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Applicability of available design methods for axial compressive bearing capacity of concrete-filled bimetallic steel tube

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Abstract

This paper aims to study the design methods for axial compressive bearing capacity of concrete-filled bimetallic steel tubular (CFBST) stub columns with circular and square cross-sections. The main design codes with provisions for conventional concrete-filled steel tubular (CFST) stub columns in various countries were introduced in detail, including the American code ANSI/AISC 360-22, the Eurocode EN 1994-1-1, the Japanese code AIJ-CFT, the Chinese codes GB 50936-2014 and GB/T 51446-2021, and the design methods proposed by other researchers were also introduced. Then the applicability of existing design methods to the CFSCBST stub columns was analysed through comparisons with the experimental results, including 13 concrete-filled stainless-clad bimetallic steel tubular (CFSCBST) stub columns and some experiments conducted by other researchers. Finally, the most accurate design methods for predicting the axial compressive bearing capacity of CFSCBST stub columns were suggested in this paper through comparisons, which can be utilized in the future application of CFSCBST stub columns.

Keywords: concrete-filled bimetallic steel tube, stub columns, axial compression, experiment, design method.

1. Introduction

Conventional Concrete-filled steel tubular (CFST) columns are structural built-up member composed of two materials, the conventional mild (CM) steel and the concrete. Due to the advantages of high bearing capacity and good ductility, the CFST columns are widely applied in engineering structures over the past few decades [1]-[4]. However, the external CM steel tube may rust when exposed to the environment over time, posing potential risks to the mechanical properties and high maintenance costs of the CFST columns [5,6]. Stainless-clad (SC) bimetallic steel is a type of high-performance laminated steel composed of cladding layer (stainless steel) with high corrosion resistance and substrate layer (CM steel) with good mechanical properties through the metallurgical bonding [7]. The application of such bimetallic steel to replace the CM steel in the CFST columns is a feasible solution to improve the durability of the CFST columns and reduce the high cost of high-performance steel.

At present, some investigations have been made on the axial compressive behaviour of concrete-filled bimetallic steel tube (CFBST) stub columns. Han and Ye [8,9,10] conducted experiments and FE analysis on 10 circular and 14 square CFBST stub columns without metallurgical bonding in the bimetallic steel; Jia et al. [11] conducted experiments and FE analysis on six square CFSCBST stub columns; Gao et al. [12] conducted experiments on six circular CFSCBST stub columns; Patel et al. [13] conducted FE analysis on 10 circular CFBST stub columns reported in [8] and proposed a new design method. This paper aims to investigate the applicability of available design methods for axial compressive bearing capacity of CFSCBST stub columns. The existing design codes widely adopted for conventional CFST stub columns and other design methods proposed by other researchers were summarized in detail, which were used for the prediction of CFSCBST stub columns in this paper, and the prediction results were compared with the test results which includes 13 CFSCBST stub columns conducted by the authors [14,15] and other experiments conducted in aforementioned studies [8]-[13]. Based on the comparisons, the design methods with best prediction results were suggested for such CFSCBST stub columns.

2. Review of experimental investigations

This section provide a brief overview of previous experimental investigations on CFSCBST stub columns. The diagram of CFSCBST stub columns are illustrated in Figure 1, where D is the outer diameter of the circular cross section, B is the width of the square cross section, t is the thickness of bimetallic steel tube, t_{ss} and t_{sc} are the thickness of the substrate layer and cladding layer of the tube respectively. All the stub columns were designed with a length of L=3D to avoid premature occurrence of overall buckling and to ensure local buckling failure modes.

(a) Circular cross section (b) Square cross section

Figure 1: Illustration of CFSCBST stub columns

A total of 49 tests on CFSCBST stub columns were collected in this paper [8,10-12,14,15], including 21 specimens with circular cross sections and 28 specimens with square cross sections. The geometric dimensions and material properties of tested specimens are summarized in Table 1, where f_{cu} is the cube compressive strength of concrete, N_{ue} is the ultimate strength of specimens. The specimens can be divided into two categories according to the different interface bonding method in bimetallic steel, i.e. metallurgical bonding and mechanical bonding. Compared with the mechanical bonding, the interface between two metal layers could achieve a perfect bonding by using metallurgical bonding method, which ensure the collaborative work of the two metal layers.

Table 1: Summarized experimental data of CFSCBST stub columns

Source	Interface bonding methods	Cross section	Specimen designation	D (mm)	t (mm)	t_{ss} (mm)	t_{sc} (mm)	f_{cu} (MPa)	N_{ue} (kN)
The authors [14,15]	Metallurgical bonding	Circular	C1-250-6-40	250	6.0	4.5	1.5	47.3	5233
			C2-350-8-40	350	8.0	6.5	1.5	47.3	9683
			C3-250-12-30	250	12.0	10.0	2.0	38.7	7390
			C4-300-12-30	300	12.0	10.0	2.0	38.7	9220
			C5-350-12-30	350	12.0	10.0	2.0	38.7	10719
		Square	B1-100-13-40	100	13.0	10.0	3.0	47.3	3943
			B2-120-13-40	120	13.0	10.0	3.0	47.3	4689
			B3-150-13-40	150	13.0	10.0	3.0	47.3	5732
			B4-100-8-40	100	8.0	5.0	3.0	47.3	2144
			B5-120-8-40	120	8.0	5.0	3.0	47.3	2433
			B6-150-8-40	150	8.0	5.0	3.0	47.3	3200
			B7-250-8-40	250	8.0	5.0	3.0	47.3	6468
			B8-300-8-40	300	8.0	5.0	3.0	47.3	8268
Han et al. [8,10]	Mechanical bonding	Circular	t1c2-1	166.04	2.89	2.37	0.52	30.2	1118
			t1c2-2	166.04	2.89	2.37	0.52	30.2	1128
			t2c2-1	166.60	3.17	2.37	0.80	30.2	1215

			t2c2-2	166.60	3.17	2.37	0.80	30.2	1238
			t3c2-1	167.72	3.73	2.37	1.36	30.2	1345
			t3c2-2	167.72	3.73	2.37	1.36	30.2	1315
			t2c1-1	166.60	3.17	2.37	0.80	21.1	1151
			t2c1-2	166.60	3.17	2.37	0.80	21.1	1177
			t2c3-1	166.60	3.17	2.37	0.80	42.8	1372
			t2c3-2	166.60	3.17	2.37	0.80	42.8	1390
		Square	t2c2-316-1	202.64	4.62	3.30	1.32	68.4	3592
			t2c2-316-2	202.64	4.62	3.30	1.32	68.4	3122
			t2c1-316-1	202.64	4.62	3.30	1.32	54.5	2663
			t2c1-316-2	202.64	4.62	3.30	1.32	54.5	2911
			t2c3-316-1	202.64	4.62	3.30	1.32	80.5	3612
			t2c3-316-2	202.64	4.62	3.30	1.32	80.5	3817
			t1c2-316-1	201.68	4.14	3.30	0.84	68.4	2918
			t1c2-316-2	201.68	4.14	3.30	0.84	68.4	3168
			t3c2-316-1	203.76	5.18	3.30	1.88	68.4	3385
			t3c2-316-2	203.76	5.18	3.30	1.88	68.4	3412
			t2c2-304-1	202.60	4.60	3.30	1.30	68.4	3150
			t2c2-304-2	202.60	4.60	3.30	1.30	68.4	3353
			t2c2-202-1	202.66	4.63	3.30	1.33	68.4	3353
			t2c2-202-2	202.66	4.63	3.30	1.33	68.4	3255
Jia et al. [11]	Metallurgical bonding	Square	SSFC-40-1	160	3.75	3.25	0.50	48.7	825.4
			SSFC-40-2	160	3.75	3.25	0.50	48.7	848.6
			SSFC-50-1	200	3.75	3.25	0.50	48.7	877.7
			SSFC-50-2	200	3.75	3.25	0.50	48.7	941.1
			SSFC-60-1	240	3.75	3.25	0.50	48.7	1028.8
			SSFC-70-1	280	3.75	3.25	0.50	48.7	1121.2
Gao et al. [12]	Mechanical bonding	Circular	D125-CFT-1	125	3.70	2.35	1.35	54.2	1442
			D125-CFT-2	125	3.70	2.35	1.35	54.2	1462
			D150-CFT-1	150	3.70	2.35	1.35	54.2	1949
			D150-CFT-2	150	3.70	2.35	1.35	54.2	1961
			D180-CFT-1	180	3.70	2.35	1.35	54.2	2647
			D180-CFT-2	180	3.70	2.35	1.35	54.2	2661

3. Design methods

3.1. Existing design methods

Up to now, there are no existing design codes available for CFSCBST stub columns, and to facilitate their design, codes for conventional CFST members were applied herein. The main design codes with provisions for CFST columns include: the American code ANSI/AISC 360-22 [16], the Eurocode EN 1994-1-1 [17], the Japanese code AIJ-CFT [18], the Chinese codes GB 50936-2014 [19] and GB/T 51446-2021 [20].

When calculating the axial compressive bearing capacity of CFSCBST stub columns, the yield strength of mild carbon (CM) steel in the code are replaced with the yield strength of SC bimetallic steel for calculation, which is defined as follows [21]:

$$f_{\mathrm{y.SC}} = \beta\sigma_{0.2} + (1-\beta) f_{\mathrm{y.s}} \tag{1}$$

in which $f_{\mathrm{y.SC}}$ represents the yield strength of SC bimetallic steel, $f_{\mathrm{y.s}}$ and $\sigma_{0.2}$ are the yield strength of substrate CM steel and cladding stainless steel respectively, and β is the clad ratio calculated by t_{sc}/t. The comparisons in the following subsections were based on the test results, and the strength factor as well as the safety factor of the material in the calculation was set to unity.

3.1.1. ANSI/AISC 360-22

The design equations in ANSI/AISC 360-22 [16] ignore the strength enhancement provided by the composite effect of the steel tube and concrete, and take the reduction in the concrete strength in consideration. Prior to calculate the compressive bearing capacity of stub columns, the stub columns are classified into three types based on the width-to-thickness ratios, including compact composite section, noncompact composite section and slender composite section, the limiting width-to-thickness ratios for stub columns subjected to axial compression are shown in Table 2.

Table 2: Limiting width-to-thickness ratios for stub columns subjected to axial compression

Section type	Width-to-thickness ratio	λ_p	λ_r	Maximum permitted
Rectangular	B/t	$2.26\sqrt{E/f_y}$	$3.00\sqrt{E/f_y}$	$5.00\sqrt{E/f_y}$
Circular	D/t	$0.15E/f_y$	$0.19E/f_y$	$0.31E/f_y$

For compact composite sections ($\lambda \le \lambda_p$):

$$N_{u,AISC} = P_p = A_s f_y + C A_c f_c' \tag{2}$$

in which f_c' is the cylinder compressive strength of the concrete, C is the calculation coefficient and is taken as 0.85 for rectangular sections and 0.95 for circular sections.

For noncompact composite sections ($\lambda_p < \lambda \le \lambda_r$):

$$N_{u,AISC} = P_p - \frac{P_p - P_y}{(\lambda_r - \lambda_p)^2}(\lambda - \lambda_p)^2 \tag{3}$$

$$P_y = A_s f_y + 0.7 A_c f_c' \tag{4}$$

in which P_p is determined from Equation (3).

For slender composite sections ($\lambda > \lambda_r$):

$$N_{u,AISC} = f_n A_s + 0.7 A_c f_c' \tag{5}$$

in which f_n is the critical buckling stress for the structural steel section of filled composite members and is determined as follows. For rectangular sections:

$$f_n = 9E_s / \lambda^2 \tag{6}$$

For circular sections:

$$f_n = \frac{0.72 f_y}{\left[\left(\frac{D}{t}\right)\frac{f_y}{E_s}\right]} \tag{7}$$

where E_s is the elastic modulus of bimetallic steel tube. It is worth noting that the CFSCBST stub columns tested in this paper are compact composite sections, and therefore the compressive ultimate bearing capacity of stub columns are calculated by Equation (2).

3.1.2. EN 1994-1-1

The design equations in EN 1994-1-1 [17] consider the strength enhancement in the concrete core compared to ANSI/AISC 360-22 [16]. The design equations are illustrated as follows. For square sections:

$$N_{u,EN} = A_s f_y + A_c f_c' \tag{8}$$

For circular sections:

$$N_{u,EN} = \eta_s A_s f_y + A_c f_c' \left(1 + \eta_c \frac{t}{D}\frac{f_y}{f_c'}\right) \tag{9}$$

$$\eta_{\mathrm{s}} = 0.25(3+2\bar{\lambda}) \quad (\mathrm{but} \leq 1.0) \tag{10}$$

$$\eta_{\mathrm{c}} = 4.9-18.5\bar{\lambda}+17\bar{\lambda}^{2} \quad (\mathrm{but} \geq 0) \tag{11}$$

$$\bar{\lambda} = \sqrt{\frac{A_{\mathrm{S}} f_{\mathrm{y}} + A_{\mathrm{c}} f_{\mathrm{c}}'}{N_{\mathrm{cr}}}} \tag{12}$$

in which f_{c}' is the cylinder strength of the concrete, η_{s} and η_{c} are the factors related to the relative slenderness($\bar{\lambda}$), the relative slenderness($\bar{\lambda}$) is given by Equation (12), and N_{cr} is the elastic critical normal force for the relevant buckling mode (the first global flexural buckling mode of the composite column in this paper), calculated with the effective flexural stiffness $(EI)_{\mathrm{eff}}$ determined as Equation (13).

$$(EI)_{\mathrm{eff}} = E_{\mathrm{s}} I_{\mathrm{s}} + 0.6 E_{\mathrm{c}} I_{\mathrm{c}} \tag{13}$$

in which E_{s} and E_{c} are the elastic modulus of bimetallic steel and concrete respectively, I_{s} and I_{c} are the moment of inertia respectively.

3.1.3. AIJ-CFT

The design equations in AIJ-CFT [18] are similar to those of ANSI/AISC 360-22 [16], which do not consider the strength enhancement provided by the composite effect. However, the design equations in AIJ-CFT [18] have a more simplified expression compared to ANSI/AISC 360-22 [16], as shown in following equations.

$$N_{\mathrm{u,AIJ}} = (1+\eta) A_{\mathrm{s}} F + 0.85 A_{\mathrm{c}} f_{\mathrm{c}}' \tag{14}$$

in which η is the stress rise coefficient, and is taken as 0.27 for the circular section and 0 for the square section, F is the strength standard value that determines the allowable strength of steel and is taken as F=min{f_{y}, 0.7σ_{u}}.

3.1.4. GB 50936-2014

The design equations in ANSI/AISC 360-22 [16], EN 1994-1-1 [17] and AIJ-CFT [18] are proposed based on the superposition theory. The bearing capacity of steel and concrete are calculated respectively, and then are multiplied by enhancement or reduction coefficients before superposition to obtain the overall bearing capacity. The superposition theory can better reflect the mechanical behaviour of stub columns, but the expression is relatively complex. As for Chinese design codes, the unified theory is widely adopted, which considers the composite cross-section of the steel and concrete as a new material, and an empirical confinement factor (ξ) was used for the regression analysis to obtain the design equations, which is defined as follow:

$$\xi = \frac{f_{\mathrm{y}} A_{\mathrm{s}}}{f_{\mathrm{ck}} A_{\mathrm{c}}} \tag{15}$$

in which f_{ck} is the characteristic compressive strength of the concrete and can be calculated by f_{ck}=0.67f_{cu}, f_{y} is the yield strength of bimetallic steel. The design equations in GB 50936-2014 [19] is expressed as follows.

$$N_{\mathrm{u,GB50936}} = \left(1.212 + B\xi + C\xi^{2}\right)\left(A_{\mathrm{c}} + A_{\mathrm{s}}\right) f_{\mathrm{ck}} \tag{16}$$

in which B and C are the coefficients related to the concrete and steel strength; for square sections, B=0.131f_{y}/213+0.723 and C=-0.070f_{ck}/14.4+0.026; for circular sections, B=0.176f_{y}/213+0.974 and C=-0.104f_{ck}/14.4+0.031.

3.1.5. GB/T 51446-2021

The design equations in GB/T 51446-2021 [20] also adopted the unified theory but the equations are simpler compared to GB 50936-2014 [19]. Similarly, the confinement factor (ξ) is also used in GB/T

51446-2021 [20] for the regression analysis to obtain the design equations, as shown in Equations (17) and (18). For square sections,

$$N_{\mathrm{u,GB/T51446}}=(1.18+0.85\xi)(A_{\mathrm{c}}+A_{\mathrm{s}})f_{\mathrm{ck}} \tag{17}$$

For circular sections,

$$N_{\mathrm{u,GB/T51446}}=(1.14+1.02\xi)(A_{\mathrm{c}}+A_{\mathrm{s}})f_{\mathrm{ck}} \tag{18}$$

3.2. Design methods proposed by other researchers

Some researchers [9,13] have conducted in-depth investigations on the design methods of CFSCBST stub columns. Han [9] proposed a new design methods for circular CFSCBST stub columns based on the unified theory, which was modified from the Chinese code GB/T 51446-2021 [20] and was proved to have better predictions. The design equation proposed by Han is shown as follows.

$$N_{\mathrm{u,Han}}=(1.14+1.02(a\xi^2+b\xi))(A_{\mathrm{c}}+A_{\mathrm{s}})f_{\mathrm{ck}} \tag{19}$$

in which ξ is the confinement factor as defined in Equation (15), a and b are the calculation coefficients related to f_{ck}; a=(-140-620f_{ck}+5f_{ck}^2)×10^{-5} and b=1.7865-0.068f_{ck}.

Patel [13] proposed a new design method which based on the superposition theory, which was modified from the Liang and Fragomeni's design model [22], as shown in Equation (20). The design models were compared with the experimental results in Han's research [9], which can be used for the predictions of CFSCBST stub columns.

$$N_{\mathrm{u,Patel}}=(\gamma_{\mathrm{c}}f_{\mathrm{c}}'+4.1f_{\mathrm{rp}})A_{\mathrm{c}}+\gamma_{\mathrm{sc}}f_{\mathrm{yc}}A_{\mathrm{sc}}+\gamma_{\mathrm{ss}}\sigma_{0.2}A_{\mathrm{ss}} \tag{20}$$

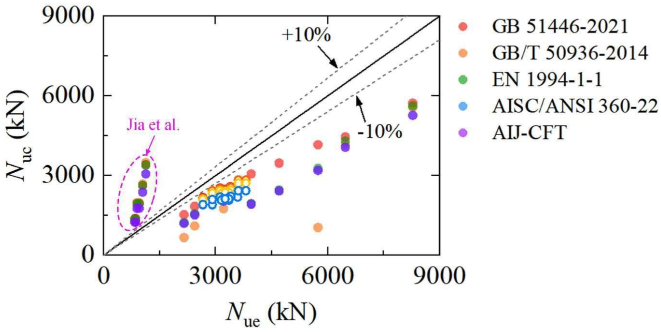
in which f_{rp} is the lateral concrete confining pressure determined by the specific equations in [13], f_{yc} and $\sigma_{0.2}$ are the yield strength of CM steel and stainless steel respectively, f_{c}' is the cylinder strength of concrete, γ_{c}, γ_{sc} and γ_{ss} are the calculation coefficients which are calculated referred to [13]. It is worth noting that both Han's and Patel's design methods were proposed for the prediction of the ultimate bearing capacity of circular CFSCBST stub columns.

3.3. Comparisons of existing design methods

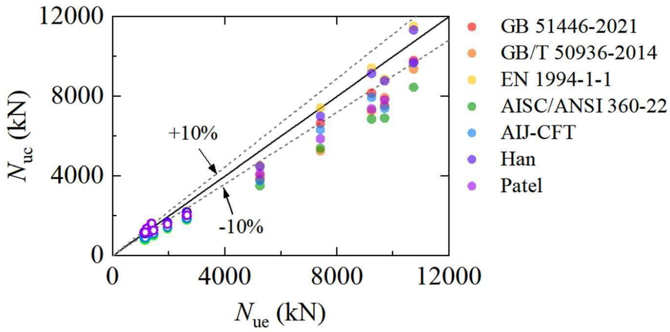
The above-mentioned design methods were used to predict the ultimate compressive bearing capacity of CFSCBST stub columns, including five design codes and two design methods proposed by researchers. The comparisons between the predicted bearing capacity (N_{uc}) from the design methods and the test results (N_{ue}) are shown in Figure 2, in which the hollow dots represent specimens with mechanical bonding, while solid dots represent specimens with metallurgical bonding. The average value (AVG) of $N_{\mathrm{ue}}/N_{\mathrm{uc}}$ and the corresponding coefficient of variation (COV) are listed in Table 3.

Table 3: Prediction results of the existing design methods for CFSCBST stub columns

Design codes	Section type	AVG	COV
AISC/ANSI 360-22 [16]	Square	1.568	0.097
	Circular	1.099	0.033
EN 1994-1-1 [17]	Square	1.408	0.079
	Circular	1.057	0.075
AIJ-CFT [18]	Square	1.568	0.097
	Circular	1.048	0.070
GB 50936-2014 [19]	Square	1.381	0.137
	Circular	0.956	0.066
GB/T 51446-2021 [20]	Square	1.340	0.062
	Circular	1.243	0.063
Han's method [9]	Circular	1.059	0.077
Patel's method [13]	Circular	1.108	0.126



(a) Square sections



(b) Circular sections

Figure 2: Comparisons between predicted value (N_{uc}) and test results (N_{ue})

From Table 3 and Figure 2, it can be seen that the application of existing design methods for predicting the compressive strength of circular CFSCBST stub columns have a relatively accurate prediction. Among these design methods, EN 1994-1-1 [17] and Han's methods [9] have the best prediction; GB 50936-2014 [20] also has a good prediction but is unsafe; AISC/ANSI 360-22 [16] has the most conservative predictions. As for the square CFSCBST stub columns, GB/T 51446-2021 [20] has the best prediction but is also conservative as other design methods. This may due to most of the existing design codes do not considered that the composite effect has a significant strength enhancement for the concrete core in square CFSCBST stub columns, so the predicted results are very conservative. It is worth noting that the predicted results for Jia's [11] specimens was relatively unsafe, because a 20mm gap was left at the top end of specimens when pouring concrete, and CFRP were wrapped on both end of specimens to strengthen the steel tube, leading to the decrease in the overall bearing capacity of specimens. Besides, the effect of different bonding method in bimetallic steel was found to have small influence on the overall bearing capacity of stub columns, as shown in Figure 2(a) and (b). However, in case of their use in structural engineering, the bimetallic steel with metallurgically bonded interface is necessary because of other more complicated stress states, e.g. in the tubular joints region.

Through the comparisons of existing design methods, it was found that the EN 1994-1-1 [17] and Han's design methods [9] have the best prediction for the axial bearing capacity of circular CFSCBST stub columns, which could be applied in the prediction of such stub columns in the future. However, the design methods adopted in this paper have very conservative predictions for square CFSCBST stub columns. Therefore, more studies need to be conducted on such square stub columns, and the existing design codes may need to be modified based on a large amount of experimental data for predicting the bearing capacity of square CFSCBST stub columns in the future research.

4. Conclusions

In this paper, the existing design methods for CFSCBST stub columns were summarized in detail, and the predictions of them were compared with the test results. The main conclusions are as follows.

(1) Five main design codes for CFST stub columns and two design methods proposed by researchers for CFSCBST stub columns were summarized in this paper. All the design methods are based on either the superposition theory or unified theory.

(2) The existing design methods were modified to predict the compressive bearing capacity of CFSCBST stub columns, and the prediction results were compared with the test results. EN 1994-1-1 [17] and Han's methods [9] have the best prediction for circular CFSCBST stub columns, while ANSI/AISC 360-22 [16] has the most conservative prediction. All the design methods have very conservative predictions for square CFSCBST stub columns.

(3) Different bonding method in bimetallic steel have small influence on the overall bearing capacity of stub columns. However, in structural engineering, it is suggested to use the metallurgical bonding method because of other more complicated stress states such as the tubular joints.

(4) The Eurocode EN 1994-1-1 [17] and Han's design methods [9] were suggested to predict the axial compressive bearing capacity of circular CFSCBST stub columns. For square CFSCBST stub columns, it was suggested that the design methods may need to be modified based on a large amount of experimental data in the future research.

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