaluate the accuracy and conservativeness of the predictions for circular and square CFST columns. It is found that the AISC 360-16 strength equations conservatively predict the compressive strength of circular CFST columns even the tube slenderness exceeds the current specification limit, while the simplified method of Eurocode 4 is not recommended for square CFST columns when the yield strength of steel tube or tube slenderness ratio exceeds the code limits. Based on the strength prediction equations, the effectiveness of circular over square CFST columns is more realized in Eurocode 4 than AISC360-16. The predicted circular-to-square column strength ratio increases as confinement factor increases, while it decreases as column length-to-depth ratio increases. Based on the experimental database, the effect of column sizes on the normalized strength of circular CFST columns is also investigated. The different tendency of the size effect is found when the confinement factor changes.

**Keywords:** Concrete-filled steel tube columns, experimental database, code predictions, size effect, confinement factor.

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## 1. Introduction

Concrete-filled steel tube (CFST) columns have been widely used for bridges and high-rise buildings due to the advantage of combining steel tube and concrete. For CFST columns subjected to axial compression, concrete core improves the local buckling resistance of steel tube, while the steel tube enhances both strength and ductility of concrete core due to the confinement effect. In the design of CFST columns, AISC 360-16 [1] and Eurocode 4 [2] provide different predicting equations for compressive strength of CFST columns with different limitations on material strength, steel ratio and slenderness of steel tube section.

Based on numerous experimental studies on CFST columns, previous researchers have compiled the test results for different specific purposes. Kato (1996) [3] examined the column buckling curves of ISO standard 1994 with 113 test results of circular and square CFST columns. A total 76 rectangular CFST columns were collected by Zhang and Shahrooz (1999) [4] to examine the applicability of ACI 1995 and AISC 1994. The examination indicated that neither design method is applicable for high-strength steel tube. Lu and Zhao (2010) [5] collected 250 experimental tests of circular CFST columns and proposed the empirical models for predicting the axial capacity of normal and high-strength circular CFST stub columns. Lai et al. (2014) [6] and Lai and Varma (2015) [7] compiled the experimental results of noncompact/slender circular and rectangular CFST sections to validate the developed benchmark finite element models and verify the conservativeness of AISC 360-10 design equations. The result showed that AISC 360-10 equations are appropriate when rectangular CFST columns are classified into compact, noncompact and slender section. Also, the design equations conservatively predict the compressive strength of CFST columns. Aslani et al. (2015) [8] examined the appropriateness of eight design codes for predicting the axial load capacity of CFST columns using high strength materials using the collected experimental results and indicated that Eurocode 4 is the most accurate for predicting the capacity of slender CFST experimental results. Ekmekyapar and AL-Eliwi (2016) [9] compiled 239 experimental data of circular CFST columns from the literature to assess AISC360-10 and Eurocode 4 equations and reported that predictions by Eurocode 4 are in better agreement with the test results. In addition, comprehensive databases of experimental and analytical research work on CFST members have been developed by Shanmugam and Lakshmi (2001) [10], Kim (2005) [11], Gourley et al. (2008) [12] and Hajjar et al. (2019) [13].

It has been recognized that the compressive strength of concrete is dependent on the size of concrete. This size effect causes the compressive strength of concrete to decrease when size of concrete increases [14]. As concrete core is an essential component of the CFST column, the size effect is possible in the CFST column.

However, the size effect in CFST column of which concrete core is confined with the steel tube can be different from unconfined concrete. Yamamoto et al. (2002) [15] investigated the size effect in CFST columns from 21 circular and square CFST specimens under axial compression. The outer diameter of the steel tube and strength of concrete varied from 100 to 200 mm and 27 to 50 MPa, respectively. The steel ratio was 13%. The results showed that the size effect in circular CFST columns was not clearly observed. Subsequently, Wang et al. (2017) [16] conducted the test on 36 short circular CFST columns with different diameters (from 150 to 469 mm) and steel ratio (from 4 to 10%). The compressive strength of concrete was 62 MPa. The test results showed that the peak axial stress of circular CFST columns tended to decrease as diameter and steel ratio increased. However, the current design equations do not have specific provision regarding the size effect.

The main objectives of this study are as follows: (1) to evaluate the accuracy and conservativeness of AISC 360-16 and Eurocode 4 design equations based on the newly-developed experimental database; (2) to compare the effectiveness of circular over square CFST columns using the design equations; and (3) to investigate the influence of a confinement factor on the size effect of circular CFST columns based on the database. The confinement factor ( $\xi$ ), which is a ratio between the maximum capacities of steel tube and concrete ( $A_s f_y / A_c f'_c$ ), represents the combined effect of steel ratio and material strength on the CFST column. Han et al. (2005) [17] introduced this confinement factor to describe the composite action between steel tube and concrete in the developed model for calculating the sectional capacity of CFST columns. Guo et al. (2007) [18] used the confinement factor to account for the confinement effect of concrete in the proposed simplified model for determining the load capacity of rectangular CFST columns. Han et al (2014) [19] also reported that the confinement of concrete core increased as confinement factor increased. In this research the confinement factor ( $\xi$ ) is used in the investigation of column size effect.

## 2. Description on New Experimental Database of CFST Columns

To investigate the effects of column properties (material strength, column slenderness, fabrication method of steel tube in square CFST section) on accuracy and conservativeness of the strength equations, a new experimental database is developed by compiling the experimental results of circular and square CFST columns from the published literature from year 1988 to present. The database has the following scope:

1. Normal weight concrete is filled in steel tube with no reinforcing steel rebar.
2. Steel tube is fabricated from carbon steel.

3. Test configuration is clearly reported in the literature.
4. Axial compressive load is applied on entire section (steel and concrete) with no eccentricity.
5. For square CFST columns, the cold-formed and welded-box section are separately compiled in experimental database.

In the calculation, the following assumptions are made: The cube compressive strength is converted into the cylinder compressive strength using the relationship proposed by Eurocode 2 [20]. The effective length factor ( $K$ ) is 0.5 and 1.0 for fixed end and pinned end supports, respectively. Also, no effect of loading rate and eccentricity in the test results is assumed.

Tables 1 and 2 summarize column properties in the experimental database of circular (335 specimens) and square (257 specimens) CFST columns, respectively.

Column parameters include the outer diameter of steel tube ( $D$  or  $B$ ), steel tube thickness ( $t$ ), column length ( $L$ ), compressive strength of concrete cylinder ( $f'_c$ ), and yield strength of steel tube ( $f_y$ ). The ultimate compressive strengths of tested CFST columns, denoted by  $P_u$ , from each reference, are also shown.

Figures 1 and 2 show histograms of columns parameters for circular and square CFST columns in the new database, respectively. Table 3 lists the limitation for column parameters as specified in AISC 360-16 and Eurocode 4. These limits are also indicated in the figures. Therefore, the new database contains a significant number of test data of columns having properties outside the specification and code limits. In this study, the high-strength material is denoted when material strengths exceed the AISC 360-16 limits specified in Table 3.

Table 1. New experimental database of circular CFST columns.

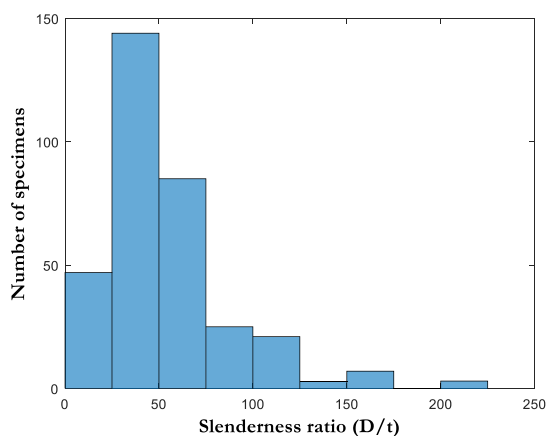
Ref.	No. of columns	$D$ (mm)	$t$ (mm)	$L$ (mm)	$f'_c$ (MPa)	$f_y$ (MPa)	$P_u$ (kN)
[21]	12	174-179	3.0-9.0	360	22-46	248-283	1304-3217
[22]	6	152	1.7	500-900	73-85	270-328	1458-1895
[23]	6	165	4.5	661-4956	41	414	782-1563
[24]	3	140	3.0-6.7	635	23-28	285-537	881-2715
[25]	12	108-133	3.5	7.0	77-85	352-429	1518-3404
[26]	15	165-190	0.9-2.8	577-664	41-108	186-363	1350-3360
[27]	11	108	4.5	3510-4158	26-37	348	280-440
[15]	13	101-318	3.0-10.4	304-956	23-53	331-452	649-8289
[28]	6	110-165	1.9-4.7	2200-2475	27	350-355	355-1058
[29]	8	114-115	3.7-5.0	300	26-90	343-265	948-1787
[30]	36	108-450	3.0-6.5	324-1350	24-82	279-853	941-13776
[31]	17	100-200	3.0	300-2000	48	303	708-2383
[32]	15	160	5.0	2000-4000	40-106	270-283	1091-2000
[33]	6	165-219	2.7-4.8	510-650	33-62	350	1560-3400
[34]	6	89-112	2.7-2.9	340	23	360	620-822
[35]	10	100	1.9	300-3000	104	404	288-1170
[36]	16	114	3.3	343-800	31-101	287	737-1453
[37]	2	300-360	6.0-12.0	1580-1760	31.5	479-498	6888-9823
[38]	24	115-194	3.0-3.5	1000-2500	26-32	345-488	566-2000
[39]	6	114-219	3.5-9.7	250-600	52-178	377-428	1550-6121
[40]	3	159	6	2135	38-120	394-487	1414-2792
[41]	3	558-559	16.5	995-997	26	546	28830-29590
[9]	18	114	2.7-5.9	300-900	54-103	235-355	877-1990
[42]	12	114-219	3.6-10.0	250-600	49-178	300-428	2340-9085
[43]	2	219-273	10.0-16.0	4195	173-178	374-412	6402-8648
[16]	36	153-477	1.5-11.4	306-954	62	290-345	1823-20462
[44]	12	216-632	2.6-11.2	657-1890	50	260-590	4030-29463
[45]	15	141-262	2.1-3.0	525-975	40-43	691-734	1550-4302
[46]	4	209-211	2.0-3.0	1370-2170	28-36	256-297	1405-1606

Table 2. New experimental database of square CFST columns.

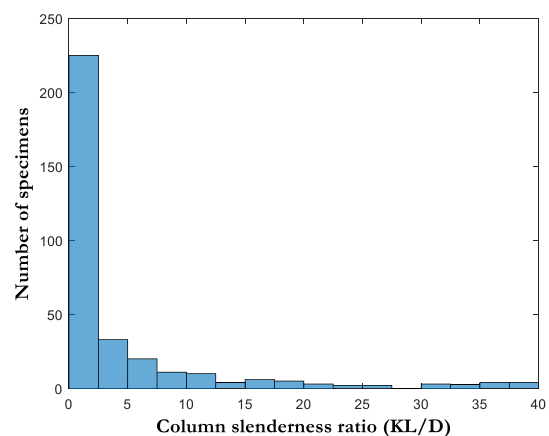
Ref.	No. of columns	$B$ (mm)	$t$ (mm)	$L$ (mm)	$f'_c$ (MPa)	$f_y$ (MPa)	$P_u$ (kN)
a. cold-formed steel section							
[47]	6	150	0.7-2.1	480-800	22-35	245	558-974
[23]	6	150	4.3	599-4494	32	438	909-1598
[24]	5	127	3.1-7.5	635	24-30	312-357	917-2069
[48]	4	305	5.8-8.9	1200	110	259-660	11390-14116
[15]	8	100-301	2.2-6.1	301-902	26-64	300-395	609-6496
[30]	48	119-323	4.4-9.4	360-969	24-87	262-835	1153-10357
[28]	6	100-140	2.0-5.0	2100-2500	27	240-366	342-1248
[49]	27	60-150	3.0-4.5	1000-2700	26-29	335-528	105-1516
[50]	6	200	6.1-10.3	600	20	382-438	2730-3980
b. welded-box section							
[51]	4	100-120	2.9	300-360	49	228	760-1050
[52]	4	65-75	3	1770	52-79	455-468	294-414
[53]	6	100-183	4.2	300-540	57-67	550	1490-4210
[54]	3	120	2.7	360-1400	16-29	340	640-816
[55]	2	130	2.7	780	18	340	760-770
[31]	11	200	3.0	600-2310	49	303	1986-2594
[56]	4	120-270	5.0	430-880	20	761	1835-3950
[57]	2	200	2.5	1190-2340	48	270	2260-2305
[58]	6	150	2.9-4.9	1085-3101	79	317-319	1558-2597
[35]	10	100	1.9	300-3000	105	404	466-1220
[59]	4	410-500	10-16	1230-1500	42	358-389	12800-17900
[60]	3	250-251	3.7	750	32	324	2677-3131
[61]	12	80-200	5.0	210-570	21-54	701	1367-3882
[62]	39	84-210	4.9	1512-3512	113	762	286-6329
[63]	16	83-209	4.9	285-1514	100-113	762	1636-7506
[42]	15	150	8.0-12.5	450	141-157	446-779	5911-8912

Table 3. Limitation for column parameters specified in AISC360-16 and Eurocode 4.

Limitation	AISC 360-16	Eurocode 4
Strength of concrete (MPa)	$21 \leq f'_c \leq 69$	$20 \leq f'_c \leq 50$
Yield strength of steel (MPa)	$f_y \leq 525$	$235 \leq f_y \leq 460$
Amount of steel	$A_s / A_g \geq 0.01$	$0.2 \leq A_s f_y / N_{pl,Rd} \leq 0.9$
Maximum $D/t$ (circular)	$D/t \leq 0.31 (E_s / f_y)$	$D/t \leq 90 (235 / f_y)$
Maximum $b/t$ (square)	$b/t \leq 5.0 \sqrt{E_s / f_y}$	$b/t \leq 52 \sqrt{235 / f_y}$



(a) Steel tube slenderness ratio



(b) Column slenderness ratio

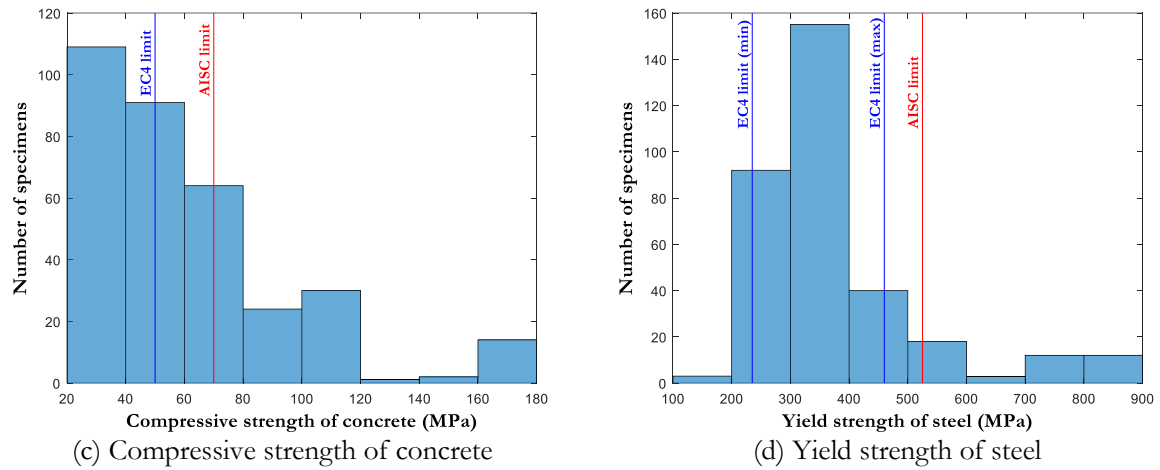


Fig. 1. Histograms of parameters of circular CFST columns in database.

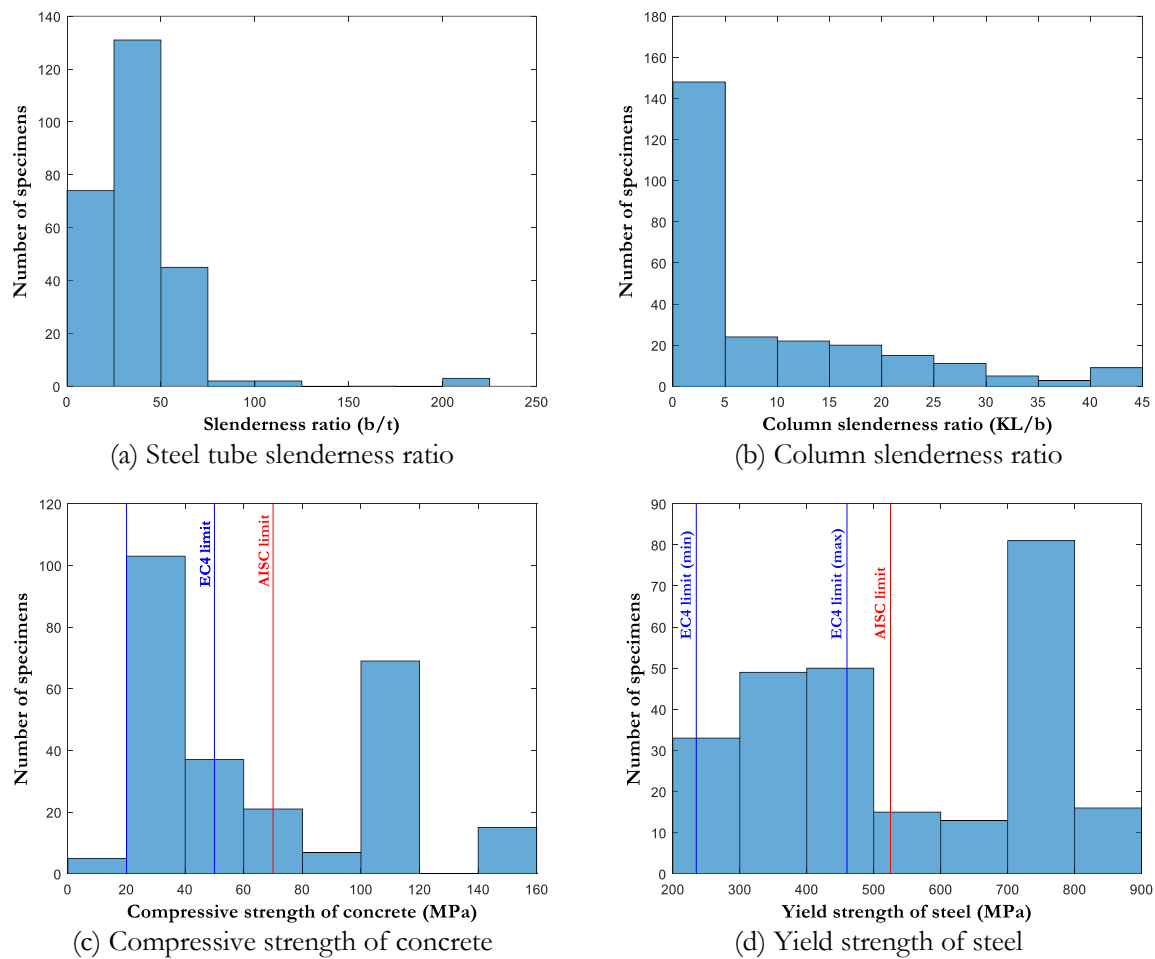


Fig. 2. Histograms of parameters of square CFST columns in database.

### 3. AISC 360-16 (2016) Provision for Compressive Strength of CFST Columns

The AISC 360-16 specification provides an approach for predicting the compressive strength of CFST columns within the specified limitations (Table 3). The compressive strength of CFST columns is determined in accordance with the CFST section classification for local buckling, as shown in Fig. 3, where  $\lambda_p = 0.15E_s / f_y$  (for a circular section) and  $2.26\sqrt{E_s / f_y}$  (for a square section),  $\lambda_r = 0.19E_s / f_y$  (for a circular section) and  $3.00\sqrt{E_s / f_y}$  (for a square section).

For a compact section, the compressive strength of the CFST section ( $P_{no}$ ) is equal to the plastic strength of section ( $P_p$ ) as follows,

$$P_{no} = P_p = A_s f_y + C_2 A_c f'_c \quad (1)$$

where  $C_2$  is equal to 0.85 and 0.95 for square and circular CFST columns, respectively, due to the confinement effect of circular section.

For a non-compact section, the compressive strength is determined by

$$P_{no} = P_p - \frac{P_p - P_y}{(\lambda_r - \lambda_p)^2} (\lambda - \lambda_p)^2 \quad (2)$$

where  $P_y$  is the yield strength of composite section given by

$$P_y = A_s f_y + 0.7 A_c f'_c \quad (3)$$

Finally, the compressive strength of the slender section is determined by

$$P_{no} = A_s F_{cr} + 0.7 A_c f'_c \quad (4)$$

where  $F_{cr}$  is the critical local buckling stress calculated from Eq. (5) and Eq. (6) for square and circular CFST, respectively.

For a square section:

$$F_{cr} = \frac{9E_s}{(b/t)^2} \quad (5)$$

For a circular section:

$$F_{cr} = \frac{0.72f_y}{((D/t)(f_y/E_s))^{0.2}} \quad (6)$$

Based on the column slenderness, the nominal compressive strength is determined as follows:

When  $P_{no} / P_e \leq 2.25$ :

$$P_n = P_{no} (0.658^{P_{no}/P_e}) \quad (7)$$

When  $P_{no} / P_e > 2.25$ :

$$P_n = 0.877 P_e \quad (8)$$

where  $P_e$  is the Euler critical buckling load (Eq. (9)). The effective stiffness of composite section ( $EI_{eff}$ ) is determined from Eq. (10), and the coefficient  $C_3$  is determined from Eq. (11).

$$P_e = \pi^2 (EI_{eff}) / (KL)^2 \quad (9)$$

$$EI_{eff} = E_s I_s + C_3 E_c I_c \quad (10)$$

$$C_3 = 0.45 + 3(A_s / A_g) \leq 0.9 \quad (11)$$

where  $E_s$  and  $E_c$  are the elastic moduli of steel and concrete, respectively;  $I_s$  and  $I_c$  are the moment of inertia of steel tube and core concrete, respectively. In the LRFD method, the design compressive strength is  $\phi_c P_n$ , where the strength reduction factor ( $\phi_c$ ) is equal to 0.75. In this study, the symbol  $\bar{\lambda}_{AISC}$ , which is  $\sqrt{P_{no} / P_e}$ , denotes the relative slenderness for the normalized AISC column strength curves to be discussed in the following section.

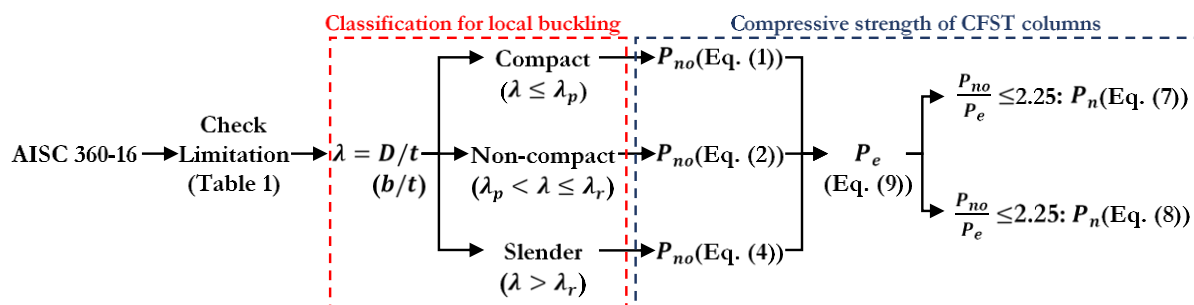


Fig. 3. AISC 360-16 procedure for determining compressive strength of CFST columns.

#### 4. Eurocode 4 Simplified Method for Compressive Strength of CFST Columns

For the doubly symmetrical and uniform cross-section over the member length, the compressive strength of CFST columns can be determined by following the procedure in Fig. 4. Limitations on the column parameters are given in Table 3. The effect of local buckling can be neglected when slenderness of steel section is less than the specified limits. The Eurocode 4 considers the fully plastic resistance of concrete ( $A_c f'_c$ ) due to good curing conditions in CFST columns [64]. Therefore, the plastic resistance of CFST section ( $N_{pl,Rd}$ ) is calculated as follows,

$$N_{pl,Rd} = A_s f_y + A_c f'_c \quad (12)$$

To consider the confinement effect in circular CFST columns, the plastic resistance is calculated from Eq. (13) where the reduction factor of steel strength ( $\eta_a$ ) and the amplification factor of concrete strength ( $\eta_c$ ) are determined from Eqs. (14) and (15), respectively

$$N_{pl,Rd} = \eta_a A_s f_y + (1 + \eta_c \frac{t}{D} \frac{f_y}{f_c}) A_c f'_c \quad (13)$$

$$\eta_a = 0.25(3 + 2\bar{\lambda}) \leq 1.0 \quad (14)$$

$$\eta_c = 4.9 - 18.5\bar{\lambda} + 17\bar{\lambda}^2 \geq 0 \quad (15)$$

However, the confinement effect is not considered when the relative slenderness ( $\bar{\lambda} = \sqrt{N_{pl,Rd} / N_{cr}}$ ) exceeds 0.5, where  $N_{cr}$  is the Euler critical load with the effective stiffness determined by

$$EI_{eff} = E_s I_s + 0.6 E_c I_c \quad (16)$$

Finally, the plastic resistance of CFST section is multiplied by the below reduction factor ( $\chi$ ),

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}} \leq 1.0 \quad (17)$$

where parameter  $\Phi$  can be determined from Eq. (18) for the CFST columns,

$$\Phi = 0.5[1 + 0.21(\bar{\lambda} - 0.2) + \bar{\lambda}^2] \quad (18)$$

In the Eurocode 4, the partial safety factor is used to reduce the strength of materials. The design material strength is determined by dividing the nominal compressive strength of concrete and yield strength of steel by partial safety factors of 1.5 and 1.0, respectively.

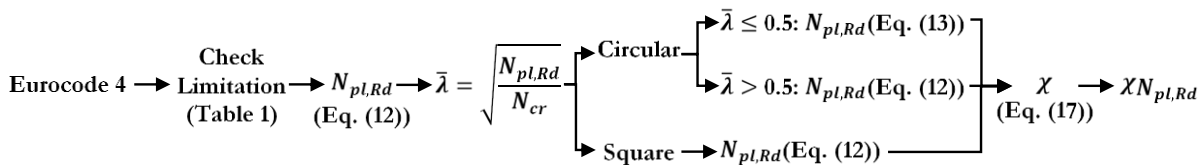


Fig. 4. Eurocode 4 procedure for determining compressive strength of CFST columns.

#### 5. Accuracy of Specification and Code Predictions

In the evaluation of specification and code predictions, the experimental data of CFST columns are classified into four groups based on the strength of constituent materials: (1) Normal-strength steel tube filled with normal-strength concrete (NS with NC), (2) Normal-strength steel tube filled with high-strength concrete (NS with HC), (3) High-strength steel tube filled with normal-strength concrete (HS with NC) and (4) High-strength steel tube filled with high-strength concrete (HS with HC). The high-strength material is denoted when the material strength exceeds the AISC 360-16 limits (Table 3).

Figures 5 to 10 show the normalized column buckling curves, i.e., column buckling curves normalized with the calculated cross-sectional strength. For a comparison purpose, the test data are also normalized

and plotted in the corresponding figures. Tables 4 and 5 summarize the average strength prediction ratios for circular and square CFST sections, respectively. The  $P_{exp} / P_{AISC}$  or  $P_{exp} / P_{EC4}$  ratio denotes the ratio of experimental strength to calculated strength based on AISC360-16 or Eurocode 4. The effect of column parameters on the accuracy of strength equations for circular and square CFST sections will be discussed in the following subsections.

##### 5.1. Circular CFST Columns

###### 5.1.1. Effect of material strength

AISC 360-16: As shown in Fig. 5, the AISC equations conservatively predict the strength of circular CFST for all groups of material strength, especially for HS with NC and HS with HC. All test data are plotted well above the AISC factored column strength curve.

The AISC curve with the reduction factor ( $\phi_c P_n$ ) is plotted with a dashed line. As shown in Fig. 5(a), the AISC strength prediction becomes less conservative for the compact sections of normal-strength steel tube filled with extra high strength concrete ( $f'_c = 178$  MPa)

Eurocode 4: As shown in Fig. 6, the Eurocode 4 equations accurately predict the strength of NS with NC and NS with HC groups. In Table 4, the average strength prediction ratios (no partial safety factor) are close to 1.00, except for HS with NC and HS with HC groups where  $P_{exp}/P_{EC4} < 1.00$ . When the partial safety factor is considered (Fig. 7), the prediction is found to be unconservative for nine short CFST columns of normal-strength steel tube filled with extra high strength concrete ( $f'_c = 178$  MPa) or extra high strength steel tube ( $f_y = 853$  MPa) filled with normal-strength concrete.

### 5.1.2. Effect of column slenderness

AISC 360-16: As shown in Fig. 5, the AISC equations are highly conservative for non-slender columns of all section classifications (compact, non-compact and slender). On the other hand, the prediction is accurate for a compact section even when the relative slenderness of column is higher than 0.9. Also, the strength of short columns with section slenderness exceeding the maximum  $D/t$  limit can be conservatively predicted with the current equations for a slender section.

Eurocode 4: As shown in Fig. 7(a), the Eurocode 4 equations overestimate the strength of some tested columns with the relative slenderness less than 0.43. The prediction is also unconservative for four short CFST columns with tube slenderness beyond the limit, as shown in Fig. 7(b).

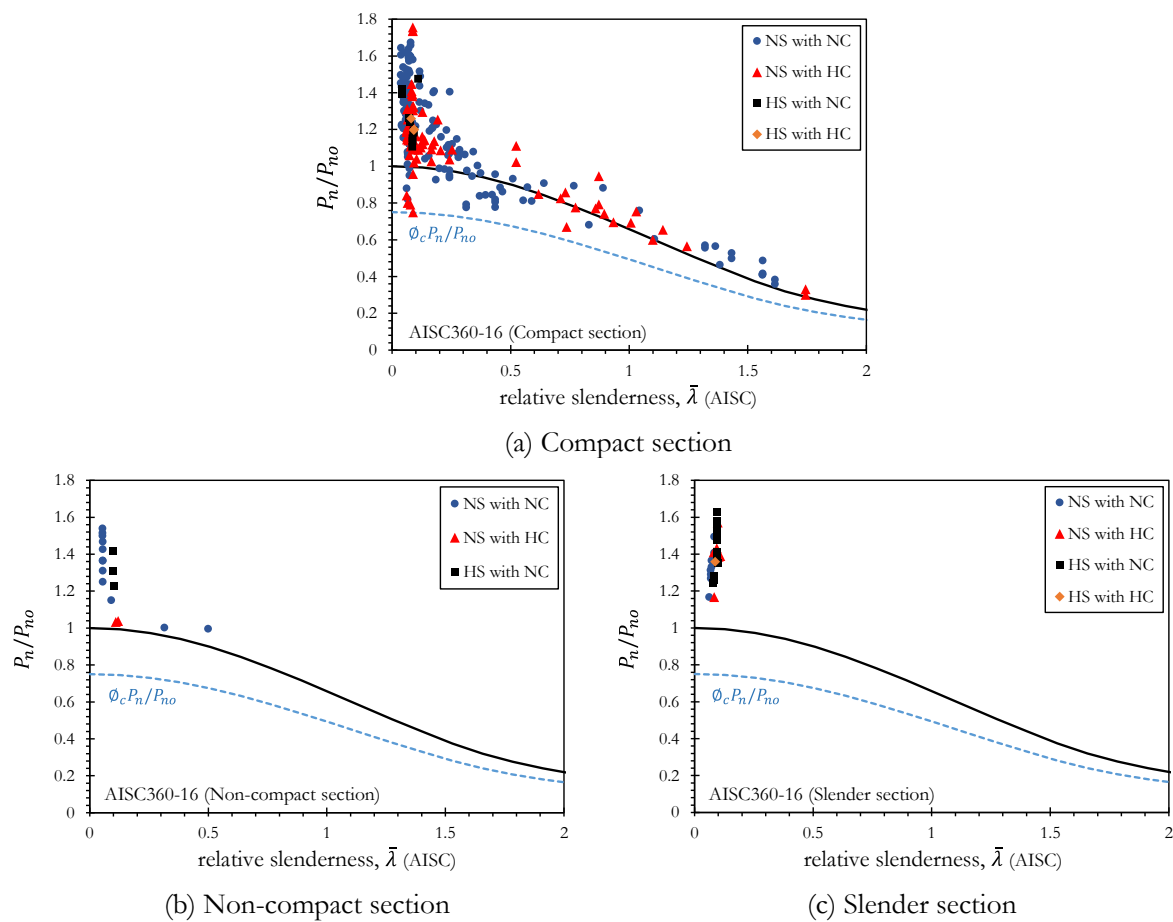


Fig. 5. Normalized AISC360-16 column buckling curves for circular CFST columns.



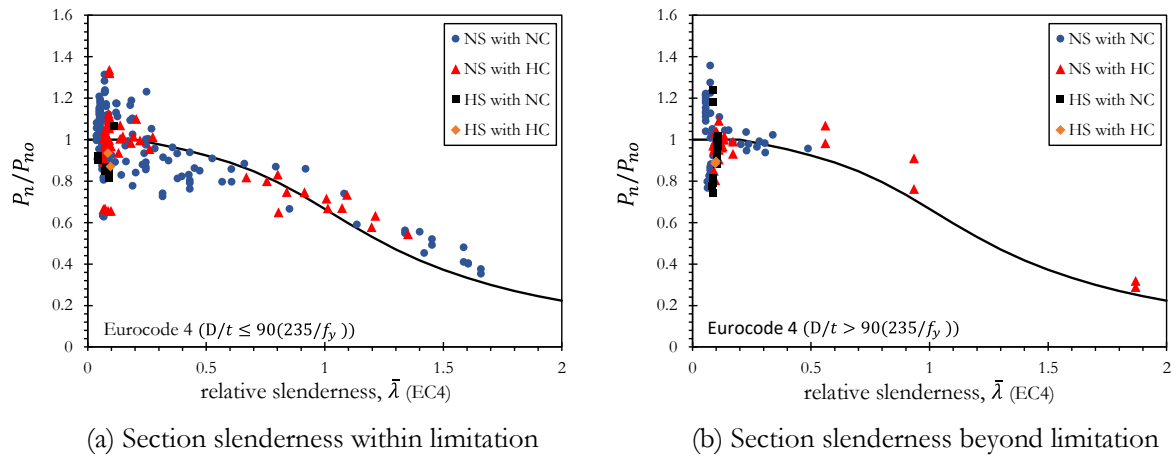


Fig. 6. Normalized Eurocode 4 column buckling curves for circular CFST columns.

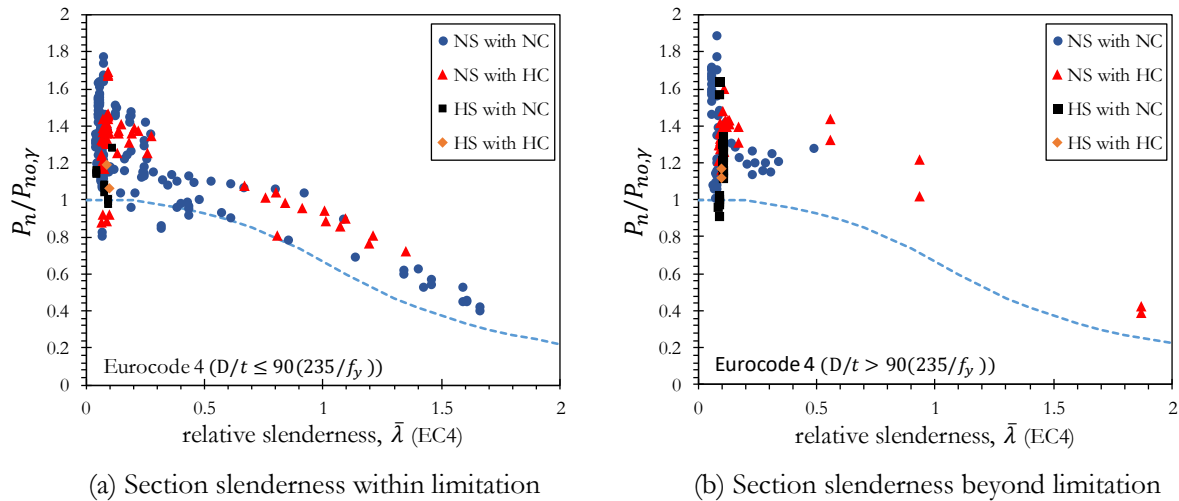


Fig. 7. Normalized Eurocode 4 column buckling curves for circular CFST columns (with partial safety factor).

Table 4. Average strength prediction ratios for circular CFST columns (no safety factor used).

Group	$(P_{exp}/P_{AISC})_{avg}$			$(P_{exp}/P_{EC4})_{avg}$	
	Compact	Non-compact	Slender	In-limit	Out-limit
NS with NC	1.25	1.34	1.33	1.02	1.02
NS with HC	1.16	1.04	1.40	1.01	1.01
HS with NC	1.26	1.32	1.42	0.89	0.86
HS with HC	1.22	-	1.36	0.90	0.89

## 5.2. Square CFST Columns

### 5.2.1. Effect of material strength

AISC 360-16: As shown in Figs. 8(a) and 8(b), the AISC equations provide an accurate strength prediction for square CFST columns with compact and non-compact sections. Table 5 shows that the average strength prediction ratios are close to 1.00 for all material strength groups. Using the strength reduction factor, the prediction becomes less conservative for some columns with extra high-strength materials ( $f'_c = 113$  MPa,  $f_y = 762$  MPa) as shown in Fig. 8(a).

Eurocode 4: As shown in Fig. 9(a), the Eurocode 4 equations accurately predict the strength of all material

strength groups of square CFST columns when the tube slenderness ratios are within the code limit. However, the prediction (with partial safety factor) over-estimates the strength of some columns with yield strength exceeding the limitation of steel tube ( $f_y = 460$  MPa), as shown in Fig. 10. Therefore, the use of the strength equations for square CFST columns when yield strength of steel tube exceeds the code limit is not recommended.

### 5.2.2. Effect of column slenderness

AISC 360-16: As shown in Fig. 8(a), the AISC equations accurately predict the strength of compact-section square CFST columns with relative slenderness greater than 1.0. For slender-section columns, the

predictions are conservative for short columns, as shown in Fig. 8(c).

Eurocode 4: As shown in Figs. 9(a) and 9(b), more scatter of data is observed for columns with section slenderness beyond the code limitation, especially ones of high strength materials. Therefore, the use of strength equations for square CFST columns with tube slenderness ratio exceeding the code limit is not recommended.

### 5.2.3. Effect of steel tube fabrication method

In Figs. 9 and 10, two symbols are used to represent the fabrication methods of steel tube, namely, cold-formed and welded-box tubes. Table 5 shows that both AISC 360-16 and Eurocode 4 accurately predict the

strength of cold-formed and welded-box square CFST columns. The average strength prediction ratios are close to 1.00. To examine the degree of scatter of data, the coefficients of variation (COV) of the strength prediction ratios are calculated [ $\text{COV} = \text{standard deviation (SD)} / \text{the average of the data } (\bar{X})$ ]. The COV values of AISC 360-16 strength prediction ratios,  $P_{\text{exp}} / P_{\text{AISC}}$ , for cold-formed and welded-box sections are 10.9% and 14.0%, respectively. While, the COV values of Eurocode 4 strength prediction ratios,  $P_{\text{exp}} / P_{\text{EC4}}$ , are 9.2% and 14.4% for cold-formed and welded-box sections, respectively. Therefore, a slightly more scatter of data is observed for welded-box than cold-formed sections based on both predictions.

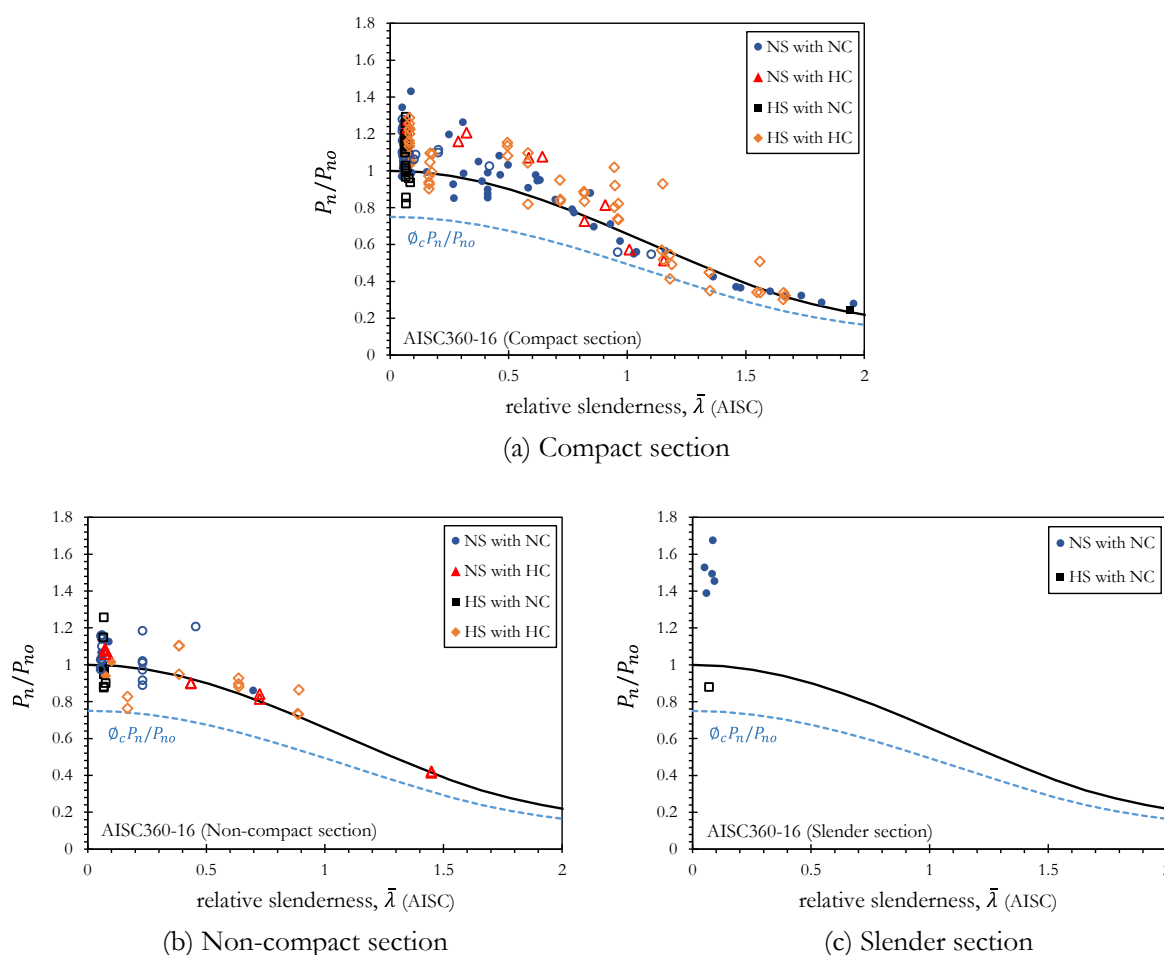


Fig. 8. Normalized AISC360-16 column buckling curves for square CFST columns (hollow markers represented welded-box section data).

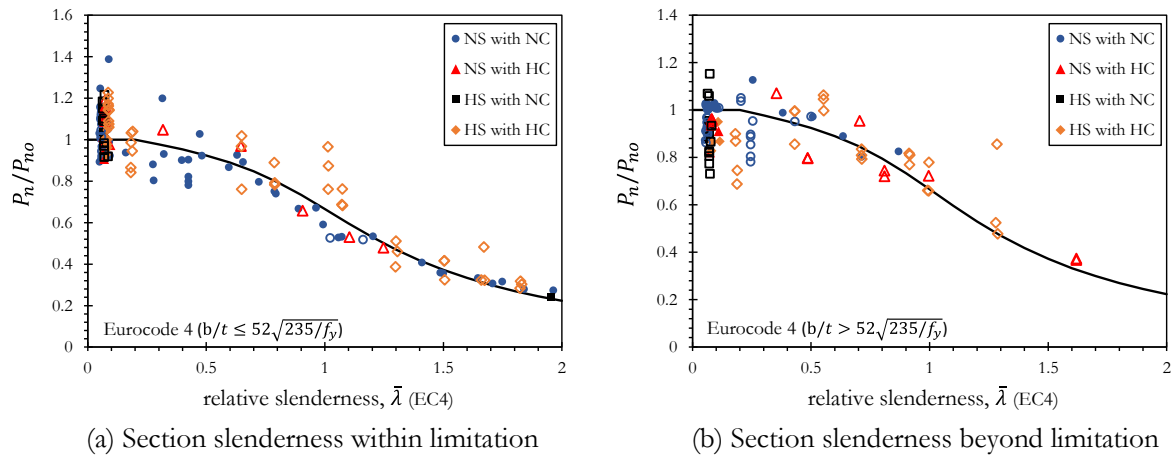


Fig. 9. Normalized Eurocode 4 column buckling curves for square CFST columns (Solid and hollow markers represent the data of cold-formed and welded-box sections, respectively.)

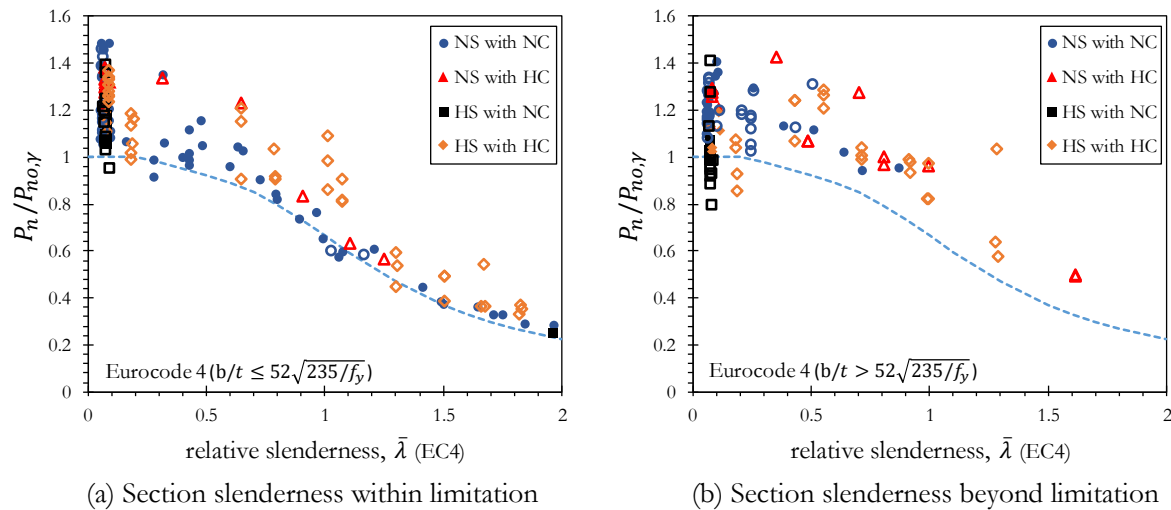


Fig. 10. Normalized Eurocode 4 column buckling curves for square CFST columns with partial safety factor (Solid and hollow markers represent the data of cold-formed and welded-box sections, respectively.)

Table 5. Average strength prediction ratios for square CFST columns (no safety factor used).

Group	$(P_{exp}/P_{AISC})_{avg}$			$(P_{exp}/P_{EC4})_{avg}$	
	Compact	Non-compact	Slender	In-limit	Out-limit
NS with NC	1.07 (1.09)	1.06 (1.08)	1.51	1.01 (1.01)	0.99 (0.95)
NS with HC	1.09 (1.15)	1.01 (1.03)	-	0.97 (1.06)	0.87 (1.00)
HS with NC	1.06 (1.07)	0.96 (1.01)	(0.88)	1.04 (1.06)	0.92 (0.90)
HS with HC	1.05 (1.11)	0.97 (1.04)	-	0.99 (1.11)	0.89 (1.04)

Remark: Numbers inside and outside the parenthesis indicate the average strength prediction ratios for welded-box and cold-formed sections, respectively.

## 6. Prediction of Circular-to-Square Column Strength Ratio

In design of CFST columns, square tube sections are often used because the design provision and structural connections for circular sections are not well defined [65]. However, the strength of square CFST columns is lower than circular ones due to the confinement effect. Currently, different strength equations are provided for circular and square CFST columns. In the Eurocode 4,

Eq. (13) includes the confinement effect on concrete. In the AISC 360-16, the coefficient for concrete strength ( $C_2$ ) in Eq. (1) increases from 0.85 to 0.95 for circular cross-section.

In this study, the predicted circular-to-square column strength ratio ( $P_{cir}/P_{sqr}$ ) is computed to compare the predicted strengths of circular and square CFST columns with the same area of steel and concrete. The strengths of circular ( $P_{cir}$ ) and square ( $P_{sqr}$ ) CFST columns of

different length-to-depth ( $L/D$ ) ratios are calculated by AISC 360-16 and Eurocode 4. The ratios are plotted in terms of the confinement factor ( $\xi$ ), as shown in Figs. 11(a) and 11(b) for two different material strengths, i.e., lower-bound and upper-bound strength limits. It is found that the  $P_{cir}/P_{sqr}$  ratio calculated by AISC 360-16 slightly decreases when the confinement factor increases. The predicted strength of the circular CFST column becomes close to the strength of the square CFST column when the confinement factor increases. In contrast, the  $P_{cir}/P_{sqr}$  ratio calculated by Eurocode 4 increases when the confinement factor increases and slightly decreases when the confinement factor is higher than 3.0.

While not significant on the  $P_{cir}/P_{sqr}$  ratio calculated by AISC 360-16, the ratio  $L/D$  governs the  $P_{cir}/P_{sqr}$  ratio calculated by Eurocode 4. According to the Eurocode 4 calculations, the  $P_{cir}/P_{sqr}$  ratio increases as the  $L/D$  ratio decreases. For short columns, the circular sections are predicted to be more effective than square sections.

## 7. Size Effect in Short Circular CFST Columns

The size effect of concrete is controlled by the development of micro-cracks [16]. In the CFST columns, the steel tube provides the confining pressure to the concrete core and reduces the micro-cracks in concrete.

Because the size effect in the CFST columns can be influenced by both concrete and steel tube, the confinement factor is used to represent the combined effect of steel ratio and material strength. To investigate the size effect in circular CFST short columns ( $L/D \leq 3.5$ ), three groups are chosen from the experimental database based on the confinement factor values ( $\xi = 0.2 \pm 0.03, 0.5 \pm 0.03, 0.8 \pm 0.03$ ). The test data are normalized with  $P_{no}$  calculated from Eq. (12). An outer diameter of steel tube represents the size of column. Fig. 12 shows the effect of column size on the normalized strength of circular CFST columns. At the confinement factor of 0.2, the normalized strength increases (8.6%) when the column size increases from 152 mm to 469 mm. At the confinement factor of 0.5, the normalized strength remains constant when the column size increases from 133 mm to 477 mm. At the highest confinement factor of 0.8, however, a reduction in the normalized strength (-5.5%) was observed when the column size increases from 100 mm to 337 mm. Based on the observation at three different confinement factors ( $\xi = 0.2, 0.5, 0.8$ ), the different tendency of the size effect is found when the confinement factor changes. Due to lack of test data of columns of the same confinement factor but different sizes, the influence of the confinement factor on the size effect of square CFST columns is not investigated.

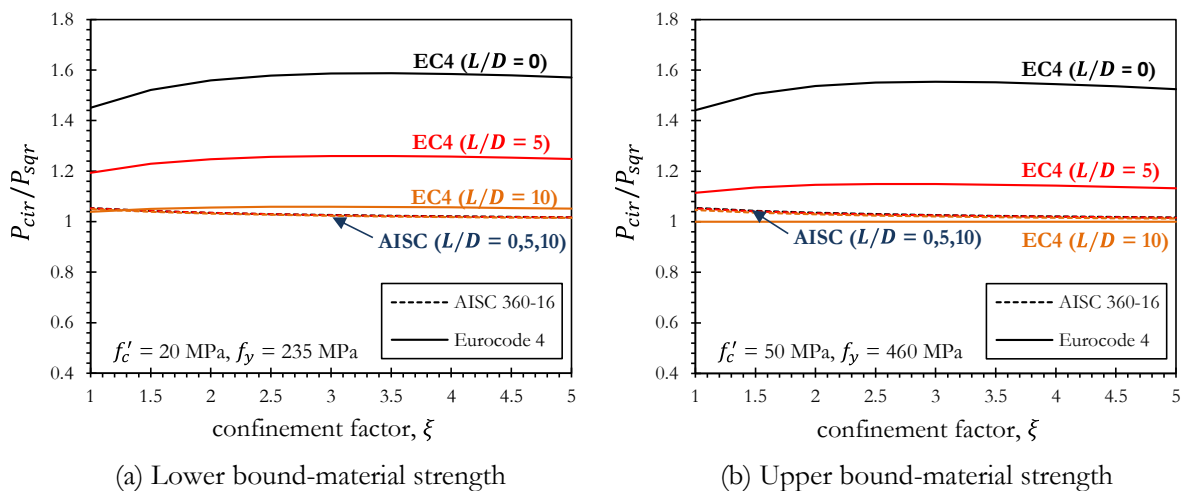


Fig. 11. Predicted circular-to-square column strength ratios using AISC 360-16 and Eurocode 4.

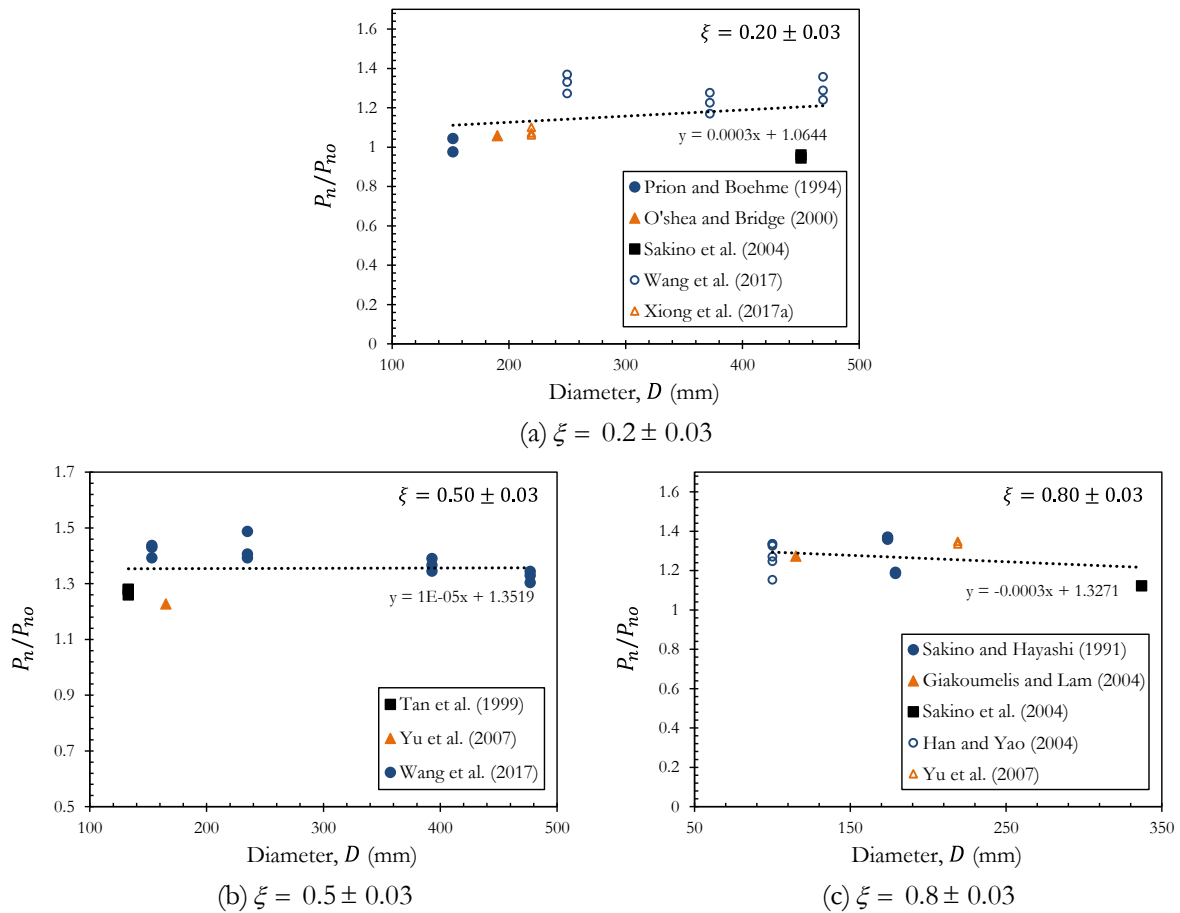


Fig. 12. Influence of confinement factor on size effect in circular CFST columns.

## 8. Conclusions

A new experimental database of CFST columns is compiled from the published literature including new experimental studies on the CFST columns with high-strength materials beyond the limitations. The database is used to evaluate the AISC 360-16 and Eurocode 4 design strength equations. The database is also used to investigate the influence of confinement factor on the size effect in short circular CFST columns. In addition, a comparison between the circular-to-square column strength ratios calculated with the two design references is discussed. From the study, the following conclusions can be drawn:

- The AISC 360-16 strength prediction is conservative for CFST columns, especially for short circular CFST columns ( $\bar{\lambda}_{AISC} \leq 0.9$ ), of normal or high strength materials beyond specification limit ( $f'_c > 70$  MPa,  $f_y > 525$  MPa). Based on the database, the design equations is also applicable for circular CFST columns with a slender section, i.e., tube slenderness ratio is higher than the specification limit ( $D/t > 0.31(E_s/f_y)$ ).
- The simplified method in Eurocode 4 accurately predicts the compressive strength for most circular CFST columns, except short columns ( $\bar{\lambda} \leq 0.3$ ). However, it is not recommended for square CFST

columns with steel tube strength exceeding the code limit ( $f_y > 460$  MPa) or ones with tube slenderness ratio beyond the code limit ( $b/t > 52\sqrt{235/f_y}$ ).

- With the same amount of concrete and steel, the square CFST columns is less effective than circular ones in terms of the compressive strength. The benefit of circular tubes is realized in Eurocode 4. The predicted circular-to-square column strength ratio increases when the confinement factor increases. Such benefit decreases when the column length-to-depth ratio increases.
- The different tendency of the size effect is found when the confinement factor changes. At the confinement factor of 0.2, the normalized strength increases (8.6%) when the column size increases. At a higher confinement factor ( $\xi = 0.8$ ), a reduction in the normalized strength (-5.5%) is observed when the column size increases.

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## List of symbols

$A_c$	Area of concrete core
$A_s$	Area of steel tube
$A_g$	Gross area of CFST columns
$B$	Outer width of square steel tube
$b$	Inner width of square steel tube ( $B - 2t$ )
$C_2$	Coefficient to account for the confinement of concrete of compact CFST sections
$C_3$	Coefficient for calculation of effective stiffness of CFST columns
$D$	Outer diameter of circular steel tube
$EI_{eff}$	Effective stiffness of CFST columns
$E_c$	Modulus of elasticity of concrete
$E_s$	Modulus of elasticity of steel
$F_{cr}$	Critical buckling stress
$f'_c$	Cylinder compressive strength of concrete
$f_c$	Characteristic value of compressive strength of concrete (without partial safety factor)
$f_y$	Yield strength of steel tube
$I_c$	Moment of inertia of concrete sections
$I_s$	Moment of inertia of steel sections
$K$	Effective length factor
$L$	Length of CFST columns
$P_e$ and $N_{cr}$	Euler critical buckling load in AISC 360-16 and Eurocode 4
$P_{no}$ and $N_{pl,Rd}$	Cross-sectional compressive strength of CFST column in AISC 360-16 and Eurocode 4
$P_u$ and $P_{exp}$	Experimental strength capacity of CFST columns
$P_{cir}$	Predicted strength of circular CFST columns
$P_{sq}$	Predicted strength of square CFST columns
$P_n$	Nominal compressive strength of CFST columns
$P_p$	Plastic strength of CFST sections
$P_y$	Yield strength of CFST sections
$t$	Thickness of steel tube wall
$\lambda_p$	Slenderness limit for compact/noncompact sections
$\lambda_r$	Slenderness limit for noncompact/slender sections
$\bar{\lambda}$	Relative slenderness for Eurocode 4 ( $\sqrt{N_{pl,Rd} / N_{cr}}$ )
$\bar{\lambda}_{AISC}$	Relative slenderness for AISC 360-16 ( $\sqrt{P_{no} / P_e}$ )
$\xi$	Confinement factor ( $A_s f_y / A_c f'_c$ )
$\eta_a$	Reduction factor of steel strength
$\eta_c$	Amplification factor of concrete strength
$\phi_c$	Resistance factor for compression ( $\phi_c = 0.75$ )
$\Phi$	Value to determine the reduction factor $\chi$
$\chi$	Reduction factor to account for column slenderness

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