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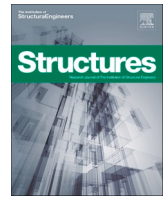
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Unified numerical model for performance analysis of various cross-sections of concrete-filled stainless-steel tubular stub columns under axial loading

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ABSTRACT

This research presents a unified numerical model for analyzing the performance of concrete-filled stainless-steel tubular (CFSST) stub columns with different cross-sectional shapes. The model converts the cross-sections of the CFSST columns with various shapes into an equivalent circular column, and a new concrete constitutive relation is proposed to estimate the compressive strength of confined concrete of CFSST columns with different cross-sections. To simulate the axial load–strain curves of CFSST columns, a computer program is used that converts the various cross-sections of CFSST columns into equivalent circular columns. To validate the model, 196 tested columns with various cross-sections gathered from previous literature are used. The unified model proposed is found to be accurately predicting the performance of CFSST columns. The model is then used to investigate the effects of concrete, steel yield stress, and the depth-to-thickness ratio on the different radius ratios and aspect ratios of CFSST columns. A unified design formula is also suggested to calculate the ultimate strength of CFSST columns with various shapes, and the proposed simplified model is shown to provide a more accurate estimation when compared to existing design codes.

1. Introduction

Concrete-filled steel tubular (CFST) columns are a popular choice for constructing high-rise buildings and bridge piers that need to carry large axial loads. They are preferred due to their strength, ductility, excellent fire, and cyclic performance than that of reinforced concrete columns. The steel tube provides lateral confinement to the confined concrete and serves as formwork during construction. Many studies have been conducted on CFST columns, leading to a better understanding of their design, and the availability of design guidelines in various publications [1–10]. Circular columns offer more uniform confinement compared to rectangular ones [11], but rectangular columns are easier to connect to adjacent beams. To achieve both a higher strength and ease of connection to adjacent beams, other cross-sections such as round-ended, octagonal, elliptical and hexagonal columns have also been proposed [12–25].

CFST columns encounter corrosion in an acidic environment, which

can significantly affect their performance. To address this issue, concrete-filled stainless-steel tubular (CFSST) columns have been proposed. These columns offer improved corrosion resistance, hardness, strength, and ductility due to the strain hardening performance of strain-hardening which is superior to that of carbon steel used in conventional CFST columns. However, due to the higher cost of stainless steel, the use of CFSST columns is limited. Researchers have conducted experimental work to examine the structural performance of CFSST columns, but design guidelines for CFSST columns are not yet available in Eurocode 4 [26], AISC 360–16 [27], ACI 318–19 [28] and DBJ 13–51-2010 [29]. Therefore, understanding the effects of stainless steel on the cost-effective design of these columns is crucial.

Numerous studies on CFSST columns have been documented in the literature, investigating their behavior under various loading conditions [30–51]. Young and Ellobody [30] studied the effects of sectional shapes, concrete strength, and loading type on the performance of CFSST columns. Lam and Gardner [31] found that CFSST columns made

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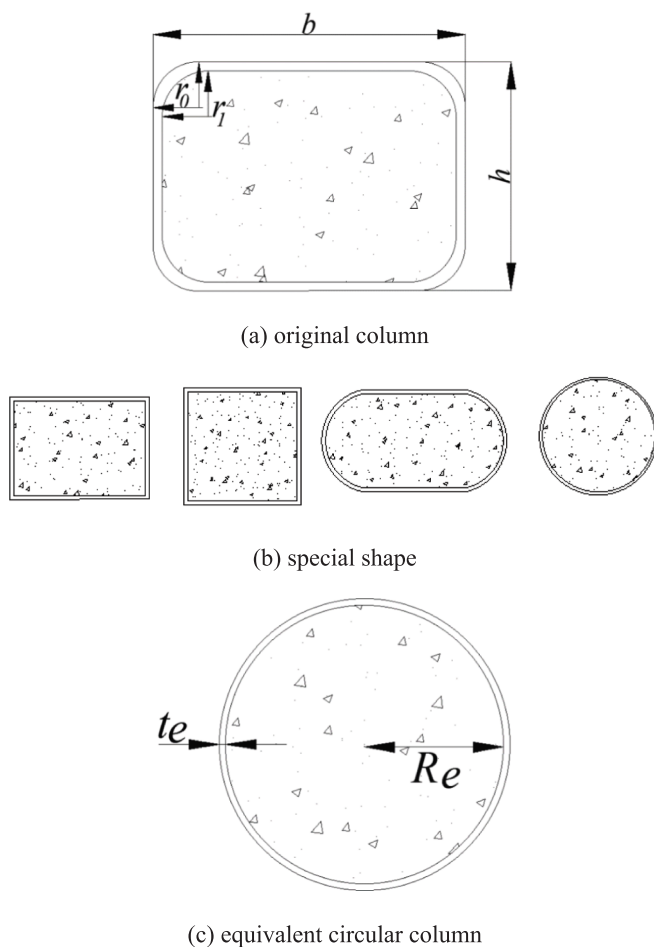


Fig. 1. Transformation of various shapes to an equivalent circular column.

with high-strength concrete (HSC) had poor ductility due to the brittle nature of HSC. Uy et al. [32] conducted extensive tests on CFSST columns with circular and rectangular shapes and analyzed the influence of loading types, cross-sectional shapes, concrete strength, column slenderness, and steel tube thickness on their performance. The circular CFSST columns exhibited higher strength and ductility than the rectangular ones. Tam et al. [40] reported that using a higher percentage of recycled aggregates in CFSST columns decreased their load-carrying capacity. Liao et al. [45] investigated the impact of different types of sand used in the concrete of CFSST columns. They found that the type of sand has insignificant influences on CFSST columns. Azad et al. [52,53] proposed formulas for determining the slenderness limit and effective diameter of CFSST columns based on their test results. Liu et al. [54] studied the size effects of CFSST stub columns under axial loading. It was concluded that the size effects of CFSST stub columns decrease as the steel ratio increases. Zhong and Zhao [55] performed tests on eccentrically loaded CFSST stub columns containing recycled aggregates. It was found that the effects of various percentages of recycled aggregates were negligible on the performance of CFSST stub columns under eccentric loading. Han et al. [56] also performed tests on CFSST columns containing recycled aggregates. It was found that the bond strength of CFSST columns containing recycled aggregates was lower than that of normal CFSST columns.

Researchers have previously developed computational models to investigate the behavior of CFSST columns, as reported in various studies [25,48,57–67]. The accuracy of these numerical models depends on how well they simulate the material behavior of CFSST columns. However, according to Ahmed et al. [66], existing numerical models of CFSST columns use confinement models designed for conventional CFST

columns, which may lead to inaccurate performance predictions. Tran et al. [68] examined the accuracy of various machine learning models in predicting the ultimate strength of circular CFSST columns under axial loading. In addition, 3D finite element models (FEM) are time-consuming and cannot account for local buckling, unlike the fiber models developed by Liang [69], Patel et al. [70] and Ahmed et al. [64,71]. Some researchers have proposed unified models for CFST columns, including Lin et al. [72,73] and Min et al. [74–76], while Lam and Teng [77] and Légeron and Paultre [78] have used a unified method to convert rectangular columns to equivalent circular columns to predict the performance of concrete columns. Although the unified model proposed by Lin et al. [72] provides good prediction of the performance of CFST columns with carbon tube but does not accurately predict the performance of CFSST columns, as it ignores the strain-hardening performance of stainless steel. Moreover, the concrete compressive strength formula proposed by Attard and Setunge [79], which was modified by incorporating a shape factor in the unified modeling, does not accurately predict the performance of CFSST columns due to the different confinement mechanisms of steel-confined concrete columns.

This paper introduces a novel unified numerical model to predict the performance of CFSST columns of different shapes, including rectangular, square, circular, and round-ended. The model converts the cross-sections of various shapes of CFSST columns into an equivalent circular column. The model is based on a database of 196 columns, which includes different cross-sections of CFSST and CFST columns. It should be noted that the length-to-width (L/b) ratio of the columns collected in the database are limited to 4 to avoid the effects of global buckling on their axial performance. The new concrete constitutive relation for estimating the compressive strength of confined concrete is developed, along with a strength reduction factor to capture the post-peak performance of confined concrete. A computer program is then created, which includes the newly proposed concrete confinement model and accurate three-stage constitutive relations of stainless steel to develop axial load–strain curves of CFSST columns. The program also converts various cross-sections of CFSST columns into equivalent circular columns. The accuracy of the proposed unified model is verified against a large test data. Finally, a unified design formula is proposed to calculate the ultimate strength of CFSST columns of different shapes.

2. The unified numerical model

2.1. Equivalent circular column

The unified model proposed in this paper takes into consideration various cross-sectional shapes of CFSST columns, such as circular, rectangular, square, and round-ended. The study assumes that these shapes are special cases of rectangular columns, as depicted in Fig. 1 [72,77]. In the model, the cross-sections of these different shapes are converted into an equivalent circular column, as shown in Fig. 1. The width and depth of the column are represented by b and h , respectively, where b is greater than or equal to h . The thickness of the steel tube is represented by t , and the outer and inner radius of the steel tube are represented by r_0 and r_1 , respectively. If $r_0 = r_1 = 0$ and $b \geq h$, then it is a rectangular column, while $r_0 = r_1 = 0$ and $b = h$ represents a square column. For $r_0 = h/2$, $r_1 = h/2 - t$ and $b = h$ refers to the circular column and $r_0 = h/2$, $r_1 = h/2 - t$ and $b > h$ refers to the column as round-ended. The performance analysis of axially loaded CFSST columns is carried out using the equivalent circular column. It should be noted that Lam and Teng [77], and Légeron and Paultre [78] developed unified models for conventional reinforced concrete columns where the cross-sectional area of the equivalent circular column was different from that of the original shape of the column. However, in this study, a unified model is developed for CFSST columns where the cross-sectional area of the steel tube and confined concrete of the original column is the same as that of the equivalent circular column. The cross-sectional area of the steel tube and confined concrete of the equivalent circular column are calculated

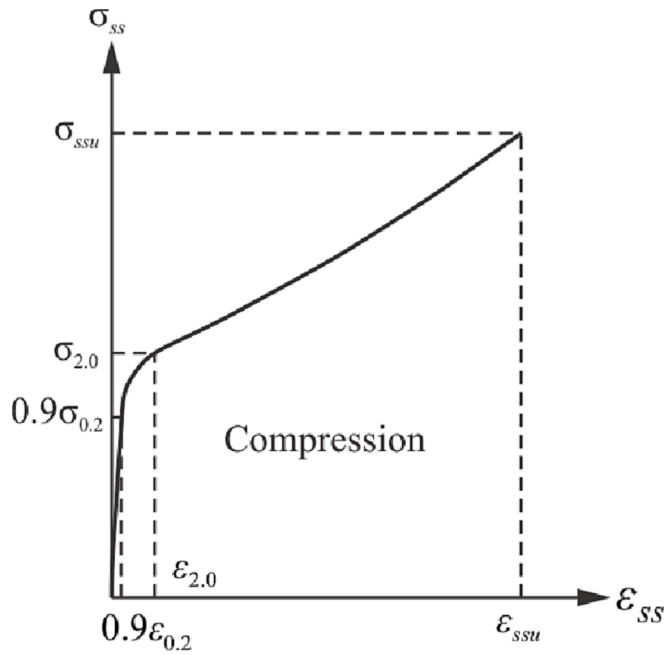


Fig. 2. Constitutive relations of stainless steel under compression.

using Eqs. (1–2).

$$A_c = \pi R_e^2 = (b - 2t)(h - 2t) - (4 - \pi)r_1^2 \quad (1)$$

$$A_s = \pi[(R_e + t_e)^2 - R_e^2] = 2t(b + h) - 4t^2 - (4 - \pi)(r_0^2 - r_1^2) \quad (2)$$

where the wall thickness of the tube and the radius of the confined concrete of the equivalent circular column are characterized by t_e and R_e , respectively.

By solving Eqs. (1) and (2), R_e and t_e can be calculated as

$$R_e = \sqrt{\frac{(b - 2t)(h - 2t) - (4 - \pi)r_1^2}{\pi}} \quad (3)$$

$$t_e = \frac{\sqrt{bh - (4 - \pi)r_0^2} - \sqrt{(b - 2t)(h - 2t) - (4 - \pi)r_1^2}}{\sqrt{\pi}} \quad (4)$$

2.2. Analysis steps

A unified numerical model is developed here to predict the axial load–strain curves of axially loaded CFSST columns. The model takes into account the areas of steel and concrete, as well as their corresponding stresses to determine the axial load. The model assumes that the plane section remains plane during plastic deformation, and that the steel and concrete are perfectly bonded. In addition, the effects of shrinkage and temperature are not considered. The stresses of steel and concrete are estimated from the axial strains employing the uniaxial constitutive relationships of steel and concrete given in the following sections. The axial force (P) of the column is taken as the stress resultant. In the analysis, the axial strain is increased incrementally and determined the axial load of the columns. The iteration procedure continues until the axial load is 50% of the maximum load or the maximum prescribed strain is attained.

The computational analysis for calculating the axial load–strain responses of CFSST short columns is as follows.

- (1) Input the following parameters of CFSST columns: b , h , t , r_0 , r_1 , $\sigma_{0.2}$ and f'_c .
- (2) Determine R_e and t_e using Eqs. (3) and (4), respectively.

- (3) Calculate the area of steel and concrete using Eqs. (1) and (2), respectively.
- (4) Initialize fiber axial strain as $\epsilon = \Delta\epsilon$.
- (5) Determine the steel and concrete's stresses from the uniaxial constitutive material relationships.
- (6) Compute the axial load (P) as $P = \sigma_s A_s + \sigma_c A_c$, where σ_s and σ_c are the stresses of steel and concrete, respectively; A_s and A_c are the area of steel and concrete, respectively.
- (7) Increase the strain by $\epsilon = \epsilon + \Delta\epsilon$.
- (8) Repeat Steps (5) to (7) until $P \leq 0.5P_{max}$ or $\epsilon \geq \epsilon_{cu}$.
- (9) Plot $P - \epsilon$ curve.

3. Material constitutive relations

3.1. Constitutive relations of stainless steel

The constitutive relationships of stainless steel in this study are determined using Quach et al.'s constitutive model [80], as depicted in Fig. 2. According to the literature, the three-stage stress–strain relationships of stainless steel in Fig. 2 yield more precise outcomes than the two-stage relationships such as Rasmussen's model [81]. In this study, the stress in stainless steel is computed from the corresponding strain using the formulas developed by Abdella et al. [82]. To account for the effects of welding, cold forming, and biaxial stress on the stainless-steel tube, a 10% reduction is applied to the 0.2% proof strength, which is considered as the yield strength of the stainless-steel tube [11,83]. It should be noted that the residual stress exists in the corner of the cold-formed steel tube with rectangular cross-sections due to the cold-forming has moderate effects on the ultimate strength of conventional CFST columns. However, all the CFSST columns collected for the validation of the unified model was constructed by welding the stainless-steel plates, therefore, the corner effects are neglected for this study. In addition, for the CFSST columns with rectangular flat plates, the local buckling formulas proposed by Liang et al. [84] considered the residual stress induced by welding.

In the first stage ($0 \leq \epsilon_s \leq \epsilon_{0.2}$) of the constitutive model, the stress is calculated as

$$\sigma_s = \frac{E_0 \epsilon_s \left[1 + C_1 \left(\frac{\epsilon_s}{\epsilon_{0.2}} \right)^{C_2} \right]}{1 + C_3 \left(\frac{\epsilon_s}{\epsilon_{0.2}} \right)^{C_4} + C_1 \left(\frac{\epsilon_s}{\epsilon_{0.2}} \right)^{C_2}} \quad (5)$$

In which σ_s and ϵ_s are the stress of the steel fiber and the corresponding strain, respectively; E_0 is the Young's modulus of steel; $\sigma_{0.2}$ and $\epsilon_{0.2}$ are the 0.2% proof stress of the stainless steel and the corresponding strain, respectively. Ramberg and Osgood [85] proposed formula for $\epsilon_{0.2}$ written as

$$\epsilon_{0.2} = \frac{\sigma_{0.2}}{E_0} + 0.002 \quad (6)$$

In Eq. (5), C_1 , C_2 , C_3 and C_4 are calculated as

$$C_1 = \frac{\Delta}{C_2 - 1} \quad (7)$$

$$C_2 = 1 + \frac{B_1}{\Delta} \quad (8)$$

$$C_3 = G_0(1 + C_1) \quad (9)$$

$$C_4 = \Delta + G_1 \quad (10)$$

where

$$\Delta = \frac{1 + \sqrt{1 + 4B_1}}{2} \quad (11)$$

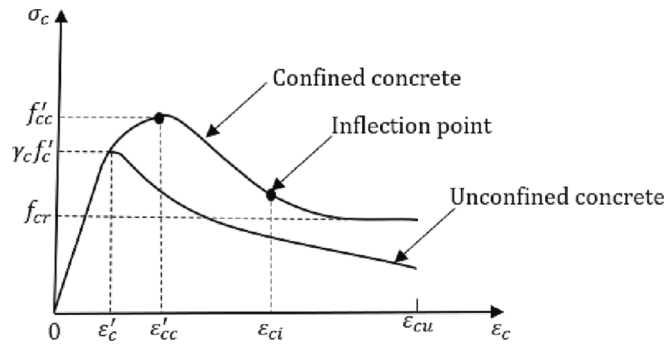


Fig. 3. Constitutive relations of confined and unconfined concrete.

$$B_1 = \frac{G_1 E_{0.2} (n + G_0)}{E_0} \tag{12}$$

$$G_0 = \frac{0.002 E_0}{\sigma_{0.2}} \tag{13}$$

$$G_1 = \frac{\varepsilon_{0.2} E_{0.2} (n - 1)}{\sigma_{0.2}} \tag{14}$$

$$E_{0.2} = \frac{E_0}{1 + 0.002 \left(\frac{n E_0}{\sigma_{0.2}} \right)} \tag{15}$$

$$n = \frac{\ln(20)}{\ln(\sigma_{0.2} / \sigma_{0.01})} \tag{16}$$

where n is the Knee factor and $E_{0.2}$ is the tangent modulus of the stainless steel at 0.2% proof strain.

The stress of stainless steel in the second stage ($\varepsilon_{0.2} < \varepsilon_s \leq \varepsilon_{2.0}$) is calculated as

$$\sigma_s = \sigma_{0.2} + \frac{E_{0.2} \left[1 + C_5 \left(\frac{\varepsilon_s - \varepsilon_{0.2}}{\varepsilon_{1.0} - \varepsilon_{0.2}} \right)^{C_6} \right] (\varepsilon_s - \varepsilon_{0.2})}{1 + C_7 \left(\frac{\varepsilon_s - \varepsilon_{0.2}}{\varepsilon_{1.0} - \varepsilon_{0.2}} \right)^{C_8} + C_5 \left(\frac{\varepsilon_s - \varepsilon_{0.2}}{\varepsilon_{1.0} - \varepsilon_{0.2}} \right)^{C_6}} \tag{17}$$

where $\sigma_{1.0}$ and $\varepsilon_{1.0}$ are the 1.0% proof stress and the corresponding strain, respectively. $\sigma_{1.0}$ and $\varepsilon_{1.0}$ were proposed by Quach et al. [80] as

$$\sigma_{1.0} = \sigma_{0.2} \left(\frac{0.662}{n} + 1.085 \right) \tag{18}$$

$$\varepsilon_{1.0} = \varepsilon_{0.2} + \frac{\sigma_{1.0} - \sigma_{0.2}}{E_{0.2}} + \left[0.008 + (\sigma_{1.0} - \sigma_{0.2}) \left(\frac{1}{E_0} - \frac{1}{E_{0.2}} \right) \right] \tag{19}$$

In Eq. (17), C_5 , C_6 , C_7 and C_8 are calculated as

$$C_5 = \frac{1}{C_6 - 1} \tag{20}$$

$$C_6 = C_8 + \frac{1}{\ln \left(\frac{\varepsilon_{2.0} - \varepsilon_{0.2}}{\varepsilon_{1.0} - \varepsilon_{0.2}} \right)} \left[\ln(1 + A_2) + \ln \left(\frac{H_0}{H_2} \right) \right] \tag{21}$$

$$C_7 = H_0 (1 + C_5) \tag{22}$$

$$C_8 = 1 + H_1 \tag{23}$$

where

$$A_2 = \frac{(n_2 - 1)^2 (H_2 - H_0)}{(1 + n_2 H_0) (1 + n_2 H_2)} \tag{24}$$

$$H_0 = \frac{\left[0.008 + (\sigma_{1.0} - \sigma_{0.2}) \left(\frac{1}{E_0} - \frac{1}{E_{0.2}} \right) \right] E_{0.2}}{\sigma_{1.0} - \sigma_{0.2}} > 0 \tag{25}$$

$$H_1 = \frac{(n_2 - 1) (H_0 + 1)}{1 + n_2 H_0} \tag{26}$$

$$H_2 = \frac{E_{0.2} (\varepsilon_{2.0} - \varepsilon_{0.2})}{\sigma_{2.0} - \sigma_{0.2}} - 1 \tag{27}$$

$$n_2 = 6.399 \left(\frac{E_{0.2}}{E_0} \right) \left(\frac{\sigma_{1.0}}{\sigma_{0.2}} \right) + 1.145 \tag{28}$$

where $\sigma_{2.0}$ and $\varepsilon_{2.0}$ are 2.0% proof stress and the corresponding strain, respectively. $\sigma_{2.0}$ and $\varepsilon_{2.0}$ are calculated using the formulas proposed by Quach et al. [80]:

$$\sigma_{2.0} = \sigma_{0.2} \left[\frac{1 + \left(\frac{\sigma_{1.0}}{\sigma_{0.2}} - 1 \right) A^{\frac{1}{n_2}}}{1 + \left(\frac{\sigma_{0.2}}{E_0} \right) \left(\frac{E_0}{E_{0.2}} - 1 \right) \left(\frac{\sigma_{1.0}}{\sigma_{0.2}} - 1 \right) \left(\frac{A^{\frac{1}{n_2}}}{n_2 B_2} \right)} \right] \tag{29}$$

$$\varepsilon_{2.0} = \varepsilon_{0.2} + \frac{\sigma_{2.0} - \sigma_{0.2}}{E_{0.2}} + \left[0.008 + (\sigma_{1.0} - \sigma_{0.2}) \left(\frac{1}{E_0} - \frac{1}{E_{0.2}} \right) \right] \left(\frac{\sigma_{2.0} - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}} \right)^{n_2} \tag{30}$$

where,

$$A = \frac{B_2}{0.008 + \left(\frac{\sigma_{0.2}}{E_0} \right) \left(\frac{\sigma_{1.0}}{\sigma_{0.2}} - 1 \right) \left(1 - \frac{E_0}{E_{0.2}} \right)} \tag{31}$$

$$B_2 = 0.018 + \left(\frac{\sigma_{0.2}}{E_0} \right) \left(\frac{E_0}{E_{0.2} - 1} \right) \tag{32}$$

The stress of stainless steel in the third stage ($\varepsilon_{2.0} < \varepsilon_s \leq \varepsilon_{su}$) is calculated as

$$\sigma_s = \frac{A_3 + B_3 \varepsilon_s}{1 - \varepsilon_s} \tag{33}$$

where

$$A_3 = \sigma_{2.0} (1 - \varepsilon_{2.0}) - B_3 \varepsilon_{2.0} \tag{34}$$

$$B_3 = \frac{\sigma_{su} (1 - \varepsilon_{su}) - \sigma_{2.0} (1 - \varepsilon_{2.0})}{\varepsilon_{su} - \varepsilon_{2.0}} \tag{35}$$

where σ_{su} and ε_{su} are the ultimate stress and the ultimate strain, respectively and can be calculated as:

$$\varepsilon_{uc} = 1 - \frac{1}{1 + \varepsilon_{ut}} \tag{36}$$

$$\sigma_{uc} = (1 + \varepsilon_{ut})^2 \sigma_{ut} \tag{37}$$

where σ_{ut} and ε_{ut} are the ultimate tensile strength and the ultimate tensile strain, respectively and calculated as

$$\sigma_{ut} = \sigma_{0.2} \left[\frac{1 - 0.0375(n - 5)}{185e + 0.2} \right] \tag{38}$$

$$\varepsilon_{ut} = 1 - \frac{\sigma_{0.2}}{\sigma_{ut}} \tag{39}$$

3.2. Constitutive relations of concrete

Fig. 3 presents the constitutive relations of concrete adopted. The constitutive relations of concrete under compression are expressed as [86,87]:

Table 1
Validation of the accuracy of the unified model for circular CFSST columns.

Specimen	b ($b = h$) (mm)	t (mm)	L (mm)	L/b	$\sigma_{0.2}$ (MPa)	f_c (MPa)	$P_{u,exp}$ (kN)	$P_{u,num}$ (kN)	$\frac{P_{u,num}}{P_{u,exp}}$	$P_{u,Lin}$ (kN)	$\frac{P_{u,Lin}}{P_{u,exp}}$	Ref.
CHS104 × 2-C30	104.0	2.0	312	3.0	412	31	699	663	0.95	648	0.93	[31]
CHS114 × 6-C60	114.3	6.0	343	3.0	266	49	1648	1380	0.84	1177	0.71	
C30-50 × 1.6A	50.8	1.6	152	3.0	298	30	260	250	0.96	163	0.63	[32]
C30-50 × 1.6B	50.8	1.6	152	3.0	298	30	280	250	0.89	163	0.58	
C30-100 × 1.6A	101.6	1.6	305	3.0	320	30	602	581	0.97	489	0.81	
C30-100 × 1.6B	101.6	1.6	305	3.0	320	30	609	593	0.97	489	0.80	
A1	300.0	8.0	900	3.0	248	34	6134	6421	1.05	5047	0.82	[43]
A2	300.0	10.0	900	3.0	242	34	7076	7524	1.06	5465	0.77	
A3	300.0	12.0	900	3.0	249	34	8088	8611	1.06	6068	0.75	
A6	300.0	12.0	900	3.0	249	38	8230	8797	1.07	6299	0.77	
A7	300.0	8.0	900	3.0	248	41	6171	6704	1.09	5477	0.89	
D2	325.0	10.0	975	3.0	542	37	11,032	11,937	1.08	10,222	0.93	
D3	325.0	12.0	975	3.0	542	37	12,962	13,789	1.06	11,328	0.87	
C-3-L-RS-1	159.0	2.9	477	3.0	384	37	1264	1337	1.06	1531	1.21	[45]
C-3-L-RS-2	159.0	2.9	477	3.0	384	37	1322	1337	1.01	1531	1.16	
C-3-H-RS-1	159.0	2.9	477	3.0	384	44	1349	1439	1.07	1661	1.23	
C-3-H-RS-2	159.0	2.9	477	3.0	384	44	1316	1439	1.09	1661	1.26	
C-4-L-RS-1	159.0	3.8	477	3.0	401	37	1627	1620	1.00	1774	1.09	
C-4-L-RS-2	159.0	3.8	477	3.0	401	37	1624	1620	1.00	1774	1.09	
C-5-L-RS-1	159.0	4.5	477	3.0	401	37	1713	1799	1.05	1941	1.13	
C-5-L-RS-2	159.0	4.5	477	3.0	401	37	1630	1799	1.10	1941	1.19	
C-3-L-DS-1	159.0	2.9	477	3.0	384	37	1310	1337	1.02	1531	1.17	
C-3-L-DS-2	159.0	2.9	477	3.0	384	37	1291	1337	1.04	1531	1.19	
C-3-H-DS-1	159.0	2.9	477	3.0	384	44	1514	1439	0.95	1661	1.10	
C-3-H-DS-2	159.0	2.9	477	3.0	384	44	1552	1439	0.93	1661	1.07	
C-4-L-DS-1	159.0	3.8	477	3.0	401	37	1598	1620	1.01	1774	1.11	
C-4-L-DS-2	159.0	3.8	477	3.0	401	37	1612	1620	1.00	1774	1.10	
C-5-L-DS-1	159.0	4.5	477	3.0	401	37	1725	1799	1.04	1941	1.13	
C-5-L-DS-2	159.0	4.5	477	3.0	401	37	1739	1799	1.03	1941	1.12	
C-3-L-SS-1	159.0	2.9	477	3.0	384	37	1366	1337	0.98	1531	1.12	
C-3-L-SS-2	159.0	2.9	477	3.0	384	37	1333	1337	1.00	1531	1.15	
C-3-H-SS-1	159.0	2.9	477	3.0	384	44	1466	1439	0.98	1661	1.13	
C-3-H-SS-2	159.0	2.9	477	3.0	384	44	1452	1439	0.99	1661	1.14	
C-4-L-SS-1	159.0	3.8	477	3.0	401	37	1642	1620	0.99	1774	1.08	
C-4-L-SS-2	159.0	3.8	477	3.0	401	37	1648	1620	0.98	1774	1.08	
C-5-L-SS-1	159.0	4.5	477	3.0	401	37	1746	1799	1.03	1941	1.11	
C-5-L-SS-2	159.0	4.5	477	3.0	401	37	1715	1799	1.05	1941	1.13	
S50-C	50.9	3.1	150	2.9	228	36	235	241	1.03	205	0.87	[41]
S101-C	101.9	2.8	400	3.9	225	36	570	581	1.02	578	1.01	
S114-C	114.1	2.8	400	3.5	280	36	766	762	0.99	764	1.00	
S165-C	168.4	3.2	400	2.4	281	36	1449	1391	0.96	1506	1.04	
50x1.6-F	49.6	1.5	150	3.0	376	42	209	208	1.00	198	0.95	[42]
50x3-F	50.9	3.1	150	2.9	229	42	244	256	1.05	217	0.89	
76x1.6-F	76.2	1.7	230	3.0	398	42	388	410	1.06	411	1.06	
89x3-F	89.2	3.2	270	3.0	259	42	548	592	1.08	569	1.04	
101x1.6-F	101.8	1.7	300	2.9	353	42	617	570	0.92	621	1.01	
101x3-F	101.9	2.8	300	2.9	226	42	610	612	1.00	622	1.02	
114x3-F	114.1	2.8	350	3.1	281	42	831	799	0.96	824	0.99	
152x1.6-F	152.6	1.6	450	2.9	314	42	1050	945	0.90	1138	1.08	
203x2-F	202.7	2.0	600	3.0	304	42	1787	1576	0.88	1955	1.09	
C-S-N	120.0	1.8	360	3.0	286	54	823	760	0.92	890	1.08	[35]
C-S-C1	120.0	1.8	360	3.0	286	51	813	732	0.90	856	1.05	
C-S-C2	120.0	1.8	360	3.0	286	49	802	714	0.89	837	1.04	
C-S-C3	120.0	1.8	360	3.0	286	48	774	705	0.91	826	1.07	
C-S-F1	120.0	1.8	360	3.0	286	50	806	723	0.90	850	1.05	
C-S-F2	120.0	1.8	360	3.0	286	48	768	705	0.92	826	1.08	
C-S-F3	120.0	1.8	360	3.0	286	47	777	696	0.90	815	1.05	
C-100S	103.0	1.7	306	3.0	213	50	552	503	0.91	588	1.07	[44]
C-150S	153.0	2.1	456	3.0	209	50	1138	1020	0.90	1235	1.09	
C-200S	203.0	2.1	608	3.0	209	50	1868	1639	0.88	2044	1.09	
C5	100.0	2.0	300	3.0	324	39	591	530	0.90	595	1.01	[34]
D73-C50	72.8	2.9	215	3.0	258	50	375	391	1.04	421	1.12	[63]
D73-C60	72.8	2.8	216	3.0	258	64	455	432	0.95	473	1.04	
D89-C60	89.3	3.1	266	3.0	321	64	685	688	1.00	755	1.10	
C-3-0.9-3.0	63.0	0.9	189	3.0	350	19	135	152	1.13	149	1.10	[36]
C-3-1.0-3.0	63.0	1.0	189	3.0	423	19	192	187	0.97	163	0.85	
C-3-1.2-3.0	63.0	1.2	189	3.0	330	19	163	182	1.12	202	1.24	
C-4-0.9-3.0	63.0	0.9	189	3.0	350	22	263	250	0.95	159	0.60	
C-4-1.0-3.0	63.0	1.0	189	3.0	423	22	184	193	1.05	172	0.93	
C-3-0.9-3.5	63.0	0.9	221	3.5	350	19	204	215	1.05	149	0.73	
C-3-1.0-3.5	63.0	1.0	221	3.5	423	19	252	264	1.05	163	0.65	
C-3-1.2-3.5	63.0	1.2	221	3.5	330	19	326	335	1.03	202	0.62	
C-4-0.9-3.5	63.0	0.9	221	3.5	350	22	125	135	1.08	159	1.27	

(continued on next page)

Table 1 (continued)

Specimen	$b(b = h)$ (mm)	t (mm)	L (mm)	L/b	$\sigma_{0.2}$ (MPa)	f'_c (MPa)	$P_{u,exp}$ (kN)	$P_{u,num}$ (kN)	$\frac{P_{u,num}}{P_{u,exp}}$	$P_{u,Lin}$ (kN)	$\frac{P_{u,Lin}}{P_{u,exp}}$	Ref.
C-4-1.0-3.5	63.0	1.0	221	3.5	423	22	203	199	0.98	172	0.85	
C-4-1.2-3.5	63.0	1.2	221	3.5	350	22	272	295	1.08	212	0.78	
C-3-1.0-4.0	63.0	1.0	252	4.0	423	19	233	240	1.03	163	0.70	
C-3-1.2-4.0	63.0	1.2	252	4.0	330	19	286	293	1.02	202	0.71	
C-4-0.9-4.0	63.0	0.9	252	4.0	350	22	135	137	1.01	159	1.18	
C-4-1.0-4.0	63.0	1.0	252	4.0	423	22	250	276	1.10	172	0.69	
C-4-1.2-4.0	63.0	1.2	252	4.0	338	22	272	281	1.03	212	0.78	
		Mean							1.00		0.99	
		Standard Deviation (SD)							0.07		0.18	
		Coefficient of Variance (CoV)							0.07		0.18	

Table 2

Validation of the accuracy of the unified model for rectangular CFSST columns.

Specimen	b (mm)	h (mm)	t (mm)	L (mm)	L/b	f'_c (MPa)	$\sigma_{0.2}$ (MPa)	$P_{u,exp}$ (kN)	$P_{u,num}$ (kN)	$\frac{P_{u,num}}{P_{u,exp}}$	$P_{u,Lin}$ (kN)	$\frac{P_{u,Lin}}{P_{u,exp}}$	Ref
SHS1C40	150.5	150.5	5.8	450	3.0	47	497	2768	2729	0.99	2594	0.94	[30]
SHS1C60	150.5	150.5	5.8	450	3.0	62	497	2972	2899	0.98	2882	0.97	
SHS1C80	150.5	150.5	5.8	450	3.0	84	497	3020	3199	1.06	3295	1.09	
S30-50 × 2A	51.0	51.0	1.8	150	2.9	35	353	268	214	0.80	205	0.76	[32]
S30-50 × 2B	51.0	51.0	1.8	150	2.9	35	353	274	214	0.78	205	0.75	
S20-100 × 3A	100.0	100.0	2.9	300	3.0	22	358	705	649	0.92	595	0.84	
S20-100 × 3B	100.0	100.0	2.9	300	3.0	22	358	716	649	0.91	595	0.83	
S30-100 × 3A	100.0	100.0	2.9	300	3.0	35	358	765	719	0.94	709	0.93	
S30-100 × 3B	100.0	100.0	2.9	300	3.0	35	358	757	728	0.96	709	0.94	
S20-100 × 5A	101.0	101.0	5.1	300	3.0	22	435	1437	1452	1.01	1020	0.71	
S20-100 × 5B	101.0	101.0	5.1	300	3.0	22	435	1449	1452	1.00	1020	0.70	
S30-100 × 5A	101.0	101.0	5.1	300	3.0	35	435	1474	1478	1.00	1136	0.77	
S30-100 × 5B	101.0	101.0	5.1	300	3.0	35	435	1490	1478	0.99	1136	0.76	
S20-150 × 3A	152.0	152.0	2.9	450	3.0	22	268	1035	893	0.86	926	0.89	
S20-150 × 3B	152.0	152.0	2.9	450	3.0	22	268	1062	893	0.84	926	0.87	
S30-150 × 3A	152.0	152.0	2.9	450	3.0	35	268	1074	1126	1.05	1207	1.12	
S30-150 × 3B	152.0	152.0	2.9	450	3.0	35	268	1209	1126	0.93	1207	1.00	
S20-150 × 5B	150.0	150.0	4.8	450	3.0	22	340	1935	2144	1.11	1380	0.71	
S30-150 × 5A	150.0	150.0	4.8	450	3.0	35	340	2048	1877	0.92	1634	0.80	
S30-150 × 5B	150.0	150.0	4.8	450	3.0	35	340	1976	1652	0.84	1634	0.83	
SHS 100 × 100 × 5 – C30	100.6	100	5.0	300	3.0	30	458	1410	1373	0.97	1121	0.80	[31]
SHS 100 × 100 × 5 – C60	99.9	101	4.9	300	3.0	53	458	1488	1422	0.96	1291	0.87	
SHS 100 × 100 × 5 – C100	99.9	101	4.9	300	3.0	74	458	1559	1532	0.98	1467	0.94	
304-t8C50	295.5	296	7.8	840	2.8	41	293	6290	5457	0.87	5854	0.93	[46]
304-t10C50	299.7	300	9.9	840	2.8	41	287	7113	6217	0.87	6517	0.92	
304-t12C50	303.7	304	11.9	840	2.8	41	301	7924	6963	0.88	7415	0.94	
304-t8C70	295.5	296	7.8	840	2.8	61	293	6743	6690	0.99	7442	1.10	
304-t10C70	299.7	300	9.9	840	2.8	61	287	7947	7356	0.93	8125	1.02	
304-t12C70	303.7	304	11.9	840	2.8	61	301	8575	8016	0.93	9025	1.05	
304-t8C80	295.5	296	7.8	840	2.8	70	293	7436	7259	0.98	8144	1.10	
304-t10C80	299.7	300	9.9	840	2.8	70	287	8430	7890	0.94	8836	1.05	
304-t12C80	303.7	304	11.9	840	2.8	70	301	9257	8520	0.92	9725	1.05	
2205-t8C50	295.5	296	7.9	840	2.8	41	634	8771	9430	1.08	8826	1.01	
2205-t10C50	299.7	300	9.8	840	2.8	41	590	10,111	10,917	1.08	9831	0.97	
2205-t12C50	303.7	304	12.5	840	2.8	41	576	12,472	13,337	1.07	11,565	0.93	
2205-t8C70	295.5	296	7.9	840	2.8	61	634	9686	10,196	1.05	10,423	1.08	
2205-t10C70	299.7	300	9.8	840	2.8	61	590	10,820	11,271	1.04	11,522	1.06	
2205-t12C70	303.7	304	12.5	840	2.8	61	576	12,560	13,760	1.10	13,114	1.04	
2205-t8C80	295.5	296	7.9	840	2.8	70	634	9962	10,699	1.07	11,120	1.12	
2205-t10C80	299.7	300	9.8	840	2.8	70	590	11,728	11,660	0.99	12,208	1.04	
2205-t12C80	303.7	304	12.5	840	2.8	70	576	13,272	13,891	1.05	13,827	1.04	
S200635	60.0	60	1.0	180	3.0	19	258	131	124	0.95	124	0.95	[37]
S200640	60.0	60	1.0	180	3.0	19	258	126	124	0.98	124	0.98	
S200830	80.0	80	1.0	240	3.0	19	258	190	193	1.02	197	1.04	
S200835	80.0	80	1.0	240	3.0	19	258	182	193	1.06	197	1.08	
S2001030	100.0	100	1.0	300	3.0	19	258	258	274	1.06	284	1.10	
S300840	80.0	80	1.0	300	3.8	25	258	211	227	1.08	234	1.11	
S-3-L-RS-2	160.0	160.0	2.9	480	3.0	37	446	1534	1612	1.05	1690	1.10	[45]
S-4-L-RS-1	160.0	160.0	3.9	480	3.0	37	415	2040	1832	0.90	1874	0.92	
S-4-L-RS-2	160.0	160.0	3.9	480	3.0	37	415	1931	1832	0.95	1874	0.97	
S-5-L-RS-1	160.0	160.0	4.8	480	3.0	37	432	2125	2167	1.02	2124	1.00	
S-5-L-RS-2	160.0	160.0	4.8	480	3.0	37	432	2012	2167	1.08	2124	1.06	
S-3-L-DS-1	160.0	160.0	2.9	480	3.0	37	446	1543	1612	1.04	1690	1.10	
S-3-L-DS-2	160.0	160.0	2.9	480	3.0	37	446	1590	1612	1.01	1690	1.06	
S-3-H-DS-1	160.0	160.0	2.9	480	3.0	44	446	1769	1748	0.99	1858	1.05	
S-3-H-DS-2	160.0	160.0	2.9	480	3.0	44	446	1914	1748	0.91	1858	0.97	
S-4-L-DS-1	160.0	160.0	3.9	480	3.0	37	415	1955	1832	0.94	1874	0.96	

(continued on next page)

Table 2 (continued)

Specimen	<i>b</i> (mm)	<i>h</i> (mm)	<i>t</i> (mm)	<i>L</i> (mm)	<i>L/b</i>	<i>f</i> _c (MPa)	<i>σ</i> _{0.2} (MPa)	<i>P</i> _{u,exp} (kN)	<i>P</i> _{u,num} (kN)	$\frac{P_{u,num}}{P_{u,exp}}$	<i>P</i> _{u,Lin} (kN)	$\frac{P_{u,Lin}}{P_{u,exp}}$	Ref
S-4-L-DS-2	160.0	160.0	3.9	480	3.0	37	415	1897	1832	0.97	1874	0.99	
S-5-L-DS-1	160.0	160.0	4.8	480	3.0	37	432	2152	2167	1.01	2124	0.99	
S-5-L-DS-2	160.0	160.0	4.8	480	3.0	37	432	2141	2167	1.01	2124	0.99	
S-3-L-SS-1	160.0	160.0	2.9	480	3.0	37	446	1724	1612	0.94	1690	0.98	
S-3-L-SS-2	160.0	160.0	2.9	480	3.0	37	446	1780	1612	0.91	1690	0.95	
S-3-H-SS-1	160.0	160.0	2.9	480	3.0	44	446	1690	1748	1.03	1858	1.10	
S-3-H-SS-2	160.0	160.0	2.9	480	3.0	44	446	1765	1748	0.99	1858	1.05	
S-4-L-SS-1	160.0	160.0	3.9	480	3.0	37	415	2007	1832	0.91	1874	0.93	
S-4-L-SS-2	160.0	160.0	3.9	480	3.0	37	415	1947	1832	0.94	1874	0.96	
S-5-L-SS-1	160.0	160.0	4.8	480	3.0	37	432	2215	2167	0.98	2124	0.96	
S-5-L-SS-2	160.0	160.0	4.8	480	3.0	37	432	2197	2167	0.99	2124	0.97	
A100	98.8	98.8	3.1	400	4.0	37	266	698	628	0.90	634	0.91	[49]
A250	248.8	248.8	3.1	850	3.4	37	266	2709	2597	0.96	2992	1.10	
D100	99.5	99.5	3.1	400	4.0	37	511	1039	989	0.95	933	0.90	
D250	249.5	249.5	3.1	850	3.4	37	511	3186	3374	1.06	3736	1.17	
60 × 40 × 4C40	59.9	40.1	3.8	179	3.0	43	479	478	525	1.10	410	0.86	[91]
60 × 40 × 4C40R	59.8	40.1	3.8	179	3.0	43	479	481	525	1.09	410	0.85	
60 × 40 × 4C80	59.9	40.1	3.8	179	3.0	81	479	531	549	1.03	474	0.89	
60 × 40 × 4C120	59.8	40.1	3.8	179	3.0	115	479	585	563	0.96	529	0.90	
60 × 60 × 3C40	60.3	60.1	2.8	179	3.0	43	449	484	473	0.98	419	0.87	
60 × 60 × 3C80	60.2	60.1	2.8	179	3.0	81	449	594	535	0.90	530	0.89	
80 × 60 × 4C40	80.1	59.9	3.7	240	3.0	43	451	712	713	1.00	605	0.85	
80 × 60 × 4C80	80.3	59.9	3.7	240	3.0	81	451	878	778	0.89	755	0.86	
80 × 60 × 4C120	80.2	59.9	3.7	240	3.0	115	451	999	881	0.88	878	0.88	
80 × 60 × 4C120R	80.2	59.9	3.7	240	3.0	115	451	976	881	0.90	883	0.90	
100 × 40 × 2C40	99.7	40.2	1.9	300	3.0	43	420	398	380	0.95	367	0.92	
100 × 40 × 2C120	99.7	40.2	1.9	300	3.0	115	420	674	600	0.89	619	0.92	
120 × 80 × 3C40	119.9	79.9	2.8	360	3.0	43	381	870	784	0.90	780	0.90	
120 × 80 × 3C80	120.0	79.9	2.8	360	3.0	81	381	1255	1069	0.85	1105	0.88	
120 × 80 × 3C120	120.0	79.9	2.8	360	3.0	115	381	1610	1333	0.83	1397	0.87	
Mean										0.97		0.95	
SD										0.07		0.11	
CoV										0.08		0.11	

Table 3

Validation of the accuracy of the unified model for round-ended CFST columns.

Specimen	<i>b</i> (mm)	<i>h</i> (mm)	<i>t</i> (mm)	<i>L</i> (mm)	<i>L/b</i>	<i>σ</i> _{0.2} (MPa)	<i>f</i> _c (MPa)	<i>P</i> _{u,exp} (kN)	<i>P</i> _{u,num} (kN)	$\frac{P_{u,num}}{P_{u,exp}}$	<i>P</i> _{u,Lin} (kN)	$\frac{P_{u,Lin}}{P_{u,exp}}$	Ref
WST1-A	299	252	3.75	750	2.5	328	34	3429	3504	1.02	3647	1.06	[92]
WST1-B	302	249	3.75	750	2.5	328	34	3328	3486	1.05	3645	1.10	
WST2-A	299	255	5.84	750	2.5	300	34	4162	3915	0.94	4222	1.01	
WST2-B	300	251	5.8	750	2.5	300	34	4168	3859	0.93	4170	1.00	
WST3-A	350	255	3.72	900	2.6	328	34	3929	3924	1.00	4210	1.07	
WST3-B	351	252	3.76	900	2.6	328	34	4158	3896	0.94	4200	1.01	
WST4-A	352	251	5.9	900	2.6	300	34	4492	4320	0.96	4792	1.07	
WST4-B	349	251	5.92	900	2.6	300	43	5530	4950	0.90	5374	0.97	
WST5-A	394	260	3.79	1000	2.5	328	43	5620	5111	0.91	5497	0.98	
WST5-B	396	264	3.8	1000	2.5	328	43	5500	5217	0.95	5594	1.02	
WST6-A	405	197	3.75	800	2.0	311	33	3240	3359	1.04	3846	1.19	
WST7-A	608	186	3.75	1200	2.0	311	33	4826	4834	1.00	5451	1.13	
WST7-B	605	194	3.77	1200	2.0	311	33	4944	4961	1.00	5599	1.13	
WST8-A	805	190	3.74	1600	2.0	311	33	6521	6504	1.00	7263	1.11	
WST8-B	806	191	3.67	1600	2.0	311	33	6493	6502	1.00	7254	1.12	
WST9-A	405	198	3.75	800	2.0	311	49	4203	4387	1.04	4922	1.17	
WST9-B	405	198	3.7	800	2.0	311	49	4180	4373	1.05	4906	1.17	
WST10-A	610	196	3.8	1200	2.0	311	49	7201	6618	0.92	7321	1.02	
WST10-B	606	189	3.77	1200	2.0	311	49	6905	6384	0.92	7060	1.02	
WST11-A	805	190	3.68	1600	2.0	311	49	9065	8526	0.94	9336	1.03	
WST11-B	805	194	3.8	1600	2.0	311	49	8799	8722	0.99	9561	1.09	
RCFST-1	168.5	117	2.86	540	3.2	325	32	925	1030	1.11	1093	1.18	[12]
RCFST-2	229	118	2.86	722	3.2	325	32	1215	1288	1.06	1435	1.18	
RCFST-4	237.5	156.5	2.86	720	3.0	325	32	1658	1696	1.02	1825	1.10	
RCFST-5	317	158.5	2.86	962	3.0	325	32	2091	2117	1.01	2393	1.14	
RND_30_00	120	50	2	300	2.5	307	41	385	400	1.04	420	1.09	[93]
Mean										0.99		1.08	
SD										0.06		0.07	
CoV										0.06		0.06	

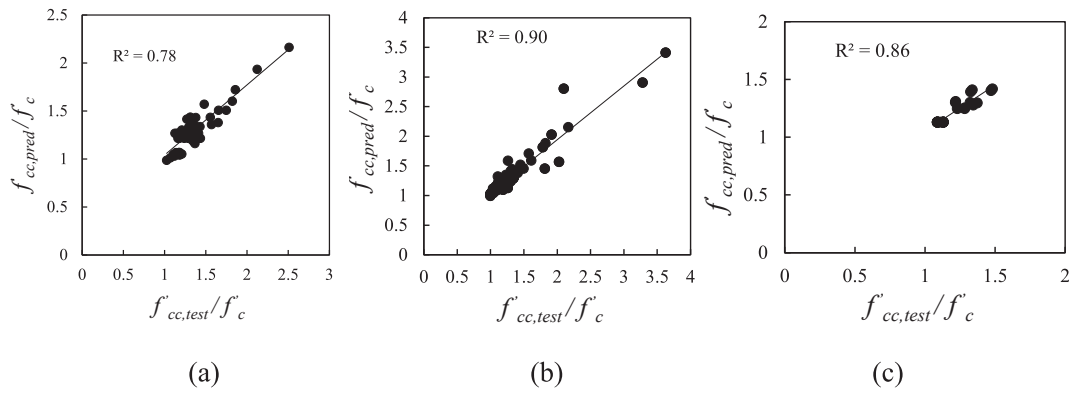


Fig. 4. Accuracy of the proposed formulas for f'_{cc}/f'_c : (a) circular, (b) rectangular and (c) round-ended cross-sections.

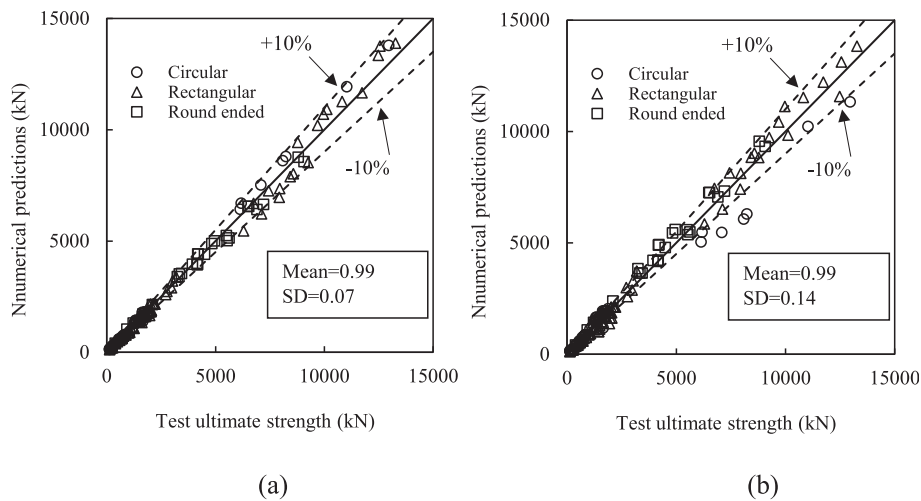


Fig. 5. Comparison of the predicted and test ultimate strength of all columns (a) unified model proposed in this study (b) unified model proposed by Lin et al. [72].

$$\sigma_c = \begin{cases} \frac{f'_{cc}(\epsilon_c/\epsilon'_{cc})^\lambda}{(\epsilon_c/\epsilon'_{cc})^\lambda + \lambda - 1} & \text{for } 0 \leq \epsilon_c \leq \epsilon'_{cc} \\ f'_{cc} - \frac{f'_{cc} - f_{cr}}{1 + \left(\frac{\epsilon_c - \epsilon'_{cc}}{\epsilon_{ci} - \epsilon'_{cc}}\right)^{-2}} & \text{for } \epsilon_c > \epsilon'_{cc} \end{cases} \quad (40)$$

where ϵ_c is the longitudinal strain at longitudinal stress σ_c ; f'_{cc} and ϵ'_{cc} are the compressive strength of the confined concrete and its associated strain, respectively; f_{cr} is the residual strength of concrete and ϵ_{ci} represents the inflection strain; λ is given by

represents the inflection strain; λ is given by

$$\lambda = \frac{E_c \epsilon'_{cc}}{E_c \epsilon'_{cc} - f'_{cc}} \quad (41)$$

in which E_c is the elastic moduli of concrete, calculated as $E_c = 4400\sqrt{\gamma_c f'_c}$ in MPa. The reduction factor γ_c was provided by Liang [69] for taking into account the effect of the column size, calculated as $\gamma_c = 1.85 D_c^{-0.135} \geq 0.85$, where D_c is the diameter of the core concrete ($D_c =$

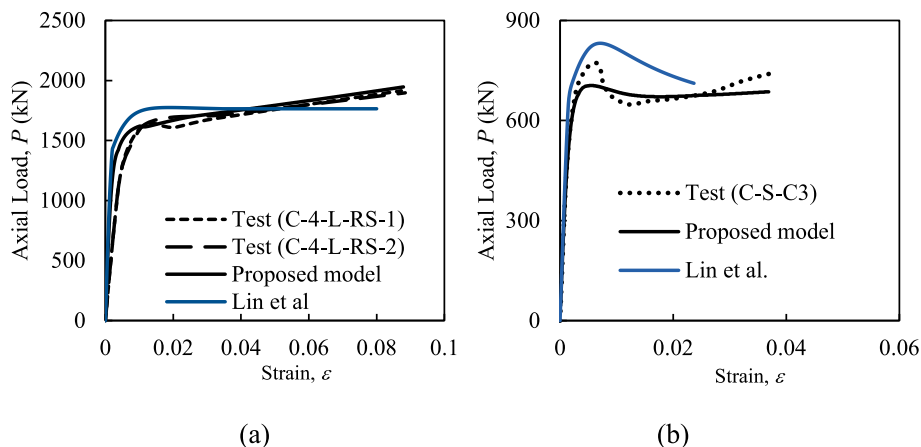


Fig. 6. Test vs numerical predictions of $P-\epsilon$ curves of circular CFSST columns.

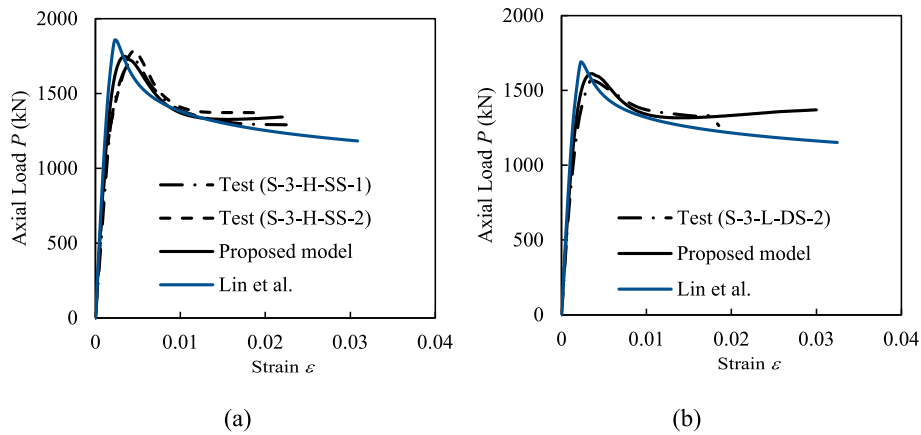


Fig. 7. Test vs numerical predictions of $P-\epsilon$ curves of rectangular and square CFSST columns.

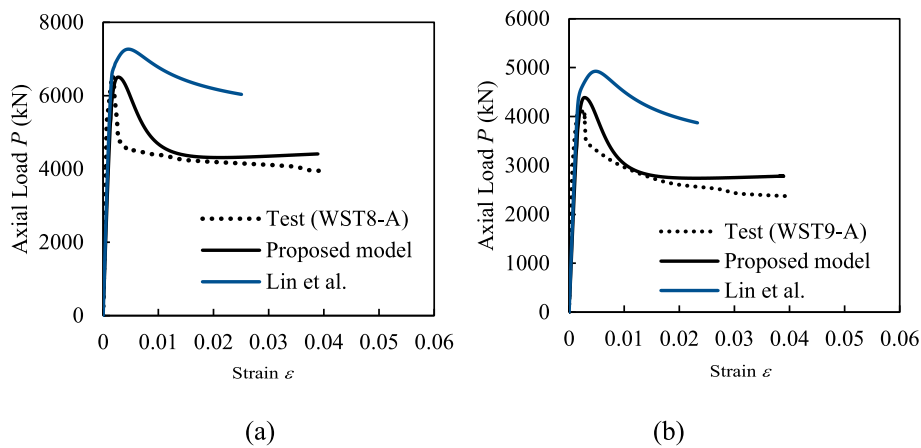


Fig. 8. Test vs numerical predictions of $P-\epsilon$ curves of round-ended CFST columns.

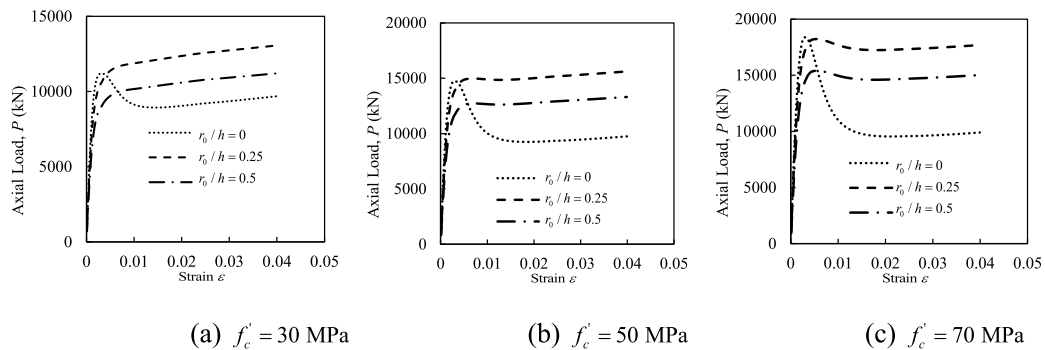


Fig. 9. Sensitivity of strength of concrete on the $P-\epsilon$ curves for varying r_0/h ratio.

$2R_c$).

The confinement effects are different for various shapes in CFSST columns. Due to the confinement, the compressive strength of confined concrete of CFSST columns is higher compared to unconfined concrete compressive strength, as can be seen from Fig. 3. The concrete compressive strength of the confined concrete (f'_{cc}) of the tested CFSST columns were calculated by subtracting the axial capacity of the stainless-steel tube from the ultimate axial load of the CFSST column. If the tested column had an obvious strain-softening branch, the ultimate strength was taken as the maximum load from their stress–strain curves. However, if the tested column had no obvious strain-softening branch,

the ultimate load was taken as the axial load of the column at 1% strain based on the definition of the maximum concrete compressive strain. Based on the test data reported in Tables 1 to 3, f'_{cc}/f'_c for all the tested columns were plotted and regression analysis was performed to proposed new formulas to calculate f'_{cc}/f'_c for various cross-sections as

$$\frac{f'_{cc}}{f'_c} = \begin{cases} 0.44\xi + 0.9 & \text{(circular shape)} \\ 0.0612 \times \xi^2 + 0.1177 \times \xi + 0.9359 & \text{(rectangular and square shapes)} \end{cases} \quad (42)$$

For round-ended columns,

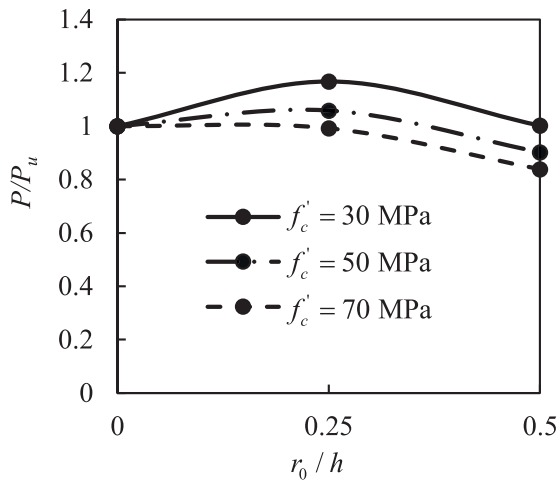


Fig. 10. Sensitivity of r_0/h ratio on the increase of the ultimate strength for various concrete strength.

$$\frac{f'_{cc}}{f'_c} = -0.0579 \times (b/h)^3 + 0.5467 \times (b/h)^2 - 1.6513 \times (b/h) + 2.6962 \geq 1.13 \tag{43}$$

where, confinement factor (ξ) is calculated as $\xi = A_s \sigma_{0.2} / A_c \gamma f'_c$, in which, the area of steel and concrete is characterized by A_s and A_c , respectively calculated using Eqs. (1–2). Fig. 4 shows the accuracy of the proposed formulas for f'_{cc}/f'_c against the test results.

The compressive strain of the confined concrete (ϵ'_{cc}) is calculated as [88]:

$$\epsilon'_{cc} = \begin{cases} 3000 - 10.4(\sigma_{0.2})^{1.4} (\gamma f'_c)^{-1.2} \left[0.73 - 3785.8 \left(\frac{2(R_e + t_e)}{t_e} \right)^{-1.5} \right] \leq 0.01 & \text{for circular shape} \\ 2300 + 31.2(\gamma f'_c)^{0.7} + [2.32 \times 10^4 - 3.88 \times 10^6 (\gamma f'_c)^{-1.8}] \left(\frac{t_e \sigma_{0.2}}{2(R_e + t_e) \gamma f'_c} \right)^2 & \text{for other shapes} \end{cases} \tag{44}$$

The residual strength of concrete (f_{cr}) is calculated as $f_{cr} = \beta_c f'_{cc}$, where $\beta_c (0 \leq \beta_c \leq 1)$ is the strength reduction factor. In determining, formulas for β_c , trial and error method was used to first determine the test value of β_c to best fit the load-axial strain curves of tested columns

$$\beta_c = \begin{cases} 1.2420 - 0.0029 \left(\frac{h}{t} \right) - 0.0044 f'_c & \text{(circular shape)} \\ 0.459 \xi + 0.046 & \text{(rectangular and square shapes)} \end{cases} \tag{45}$$

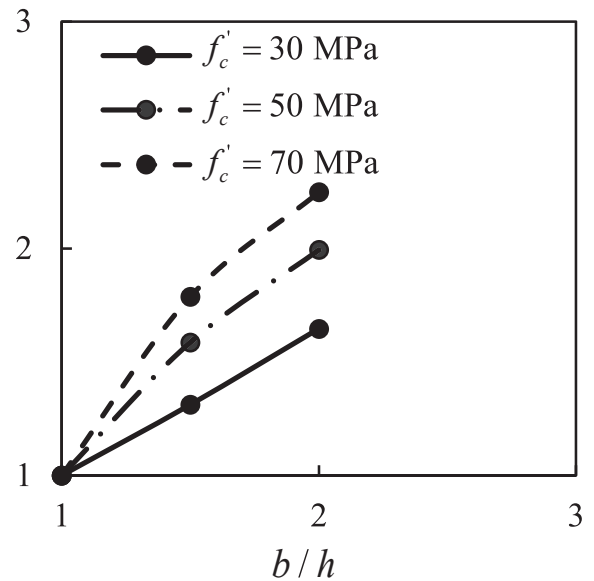


Fig. 12. Sensitivity of b/h ratio on the increase of the ultimate strength for various concrete strength.

collected for the verification purposes, listed in Tables 1 to 3. It should be noted that for rectangular and round-ended cross-sections of CFSST columns, local buckling of rectangular flat steel plates was considered, similar to the studies carried out by the authors previously [22,64] using the local buckling formulas proposed by Liang et al. [84] taking account for the residual stress of steel tube induced by welding. A regression analysis was then performed to express a formula for β_c proposed in this study as

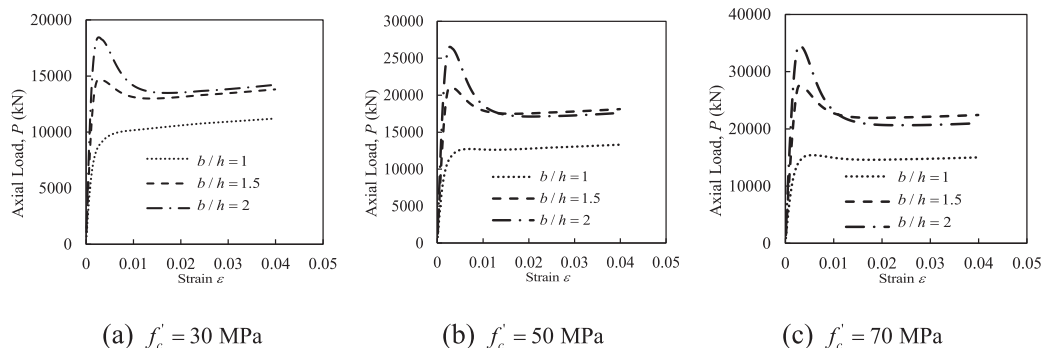


Fig. 11. Sensitivity of strength of concrete on the $P-\epsilon$ curves for varying b/h ratio.

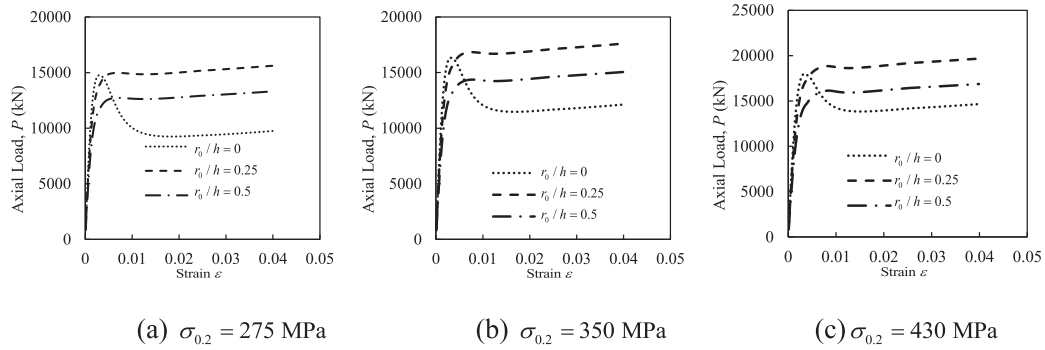


Fig. 13. Sensitivity of steel proof strength on the $P-\epsilon$ curves for varying r_0/h ratio.

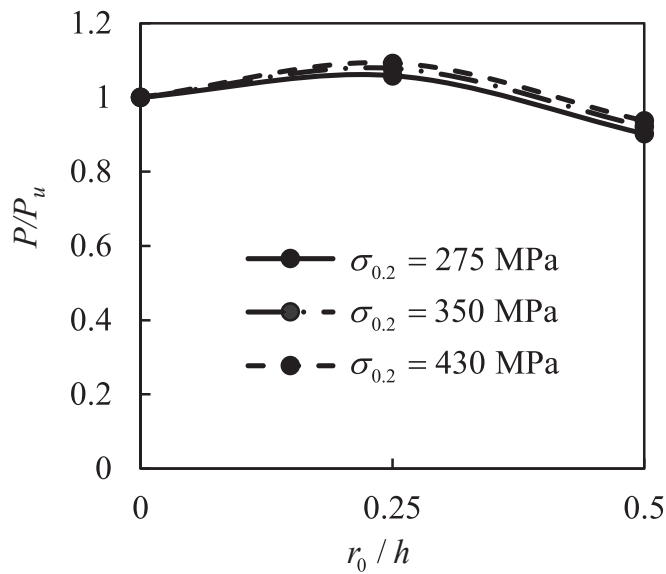


Fig. 14. Sensitivity of r_0/h ratio on the increase of the ultimate strength for various steel proof strength.

For the round-ended columns,

$$\beta_c = \begin{cases} 1.436 - 0.512(b/h) + 0.015\xi & \text{for } 1.2 \leq b/h \leq 2 \\ 0.4 & \text{for } 2 < b/h \leq 4.2 \end{cases} \quad (46)$$

The inflection strain (ϵ_{ci}) is specified in this study as 0.007 for rectangular and round-ended shapes and 0.01 for circular columns.

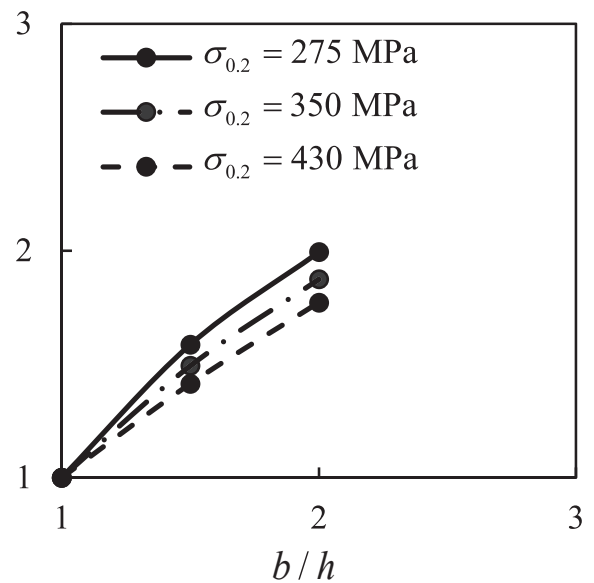


Fig. 16. Sensitivity of b/h ratio on the increase of the ultimate strength for various steel proof strength.

4. Validation

The proposed unified model’s accuracy is assessed by comparing its predicted ultimate load of CFSST columns with different cross-sections against test data in Tables 1-3. It is worth mentioning that the reported concrete cube strength was converted to cylindrical strength by multiplying by 0.85 [89]. It should be note that when stainless-steel’s hardening exponent (n) was not reported, values suggested in AS/NZS 4673–2001 [90] were utilized in the computational analysis. The

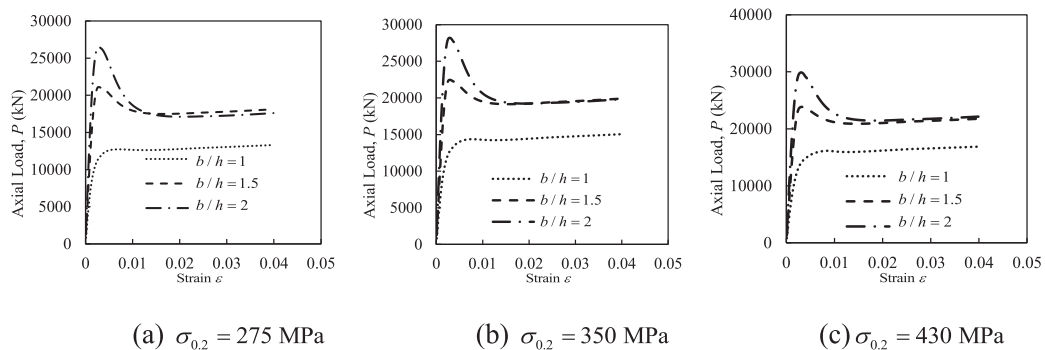


Fig. 15. Sensitivity of steel proof strength on the $P-\epsilon$ curves for varying b/h ratio.

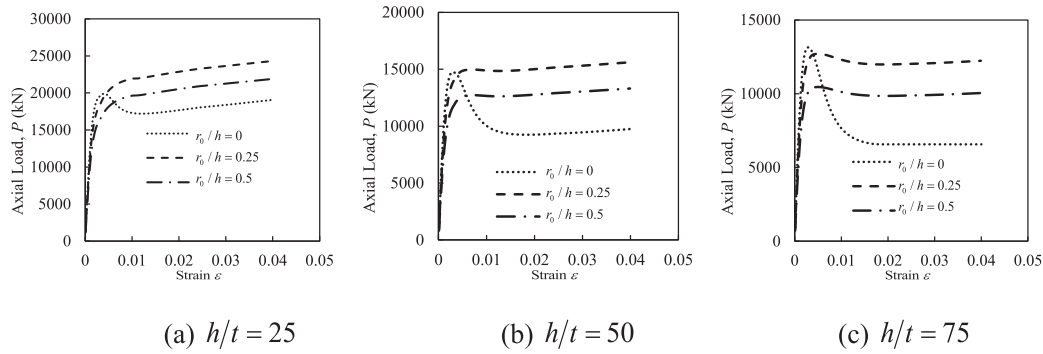


Fig. 17. Sensitivity of h/t ratio on the $P-\epsilon$ curves for varying r_0/h ratio.

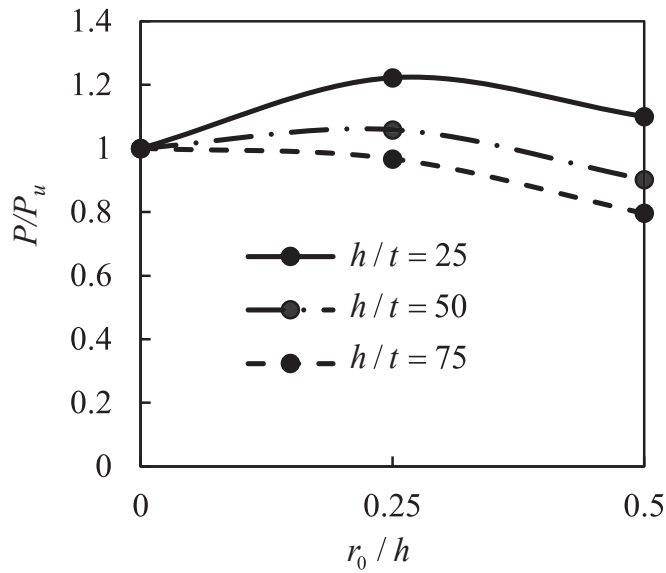


Fig. 18. Sensitivity of r_0/h ratio on the increase of the ultimate strength for various h/t ratio of the columns.

comparative study encompassed 196 tested columns with various cross-sections, including 80 circular, 87 rectangular/square, and 29 round-ended shapes. In the collected test data for circular columns, the range of parameters including: $50 \leq b \leq 325$ mm, $0.9 \leq t \leq 12$ mm, $19 \leq f'_c \leq 64$ MPa, $209 \leq \sigma_{0.2} \leq 542$ MPa, $0.2 \leq \xi \leq 2.87$ and $2.8 \leq L/b \leq 4.0$. For rectangular and square columns, the range of parameters including: $51 \leq b \leq 304$ mm, $40 \leq h \leq 304$ mm, $1 \leq t \leq 12.5$ mm, $19 \leq f'_c \leq 115$ MPa, $258 \leq \sigma_{0.2} \leq 634$ MPa, $0.4 \leq \xi \leq 4.8$ and $2.4 \leq L/b \leq 4.0$. It should be noted

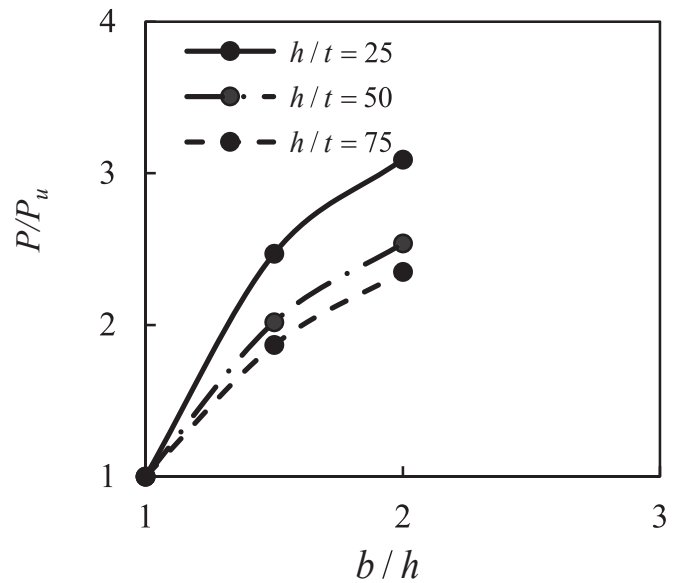


Fig. 20. Sensitivity of b/h ratio on the increase of the ultimate strength for various h/t ratio.

that in the absence of the test data on CFSST columns with round-ended shapes, experimental data of round-ended CFST columns with carbon steel was used for validation purposes where the range of parameters including: $120 \leq b \leq 806$ mm, $50 \leq h \leq 264$ mm, $2 \leq t \leq 6$ mm, $32 \leq f'_c \leq 49$ MPa, $300 \leq \sigma_{0.2} \leq 324$ MPa, $0.4 \leq \xi \leq 0.9$ and $2.0 \leq L/b \leq 3.2$. The stress–strain model of carbon steel used by Ahmed and Liang [22] was adopted in the computational modeling. As can be seen from the comparisons presented in Tables 1-3, the unified model developed can

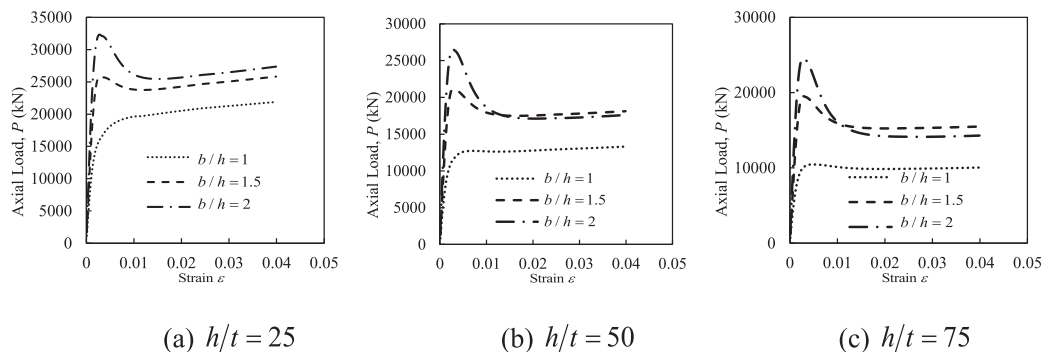


Fig. 19. Sensitivity of h/t ratio on the $P-\epsilon$ curves for varying b/h ratio.

Table 4
Summary of the design specifications given by various design codes.

Design Codes	Formulas to calculate the ultimate strength
AISC 360–16 [27]	$P_{u,AISC} = \begin{cases} P_o \left[0.658^{(P_o/P_e)} \right] & \text{for } P_e \geq 0.44P_o \\ 0.877P_e & \text{for } P_e < 0.44P_o \end{cases}$ $P_o = \sigma_{0.2}A_s + C_2A_c f_c$ $P_e = \frac{\pi^2}{(KL)^2} (EI)_{eff}$ $(EI)_{eff} = E_{cs}I_{cs} + E_{ss}I_{ss} + C_4E_cI_c$ $C_4 = 0.6 + 2 \left(\frac{A_s}{A_s + A_c} \right) \leq 0.9$ <p>where $C_2 = \begin{cases} 0.85 & \text{for circular columns} \\ 0.95 & \text{for rectangular columns} \end{cases}$</p>
Eurocode 4 [26]	<p>For circular columns:</p> $P_{u,EC4} = \eta_a A_s \sigma_{0.2} + A_c f_c \left(1 + \eta_c \frac{t}{D} \frac{\sigma_{0.2}}{f_c} \right)$ $\eta_a = 0.25(3 + 2\lambda) \eta_a \leq 1.0$ $\eta_c = 4.9 - 18.5\lambda + 17\lambda^2 \quad (\eta_c > 0)$ $\lambda = \sqrt{\frac{N_{pl,Rk}}{N_{cr}}}$ <p>For rectangular columns:</p> $P_{u,EC4} = \sigma_{0.2}A_s + A_c f_c$
ACI 318–19 [28]	$P_{u,ACI} = A_s \sigma_{0.2} + 0.85A_c f_c$
DBJ 13–51–2010 [29]	$P_{u,DBJ} = f_{sc}(A_s + A_c) f_{sc} = \begin{cases} f_{ck}(1.14 + 1.02\xi) & \text{circular columns} \\ f_{ck}(1.18 + 0.85\xi) & \text{rectangular columns} \end{cases} \quad f_{ck} = 0.67f_{cu}$

Table 5
Validation of the accuracy of the unified design model for estimating the ultimate strength of circular CFSST columns.

Specimen	$P_{u,exp}$ (kN)	$P_{u,des}$ (kN)	$\frac{P_{u,des}}{P_{u,exp}}$	$P_{u,EC4}$ (kN)	$P_{u,ACI}$ (kN)	$P_{u,AISC}$ (kN)	$P_{u,DBJ}$ (kN)	$\frac{P_{u,EC4}}{P_{u,exp}}$	$\frac{P_{u,ACI}}{P_{u,exp}}$	$\frac{P_{u,AISC}}{P_{u,exp}}$	$\frac{P_{u,DBJ}}{P_{u,exp}}$
CHS104 × 2-C30	650	584	0.90	682	471	492	468	1.05	0.72	0.76	0.72
CHS114 × 6-C60	1354	1149	0.85	1285	887	922	1004	0.95	0.65	0.68	0.74
C30-50 × 1.6A	167	154	0.92	177	119	124	122	1.06	0.71	0.74	0.73
C30-50 × 1.6B	162	154	0.95	177	119	124	122	1.09	0.74	0.76	0.75
C30-100 × 1.6A	477	436	0.91	501	355	375	357	1.05	0.74	0.79	0.75
C30-100 × 1.6B	477	436	0.91	501	355	375	357	1.05	0.74	0.79	0.75
A1	4603	4686	1.02	5235	3651	3844	4052	1.14	0.79	0.84	0.88
A2	4950	5211	1.05	5808	3984	4171	4513	1.17	0.80	0.84	0.91
A3	5247	5907	1.13	6549	4433	4611	5124	1.25	0.84	0.88	0.98
A6	5400	6104	1.13	6753	4619	4818	5357	1.25	0.86	0.89	0.99
A7	4750	5057	1.06	5624	4001	4231	4465	1.18	0.84	0.89	0.94
D2	11,032	10,528	0.95	11,196	7634	7830	8454	1.01	0.69	0.71	0.77
D3	12,926	12,023	0.93	12,665	8606	8787	9726	0.98	0.67	0.68	0.75
C-3-L-RS-1	1264	1391	1.10	1590	1129	1188	1168	1.26	0.89	0.94	0.92
C-3-L-RS-2	1322	1391	1.05	1590	1129	1188	1168	1.20	0.85	0.90	0.88
C-3-H-RS-1	1349	1495	1.11	1700	1227	1297	1280	1.26	0.91	0.96	0.95
C-3-H-RS-2	1316	1495	1.14	1700	1227	1297	1280	1.29	0.93	0.99	0.97
C-4-L-RS-1	1627	1696	1.04	1894	1315	1372	1368	1.16	0.81	0.84	0.84
C-4-L-RS-2	1624	1696	1.04	1894	1315	1372	1368	1.17	0.81	0.84	0.84
C-5-L-RS-1	1713	1880	1.10	2093	1438	1492	1509	1.22	0.84	0.87	0.88
C-5-L-RS-2	1630	1880	1.15	2093	1438	1492	1509	1.28	0.88	0.92	0.93
C-3-L-DS-1	1310	1391	1.06	1590	1129	1188	1168	1.21	0.86	0.91	0.89
C-3-L-DS-2	1291	1391	1.08	1590	1129	1188	1168	1.23	0.87	0.92	0.90
C-3-H-DS-1	1514	1495	0.99	1700	1227	1297	1280	1.12	0.81	0.86	0.85
C-3-H-DS-2	1552	1495	0.96	1700	1227	1297	1280	1.10	0.79	0.84	0.82
C-4-L-DS-1	1598	1696	1.06	1894	1315	1372	1368	1.19	0.82	0.86	0.86
C-4-L-DS-2	1612	1696	1.05	1894	1315	1372	1368	1.17	0.82	0.85	0.85
C-5-L-DS-1	1725	1880	1.09	2093	1438	1492	1509	1.21	0.83	0.87	0.87
C-5-L-DS-2	1739	1880	1.08	2093	1438	1492	1509	1.20	0.83	0.86	0.87
C-3-L-SS-1	1366	1391	1.02	1590	1129	1188	1168	1.16	0.83	0.87	0.85
C-3-L-SS-2	1333	1391	1.04	1590	1129	1188	1168	1.19	0.85	0.89	0.88
C-3-H-SS-1	1466	1495	1.02	1700	1227	1297	1280	1.16	0.84	0.88	0.87
C-3-H-SS-2	1452	1495	1.03	1700	1227	1297	1280	1.17	0.85	0.89	0.88
C-4-L-SS-1	1642	1696	1.03	1894	1315	1372	1368	1.15	0.80	0.84	0.83
C-4-L-SS-2	1648	1696	1.03	1894	1315	1372	1368	1.15	0.80	0.83	0.83
C-5-L-SS-1	1746	1880	1.08	2093	1438	1492	1509	1.20	0.82	0.85	0.86
C-5-L-SS-2	1715	1880	1.10	2093	1438	1492	1509	1.22	0.84	0.87	0.88
SS0-C	210	202	0.96	229	153	158	175	1.09	0.73	0.75	0.83
S101-C	555	516	0.93	571	417	439	438	1.03	0.75	0.79	0.79
S114-C	741	694	0.94	773	555	583	576	1.04	0.75	0.79	0.78

(continued on next page)

accurately predict the ultimate strength of the CFSST columns. The mean value of $P_{u,num}/P_{u,exp}$ for different cross-sections scatter within $\pm 10\%$. Considering the significant strain hardening performance of CFSST columns particularly for the circular cross-section and as the comparisons of the ultimate strength was made at the maximum strain recorded during the test, the model overestimated the ultimate strength of some columns. The average value of $P_{u,num}/P_{u,exp}$ for circular, rectangular and round-ended columns was calculated as 1.00, 0.97 and 0.99, respectively. Fig. 5 shows the comparison of the predicted and test ultimate strength of all columns, and the mean $P_{u,num}/P_{u,exp}$ was calculated as 0.99 with standard deviation of 0.07.

To confirm the accuracy of the model, the estimated $P-\epsilon$ curves for various cross-sections are compared with equivalent circular columns with test results, shown in Figs. 6–8. The comparisons reveal an excellent match between the numerical predictions and the tests, indicating that the material laws of concrete developed can accurately predict the post-peak behavior of confined concrete. Furthermore, the stainless steel model adopted can accurately predict the significant strain hardening performance of CFSST columns. In addition, the accuracy of the unified model developed is evaluated against the unified model developed by Lin et al. [72]. The comparison shows that there is a significant deviations between the test and the predicted ultimate strength of CFSST columns for the unified model developed by Lin et al. [72]. The mean $P_{u,lin}/P_{u,exp}$ for all tested columns is calculated as 0.99 with a standard deviation of 0.14. Moreover, based on the comparison of the predicted $P-\epsilon$ curves with the unified model developed by Lin et al. [72]

Table 5 (continued)

Specimen	$P_{u,exp}$ (kN)	$P_{u,des}$ (kN)	$\frac{P_{u,des}}{P_{u,exp}}$	$P_{u,EC4}$ (kN)	$P_{u,ACI}$ (kN)	$P_{u,AISC}$ (kN)	$P_{u,DBJ}$ (kN)	$\frac{P_{u,EC4}}{P_{u,exp}}$	$\frac{P_{u,ACI}}{P_{u,exp}}$	$\frac{P_{u,AISC}}{P_{u,exp}}$	$\frac{P_{u,DBJ}}{P_{u,exp}}$
S165-C	1449	1355	0.94	1572	1096	1165	1155	1.08	0.76	0.80	0.80
50x1.6-F	198	189	0.96	213	148	154	152	1.07	0.75	0.78	0.77
50x3-F	226	212	0.94	239	162	168	187	1.06	0.72	0.74	0.83
76x1.6-F	388	380	0.98	429	304	319	308	1.11	0.78	0.82	0.79
89x3-F	548	528	0.96	599	417	437	446	1.09	0.76	0.80	0.81
101x1.6-F	617	551	0.89	634	460	488	470	1.03	0.75	0.79	0.76
101x3-F	610	558	0.92	638	456	484	485	1.05	0.75	0.79	0.79
114x3-F	831	747	0.90	844	604	639	634	1.02	0.73	0.77	0.76
152x1.6-F	1050	934	0.89	1137	864	930	903	1.08	0.82	0.89	0.86
203x2-F	1787	1606	0.90	1945	1489	1606	1570	1.09	0.83	0.90	0.88
C-S-N	823	790	0.96	885	676	727	713	1.08	0.82	0.88	0.87
C-S-C1	813	759	0.93	852	647	695	680	1.05	0.80	0.86	0.84
C-S-C2	802	740	0.92	832	629	675	660	1.04	0.78	0.84	0.82
C-S-C3	774	736	0.95	828	625	671	656	1.07	0.81	0.87	0.85
C-S-F1	806	750	0.93	843	639	686	671	1.05	0.79	0.85	0.83
C-S-F2	768	731	0.95	823	621	666	651	1.07	0.81	0.87	0.85
C-S-F3	777	724	0.93	814	614	658	643	1.05	0.79	0.85	0.83
C-100S	552	517	0.94	583	446	482	474	1.06	0.81	0.87	0.86
C-150S	1138	1088	0.96	1219	947	1026	1014	1.07	0.83	0.90	0.89
C-200S	1868	1828	0.98	2016	1596	1736	1711	1.08	0.85	0.93	0.92
C5	591	541	0.92	615	439	464	449	1.04	0.74	0.79	0.76
D73-C50	375	391	1.04	443	312	327	340	1.18	0.83	0.87	0.91
D73-C60	455	434	0.95	488	352	372	390	1.07	0.77	0.82	0.86
D89-C60	685	701	1.02	783	564	594	610	1.14	0.82	0.87	0.89
C-3-0.9-3.0	135	127	0.94	157	106	111	103	1.16	0.79	0.82	0.77
C-3-1.0-3.0	152	143	0.94	173	116	121	113	1.14	0.76	0.80	0.74
C-3-1.2-3.0	163	183	1.12	221	146	150	140	1.36	0.89	0.92	0.86
C-4-0.9-3.0	155	135	0.87	165	114	120	112	1.07	0.74	0.77	0.72
C-4-1.0-3.0	185	151	0.82	182	124	130	121	0.98	0.67	0.70	0.66
C-3-0.9-3.5	128	127	0.99	153	106	111	103	1.19	0.83	0.87	0.81
C-3-1.0-3.5	140	143	1.02	169	116	121	113	1.20	0.83	0.86	0.80
C-3-1.2-3.5	160	183	1.14	214	146	150	140	1.34	0.91	0.94	0.87
C-4-0.9-3.5	135	135	1.00	161	114	119	112	1.20	0.84	0.89	0.83
C-4-1.0-3.5	165	151	0.92	177	124	129	121	1.07	0.75	0.78	0.73
C-4-1.2-3.5	185	191	1.03	223	153	158	148	1.20	0.83	0.86	0.80
C-3-1.0-4.0	158	143	0.91	164	116	120	113	1.04	0.73	0.76	0.71
C-3-1.2-4.0	168	183	1.09	208	146	150	140	1.24	0.87	0.89	0.83
C-4-0.9-4.0	135	135	1.00	158	114	119	112	1.17	0.84	0.88	0.83
C-4-1.0-4.0	165	151	0.92	173	124	129	121	1.05	0.75	0.78	0.73
C-4-1.2-4.0	200	191	0.95	217	153	158	148	1.08	0.77	0.79	0.74
Mean			0.99					1.13	0.80	0.84	0.83
SD			0.08					0.09	0.06	0.06	0.07
CoV			0.08					0.08	0.07	0.08	0.08

presented in Figs. 6-8, it is evident that the unified model developed in this study can provide more accurate results than that of Lin et al. [72].

5. Parametric study

The unified model is used to study the influences of concrete, steel yield stress and the depth-to-thickness (h/t) ratio for the various radius ratio (r_0/h) and aspect ratios (b/h) of CFSST columns under axial load. It should be noted that when $b/h = 1$ and $r_0/h = 0.5$, the cross-sectional shape of the column is circular. Similarly, for a column with $b/h > 1$ and $r_0/h = 0.5$ is considered round-ended, for a column with $b/h = 1$ and $r_0/h = 0$ is considered square and a column with $b/h > 1$ and $r_0/h = 0$ is considered rectangular. The geometry and material properties of the reference column are taken as: $b = h = 500$ mm, $t = 10$ mm, $r_0/h = 0.5$, $\sigma_{0.2} = 275$ MPa, $f_c = 50$ MPa.

5.1. Effects of concrete strength

The developed unified model was used to analyze the effect of concrete strength on the CFSST column. The concrete strength was varied between 30 MPa and 70 MPa. The results obtained from Figs. 9 and 10 show that the ultimate load increases as the r_0/h ratio increases from 0 to 0.25, but then decreases as the ratio r_0/h increases further. It should be noted that in Fig. 10, the benchmark ultimate strength of the columns

for various concrete strengths is taken as the ultimate strength of the column with r_0/h ratio equal 0. With the increase of the r_0/h ratio, the cross-sectional area of the column decreases, which results in the reduction of the ultimate strength of the columns. However, the confinement to the core concrete increases with the increase of the r_0/h ratio. The results show that for columns with a r_0/h ratio less than or equal to 0.25, the higher confinement effects can compensate for the reduction of the load-carrying capacity due to the reduction of the cross-sectional area, especially for normal strength concrete. However, for an increase in the concrete strength, the confinement effects diminish, and the increase of the ultimate load becomes insignificant. Additionally, increasing the r_0/h ratio of the columns increases the ductility of the columns, as shown in Figs. 11-12. The ultimate load of the columns increases with the increase in b/h ratio regardless of the concrete strength. However, columns' ductility decreases. The benchmark ultimate strength of the columns for various concrete strengths is taken as the ultimate strength of the column with b/h ratio equal to 1 in Fig. 12. The rate of increase in the ultimate load seems to be linear, as illustrated in Fig. 12.

5.2. Effects of steel proof strength

The study investigates the effects of steel proof strength by altering the proof stress within the range of 275 to 430 MPa. The results shown in Figs. 13-14 indicate that increasing the r_0/h ratio from 0 to 0.25

Table 6
Validation of the accuracy of the unified design model for estimating the ultimate strength of rectangular CFSST columns.

Specimen	$P_{u,exp}$ (kN)	$P_{u,des}$ (kN)	$\frac{P_{u,des}}{P_{u,exp}}$	$P_{u,EC4}$ (kN)	$P_{u,ACI}$ (kN)	$P_{u,AISC}$ (kN)	$P_{u,DBJ}$ (kN)	$\frac{P_{u,EC4}}{P_{u,exp}}$	$\frac{P_{u,ACI}}{P_{u,exp}}$	$\frac{P_{u,AISC}}{P_{u,exp}}$	$\frac{P_{u,DBJ}}{P_{u,exp}}$
SHS1C40	2768	2866	1.04	2576	2441	2415	2394	0.93	0.88	0.87	0.87
SHS1C60	2972	3074	1.03	2871	2692	2661	2717	0.97	0.91	0.90	0.91
SHS1C80	3020	3398	1.13	3287	3046	3009	3172	1.09	1.01	1.00	1.05
S30-50 × 2A	268	226	0.84	204	192	191	182	0.76	0.72	0.71	0.68
S30-50 × 2B	274	226	0.83	204	192	191	182	0.74	0.70	0.70	0.66
S20-100 × 3A	705	671	0.95	588	559	555	503	0.83	0.79	0.79	0.71
S20-100 × 3B	716	671	0.94	588	559	555	503	0.82	0.78	0.77	0.70
S30-100 × 3A	765	761	0.99	707	660	655	628	0.92	0.86	0.86	0.82
S30-100 × 3B	742	761	1.03	707	660	655	628	0.95	0.89	0.88	0.85
S20-100 × 5A	1352	1354	1.00	1021	994	985	908	0.76	0.74	0.73	0.67
S20-100 × 5B	1348	1354	1.00	1021	994	985	908	0.76	0.74	0.73	0.67
S30-100 × 5A	1434	1362	0.95	1131	1088	1078	1035	0.79	0.76	0.75	0.72
S30-100 × 5B	1461	1362	0.93	1131	1088	1078	1035	0.77	0.74	0.74	0.71
S20-150 × 3A	1035	939	0.91	916	847	841	817	0.88	0.82	0.81	0.79
S20-150 × 3B	1062	939	0.88	916	847	841	817	0.86	0.80	0.79	0.77
S30-150 × 3A	1074	1177	1.10	1203	1091	1082	1105	1.12	1.02	1.01	1.03
S30-150 × 3B	1209	1177	0.97	1203	1091	1082	1105	0.99	0.90	0.90	0.91
S20-150 × 5B	1798	1569	0.87	1372	1308	1299	1226	0.76	0.73	0.72	0.68
S30-150 × 5A	1947	1746	0.90	1636	1533	1520	1507	0.84	0.79	0.78	0.77
S30-150 × 5B	1976	1746	0.88	1636	1533	1520	1507	0.83	0.78	0.77	0.76
SHS 100 × 100 × 5 – C30	1410	1394	0.99	1117	1080	1070	1008	0.79	0.77	0.76	0.72
SHS 100 × 100 × 5 – C60	1488	1462	0.98	1289	1224	1211	1206	0.87	0.82	0.81	0.81
SHS 100 × 100 × 5 – C100	1559	1593	1.02	1461	1371	1355	1403	0.94	0.88	0.87	0.90
304-t8C50	6290	5631	0.90	5826	5344	5301	5620	0.93	0.85	0.84	0.89
304-t10C50	7113	6470	0.91	6496	6015	5969	6388	0.91	0.85	0.84	0.90
304-t12C50	7924	7609	0.96	7383	6901	6849	7382	0.93	0.87	0.86	0.93
304-t8C70	6743	6828	1.01	7392	6675	6614	7243	1.10	0.99	0.98	1.07
304-t10C70	7947	7637	0.96	8063	7346	7282	8058	1.01	0.92	0.92	1.01
304-t12C70	8575	8728	1.02	8949	8233	8163	9096	1.04	0.96	0.95	1.06
304-t8C80	7436	7367	0.99	8085	7264	7193	7961	1.09	0.98	0.97	1.07
304-t10C80	8430	8168	0.97	8756	7935	7863	8796	1.04	0.94	0.93	1.04
304-t12C80	9257	9246	1.00	9642	8822	8743	9855	1.04	0.95	0.94	1.06
2205-t8C50	8771	9718	1.11	8954	8473	8368	8379	1.02	0.97	0.95	0.96
2205-t10C50	10,111	11,061	1.09	9921	9439	9327	9471	0.98	0.93	0.92	0.94
2205-t12C50	12,472	13,490	1.08	11,565	11,087	10,957	11,349	0.93	0.89	0.88	0.91
2205-t8C70	9686	10,720	1.11	10,517	9802	9671	10,001	1.09	1.01	1.00	1.03
2205-t10C70	10,820	11,979	1.11	11,489	10,771	10,635	11,140	1.06	1.00	0.98	1.03
2205-t12C70	12,560	14,207	1.13	13,117	12,407	12,252	13,063	1.04	0.99	0.98	1.04
2205-t8C80	9962	11,207	1.13	11,209	10,390	10,247	10,719	1.13	1.04	1.03	1.08
2205-t10C80	11,728	12,445	1.06	12,182	11,361	11,213	11,879	1.04	0.97	0.96	1.01
2205-t12C80	13,272	14,619	1.10	13,804	12,991	12,825	13,822	1.04	0.98	0.97	1.04
S200635	131	132	1.01	126	116	115	108	0.96	0.89	0.88	0.83
S200640	126	132	1.05	126	116	115	108	1.00	0.92	0.92	0.86
S200830	190	205	1.08	199	181	180	173	1.05	0.96	0.95	0.91
S200835	182	205	1.12	199	181	180	173	1.09	1.00	0.99	0.95
S2001030	258	288	1.12	288	260	258	253	1.12	1.01	1.00	0.98
S300840	211	236	1.12	234	211	209	206	1.11	1.00	0.99	0.98
S-3-L-RS-2	1534	1719	1.12	1697	1564	1548	1522	1.11	1.02	1.01	0.99
S-4-L-RS-1	2040	1957	0.96	1877	1747	1731	1701	0.92	0.86	0.85	0.83
S-4-L-RS-2	1931	1957	1.01	1877	1747	1731	1701	0.97	0.90	0.90	0.88
S-5-L-RS-1	2125	2301	1.08	2133	2006	1987	1946	1.00	0.94	0.94	0.92
S-5-L-RS-2	2012	2301	1.14	2133	2006	1987	1946	1.06	1.00	0.99	0.97
S-3-L-DS-1	1543	1719	1.11	1697	1564	1548	1522	1.10	1.01	1.00	0.99
S-3-L-DS-2	1590	1719	1.08	1697	1564	1548	1522	1.07	0.98	0.97	0.96
S-3-H-DS-1	1769	1841	1.04	1847	1691	1673	1672	1.04	0.96	0.95	0.95
S-3-H-DS-2	1914	1841	0.96	1847	1691	1673	1672	0.96	0.88	0.87	0.87
S-4-L-DS-1	1955	1957	1.00	1877	1747	1731	1701	0.96	0.89	0.89	0.87
S-4-L-DS-2	1897	1957	1.03	1877	1747	1731	1701	0.99	0.92	0.91	0.90
S-5-L-DS-1	2152	2301	1.07	2133	2006	1987	1946	0.99	0.93	0.92	0.90
S-5-L-DS-2	2141	2301	1.07	2133	2006	1987	1946	1.00	0.94	0.93	0.91
S-3-L-SS-1	1724	1719	1.00	1697	1564	1548	1522	0.98	0.91	0.90	0.88
S-3-L-SS-2	1780	1719	0.97	1697	1564	1548	1522	0.95	0.88	0.87	0.85
S-3-H-SS-1	1690	1841	1.09	1847	1691	1673	1672	1.09	1.00	0.99	0.99
S-3-H-SS-2	1765	1841	1.04	1847	1691	1673	1672	1.05	0.96	0.95	0.95
S-4-L-SS-1	2007	1957	0.97	1877	1747	1731	1701	0.94	0.87	0.86	0.85
S-4-L-SS-2	1947	1957	1.00	1877	1747	1731	1701	0.96	0.90	0.89	0.87
S-5-L-SS-1	2215	2301	1.04	2133	2006	1987	1946	0.96	0.91	0.90	0.88
S-5-L-SS-2	2197	2301	1.05	2133	2006	1987	1946	0.97	0.91	0.90	0.89
A100	698	662	0.95	630	583	579	577	0.90	0.83	0.83	0.83
A250	2709	2686	0.99	2981	2655	2632	2782	1.10	0.98	0.97	1.03
D100	1039	1047	1.01	929	881	872	809	0.89	0.85	0.84	0.78
D250	3186	3589	1.13	3742	3414	3376	3403	1.17	1.07	1.06	1.07
60 × 40 × 4C40	478	539	1.13	409	398	395	414	0.86	0.83	0.83	0.87

(continued on next page)

Table 6 (continued)

Specimen	$P_{u,exp}$ (kN)	$P_{u,des}$ (kN)	$\frac{P_{u,des}}{P_{u,exp}}$	$P_{u,EC4}$ (kN)	$P_{u,ACI}$ (kN)	$P_{u,AISC}$ (kN)	$P_{u,DBJ}$ (kN)	$\frac{P_{u,EC4}}{P_{u,exp}}$	$\frac{P_{u,ACI}}{P_{u,exp}}$	$\frac{P_{u,AISC}}{P_{u,exp}}$	$\frac{P_{u,DBJ}}{P_{u,exp}}$
60 × 40 × 4C40R	481	539	1.12	408	397	394	413	0.85	0.83	0.82	0.86
60 × 40 × 4C80	531	555	1.05	474	453	449	499	0.89	0.85	0.85	0.94
60 × 40 × 4C120	585	593	1.01	530	501	496	574	0.91	0.86	0.85	0.98
60 × 60 × 3C40	484	482	1.00	416	397	393	379	0.86	0.82	0.81	0.78
60 × 60 × 3C80	594	569	0.96	529	493	487	507	0.89	0.83	0.82	0.85
80 × 60 × 4C40	712	721	1.01	605	581	576	563	0.85	0.82	0.81	0.79
80 × 60 × 4C80	878	824	0.94	753	706	700	735	0.86	0.80	0.80	0.84
80 × 60 × 4C120	999	932	0.93	881	815	807	885	0.88	0.82	0.81	0.89
80 × 60 × 4C120R	976	932	0.96	881	815	807	885	0.90	0.84	0.83	0.91
100 × 40 × 2C40	398	401	1.01	366	344	342	326	0.92	0.86	0.86	0.82
100 × 40 × 2C120	674	624	0.93	617	557	554	594	0.92	0.83	0.82	0.88
120 × 80 × 3C40	870	827	0.95	776	722	717	696	0.89	0.83	0.82	0.80
120 × 80 × 3C80	1255	1115	0.89	1102	999	991	1039	0.88	0.80	0.79	0.83
120 × 80 × 3C120	1610	1375	0.85	1389	1243	1231	1339	0.86	0.77	0.76	0.83
Mean			1.01					0.96	0.89	0.88	0.89
SD			0.08					0.10	0.09	0.09	0.11
CoV			0.08					0.11	0.10	0.10	0.12

Table 7

Validation of the accuracy of the unified design model for estimating the ultimate strength of round-ended CFST columns.

Specimen	$P_{u,exp}$ (kN)	$P_{u,des}$ (kN)	$\frac{P_{u,des}}{P_{u,exp}}$	$P_{u,EC4}$ (kN)	$P_{u,ACI}$ (kN)	$P_{u,AISC}$ (kN)	$P_{u,DBJ}$ (kN)	$\frac{P_{u,EC4}}{P_{u,exp}}$	$\frac{P_{u,ACI}}{P_{u,exp}}$	$\frac{P_{u,AISC}}{P_{u,exp}}$	$\frac{P_{u,DBJ}}{P_{u,exp}}$
WST1-A	3429	3529	1.03	3768	2780	2923	2935	1.10	0.81	0.85	0.86
WST1-B	3328	3511	1.06	3764	2788	2926	2941	1.13	0.84	0.88	0.88
WST2-A	4162	3944	0.95	4469	3193	3335	3423	1.07	0.77	0.80	0.82
WST2-B	4168	3888	0.93	4407	3165	3301	3388	1.06	0.76	0.79	0.81
WST3-A	3929	3952	1.01	4346	3285	3429	3465	1.11	0.84	0.87	0.88
WST3-B	4158	3925	0.94	4334	3282	3421	3460	1.04	0.79	0.82	0.83
WST4-A	4492	4356	0.97	5052	3734	3867	3981	1.12	0.83	0.86	0.89
WST4-B	5530	4985	0.90	5583	4202	4368	4527	1.01	0.76	0.79	0.82
WST5-A	5620	5129	0.91	5586	4386	4563	4671	0.99	0.78	0.81	0.83
WST5-B	5500	5230	0.95	5689	4459	4643	4751	1.03	0.81	0.84	0.86
WST6-A	3240	3386	1.05	3915	3113	3183	3255	1.21	0.96	0.98	1.00
WST7-A	4826	4872	1.01	5282	4501	4495	4696	1.09	0.93	0.93	0.97
WST7-B	4944	4999	1.01	5444	4616	4621	4819	1.10	0.93	0.93	0.97
WST8-A	6521	6552	1.00	6910	6041	5922	6296	1.06	0.93	0.91	0.97
WST8-B	6493	6550	1.01	6908	6035	5918	6291	1.06	0.93	0.91	0.97
WST9-A	4203	4411	1.05	4950	4012	4113	4279	1.18	0.95	0.98	1.02
WST9-B	4180	4398	1.05	4931	3998	4100	4264	1.18	0.96	0.98	1.02
WST10-A	7201	6654	0.92	7141	6083	6087	6484	0.99	0.84	0.85	0.90
WST10-B	6905	6418	0.93	6871	5871	5861	6256	1.00	0.85	0.85	0.91
WST11-A	9065	8569	0.95	8974	7822	7629	8329	0.99	0.86	0.84	0.92
WST11-B	8799	8766	1.00	9193	8005	7824	8524	1.04	0.91	0.89	0.97
RCFST-1	925	1036	1.12	1127	854	877	865	1.22	0.92	0.95	0.93
RCFST-2	1215	1300	1.07	1417	1158	1170	1173	1.17	0.95	0.96	0.97
RCFST-4	1658	1700	1.03	1843	1426	1469	1467	1.11	0.86	0.89	0.88
RCFST-5	2091	2128	1.02	2333	1919	1944	1980	1.12	0.92	0.93	0.95
RND_30_00	385	404	1.05	418	348	349	348	1.08	0.90	0.91	0.90
Mean			1.00					1.09	0.87	0.89	0.91
SD			0.06					0.07	0.07	0.06	0.06
CoV			0.06					0.06	0.08	0.07	0.07

increases the ultimate load, but beyond this range, the ultimate load decreases as the r_0/h ratio increases. Moreover, the increase in the proof stress leads to a more significant rate of increase in the ultimate load. Regardless of the proof strength of the columns, the ductility of the column increases with an increase in the r_0/h ratio, owing to the increase in the confinement effects. However, the ductility of the columns decreases as the b/h ratio increases, as illustrated in Fig. 15. Fig. 16 reveals that the increase in the ultimate strength due to the increase in the b/h ratio is linear for different proof strengths of the steel tube.

5.3. Effects of h/t ratio of the columns

The effects of different h/t ratios are explored by altering the thickness of the steel tube to vary h/t ratio from 25 to 75. The results depicted in Figs. 17-18 show that, for a given r_0/h ratio, increasing h/t ratio decreases the ultimate strength of the columns. This is because the h/t ratio

is directly related to the confinement provided to the concrete core. The confinement effect occurs due to the confinement pressure exerted by the steel tube on the concrete core, which improves the strength and ductility of the column. A thinner steel tube which leads to higher h/t ratio provides less confinement to the concrete, leading to reduced strength and ductility. Therefore, an increase in the h/t ratio reduces the confinement effects, ultimately leading to a decrease in the ultimate axial strength. Although the ultimate strength of the column increases with an increase in b/h ratio regardless of the h/t ratio, the rate of increase declines as the h/t ratio goes up, as shown in Figs. 19-20.

6. The ultimate strength of CFSST columns

6.1. Design codes

This section assesses the precision of the design specifications

outlined in four different codes, namely Eurocode 4 [26], ACI 318–11 [28], AISC 360–16 [27] and DBJ 13–51–2010 [29], for conventional CFST columns. The evaluation focuses on the ability of these codes to estimate the ultimate strength of CFSST columns with different cross-sectional shapes. The formulas specified by each code are summarized in Table 4. To evaluate their accuracy, the design predictions are compared with the test results presented in Tables 5–7. It should be noted that in the comparisons, the ultimate strength of the columns is taken as the axial load at 1% strain if the tested column had no obvious strain-softening branch [25,64,94,95]. Otherwise, the ultimate strength is taken as the maximum load for columns with an apparent strain-softening branch. The analysis reveals significant discrepancies between the actual and design predictions. Eurocode 4 [26] is observed to overestimate the ultimate strength of columns with circular and round-ended shapes while underestimating the ultimate strength of rectangular CFSST columns. Similarly, the other design codes substantially underestimate the ultimate strength of stub columns across all cross-sectional shapes.

6.2. Unified design model

Based on the unified numerical model, a unified design model to predict the maximum compressive load for various shapes of CFSST columns replaced by equivalent circular column theory is proposed herein as

$$P_{u,des} = A_s \sigma_{0.2} + A_c f_{cc} \quad (47)$$

The area of steel and concrete of the equivalent circular column is calculated using Eq. (1) and (2), respectively. The compressive strength of concrete (f_{cc}) for various cross-sections should be calculated using the formulas given in Eqs. (42)–(43). An excellent match between the test and the design prediction can be observed based on the comparison. The mean value of $P_{u,des}/P_{u,exp}$ for circular, rectangular and round-ended columns are calculated as 0.99, 1.01 and 1.00, respectively. The proposed unified model can provide a more accurate design estimation of CFSST columns with various cross-sectional shapes.

7. Conclusions

A unified numerical model has been created in this paper to examine the performance of axially loaded CFSST stub columns, using various cross-sectional shapes. This model converts the different cross-sections of CFSST columns into equal circular columns, and incorporates a newly proposed formula for concrete compressive strength and a strength reduction factor to account for the residual strength of confined concrete. The accuracy of this unified model has been verified using a large data set collected from literature. An extensive parametric study is performed to study the effects of various column parameters on CFSST columns with various r_0/h and b/h ratios. The accuracy of the various design codes in predicting the ultimate strength of CFSST columns is studied and the accuracy of the proposed unified design model is examined. The following conclusions can be drawn from this study:

1. The unified model developed can predict the behavior of CFSST columns with different cross-sections accurately. The average value of $P_{u,num}/P_{u,exp}$ for circular, rectangular and round-ended columns is calculated as 1.00, 0.97 and 0.99, respectively. For all columns, the mean $P_{u,num}/P_{u,exp}$ is estimated as 0.99.
2. The developed model is validated for circular columns with $50 \leq b \leq 325$ mm, $0.9 \leq t \leq 12$ mm, $19 \leq f_c \leq 64$ MPa, $209 \leq \sigma_{0.2} \leq 542$ MPa, $0.2 \leq \xi \leq 2.87$ and $2.8 \leq L/b \leq 4.0$; for rectangular and square columns, the range of parameters including: $51 \leq b \leq 304$ mm, $40 \leq h \leq 304$ mm, $1 \leq t \leq 12.5$ mm, $19 \leq f_c \leq 115$ MPa, $258 \leq \sigma_{0.2} \leq 634$ MPa, $0.4 \leq \xi \leq 4.8$ and $2.4 \leq L/b \leq 4.0$. Due to the absence of the test data on round-ended CFSST columns, the model is validated against the round-

ended conventional CFST columns with $120 \leq b \leq 806$ mm, $50 \leq h \leq 264$ mm, $2 \leq t \leq 6$ mm, $32 \leq f_c \leq 49$ MPa, $300 \leq \sigma_{0.2} \leq 324$ MPa, $0.4 \leq \xi \leq 0.9$ and $2.0 \leq L/b \leq 3.2$.

3. From the parametric study, it was found that the behavior of CFSST columns is influenced by r_0/h and b/h ratios of the columns. For a given r_0/h ratio, increasing h/t ratio decreases the ultimate strength of the columns. The ultimate load of the columns increases with the increase in b/h ratio regardless of the concrete strength. In addition, regardless of the steel proof stress, increasing b/h ratio increases the ultimate strength of the columns.
4. The proposed unified design model for determining the ultimate strength of CFSST columns with various cross-sections is more accurate than existing design codes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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