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Assessment of Axial Strength and Post-Peak Response in Circular CFST Stub Columns

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***Abstract* - This study presents a set of analytical equations for evaluating the axial load-carrying capacity and predicting the post-peak behaviour of circular concrete-filled steel tube (CFST) stub columns. The proposed formulations were validated using experimental results reported by previous researchers, demonstrating close agreement with observed load–deformation responses. A comprehensive parametric study was conducted to examine the influence of four key parameters on the behaviour of circular CFST stub columns: diameter-to-thickness ratio (D/t), steel grade, concrete grade, and steel contribution ratio (δ_s). Eurocode 4 (EC4), one of the most widely adopted design standards for composite structures, was also examined for comparison. EC4 provides design guidelines for concrete-encased, partially encased, and concrete-filled steel sections, incorporating limit state concepts with partial safety factors for material and load combinations. It remains the only major design code that separately considers long-term loading effects. In this study, the axial capacities predicted by EC4 were compared with both the experimental peak loads and the capacities obtained using the proposed analytical equations. The comparison highlights the accuracy and applicability of the proposed model in capturing both the peak and post-peak response of circular CFST stub columns, offering improved predictive capability over existing design provisions. The findings contribute to a deeper understanding of the composite action in CFST columns and provide a reliable analytical tool for practical design and assessment.**

Keywords - Circular CFST, Stress-strain, Modelling, Axial capacity.

I INTRODUCTION

Concrete-filled steel tube (CFST) members have gained significant attention in modern structural engineering due to their superior strength, stiffness, and ductility compared to conventional reinforced concrete or bare steel sections. In particular, circular CFST stub columns exhibit excellent axial load-carrying capacity resulting from the composite interaction between the infilled concrete and the surrounding steel tube. The steel tube provides effective confinement, delaying local buckling and enhancing the compressive strength of the concrete core, while the concrete restrains inward buckling of the steel tube, resulting in improved structural performance under axial compression. The axial capacity and post-peak behaviour of CFST stub columns are critical parameters for safe and economical design, especially in seismic and high-load applications where ductility and energy dissipation are essential. Numerous experimental and analytical studies have shown that the confinement effect in circular CFST sections is more pronounced than in square or rectangular sections due to their uniform lateral restraint. This confinement significantly modifies the stress–strain characteristics of the concrete core, leading to higher ultimate strength and a more stable post-peak response. Despite these advantages, post-peak softening behaviour remains complex, influenced by factors such as steel tube thickness, diameter–to–thickness ratio (D/t), concrete strength, steel yield strength, and bonding conditions between steel and concrete. Various researchers have extensively analysed the behaviour, strength, and modelling of CFST columns. Giakoumelis and Lam [1] examined short circular CFT columns filled with 30–100 MPa concrete and D/t ratios between 22.9 and 30.5. They concluded that higher concrete strength increased sensitivity to bond conditions, with greasing reducing axial capacity by about 17%. Eurocode 4 gave the closest predictions, while ACI and AS codes underestimated strength. Binici [2] developed an analytical model capable of capturing complete stress–strain behaviour of uniformly confined concrete. Comparisons with former studies showed good agreement, highlighting that steel yield strength and confinement ratio strongly influence the post-peak response. Biag et al. [3] tested 28 circular and square CFST specimens, reporting ductile behaviour and failure dominated by local buckling and concrete crushing. Circular columns showed greater strength enhancement, and most design codes gave conservative estimates except the Chinese code for circular specimens. Yu et al. [4] investigated circular CFT stub columns with SCC and normal concrete. Increasing concrete strength significantly raised ultimate load without affecting residual strength. Strong confinement was observed after a certain load level, and Eurocode 4 predictions aligned well with test results. Han et al. [5] tested 32 circular and square CFST stub columns under local compression and validated results using finite element analysis (FEA). Thicker endplates improved strength and ductility, while increased local compression area reduced strength index. Kuranovas et al. [6] analysed over 1300 CFST tests, reporting excellent agreement with EC4 for circular columns. Rectangular sections aligned well except when concrete strength exceeded 75 MPa. Preloading steel tubes showed negligible effect. Oliveira et al. [7] demonstrated that CFT strength increases with concrete grade and decreases with slenderness (L/D). Columns with L/D = 3 benefitted most from confinement. All four design codes studied overestimated strength for L/D ≤ 3. Liang and Fragomeni [8] proposed a fibre element model for circular CFSTs, showing that high-strength concrete reduces ductility despite increasing axial capacity. Larger D/t ratios also lowered strength and ductility. Chitawadagi et al. [9] conducted 243 tests to derive an axial-capacity equation using regression. Diameter had the strongest influence, and EC4 showed large deviations from experimental values. Zhao et al. [10] introduced a computationally efficient macro-model that effectively replicated overall CFST column behaviour, including local buckling and confinement effects. Yu et al. [11] validated an FEA model for STCC and CFST columns, noting slightly higher capacity in circular STCC columns and greater ductility for square ones. Yang and Han [12] tested circular, square, and rectangular CFST stub columns and found all behaved ductile. FEA simulations matched experimental behaviour well. Xue et al. [13] studied debonding effects and found that while overall failure mode remained similar, debonding increased steel buckling and reduced ultimate load depending on debonding extent and confinement factor. An et al. [14] modelled slender CFST columns, reporting that capacity increases with steel ratio and concrete strength, but decreases with slenderness. Steel yield strength had minimal influence, and EC4 and AISC provided conservative predictions. Dundu [15] tested CFST columns with varying lengths and diameters and observed ductile behaviour, with EC4 and SANS codes giving conservative results. Gupta et al. [16] developed FE models capturing confinement behaviour and load transfer mechanisms for normal- and high-strength concrete, showing that confinement is non-uniform along column height. Patel et al. [17] used a three-stage stainless-steel model, concluding that capacity increases with concrete strength and yield strength, while ACI and EC4 remained conservative. Ding et al. [18] combined experiments and FE modelling for circular and square CFT stub columns and confirmed that concrete strength, steel strength, and pressure area ratio significantly influence bearing capacity and ductility.

II. MATERIAL MODELLING AND METHODS

The primary objective of this study is to evaluate and predict the post-peak behaviour of circular Concrete-Filled Steel Tube (CFST) stub columns subjected to axial compression. Additionally, the study aims to develop a reliable analytical equation for estimating the axial load-carrying capacity of circular CFST columns, enabling improved accuracy in design and performance assessment.

III. Concrete Core Constitutive Model

In circular CFST columns subjected to axial compression, the concrete core tends to expand laterally. However, the surrounding steel tube restrains this lateral dilation, generating a confinement pressure in the concrete. This confinement enhances both the strength and ductility of the concrete, a mechanism known as composite action. Under this behaviour, the concrete core is assumed to experience triaxial compressive stress, while the steel tube is subjected to biaxial stress due to axial compression and hoop tension. To describe the ascending branch of the concrete stress–strain curve, the model proposed by Samani and Attard (2012) is adopted:

$$\frac{\sigma}{f_c'} = \frac{A \cdot X + B \cdot X^2}{1 + (A-2)X + (B+1)X^2} \qquad 0 < \varepsilon \le \varepsilon_{co} \qquad (1)$$

Where, $X = {}^{\varepsilon}/_{\varepsilon_{co}}$; $A = \frac{E_c \varepsilon_{co}}{f_c'}$; $B = \frac{(A-1)^2}{0.55} - 1$

The strain corresponding to the peak uniaxial compressive stress ε_{co} is obtained using the relationship proposed by De Nicolo et al. (1994):

$$\varepsilon_{co} = 0.00076 + \sqrt{(0.626 f_c' - 4.33) \times 10^{-7}} \qquad (2)$$

where f'_c is the concrete compressive strength in MPa.

The strain at Point B, ε_{cc}, marking the transition from the ascending to the descending branch under confinement, is evaluated using the equation by Samani and Attard (2012):

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = e^k, k = (2.9224 - 0.00367 f_c') \left(\frac{f_B}{f_c'}\right)^{0.3124 + 0.002 f_c'} \qquad (3)$$

The corresponding confined concrete stress at Point B is given by:

$$f_B = \frac{(1 + 0.027 f_y) \cdot e^{-0.02\frac{D}{t}}}{1 + 1.6e^{-10} (f_c')^{4.8}}. \qquad (4)$$

For the descending branch (BC), the exponential softening function recommended by Binici (2005) is used:

$$\sigma = f_r + (f_c' - f_r) \exp\left[-\left(\frac{\varepsilon - \varepsilon_{cc}}{\alpha}\right)^{\beta}\right] \varepsilon \ge \varepsilon_{cc} \qquad (5)$$

In which f_r is the residual stress as shown in Fig. 4.1; α and β are parameters determining the shape of the softening branch. The expression for f_r is proposed as:

$$f_r = 0.7(1 - e^{-1.38\xi_c}) f_c' \qquad (6)$$

The parameter α is determined as:

$$\alpha = 0.04 - \frac{0.036}{1 + e^{6.08\xi_c - 3.49}} \qquad (7)$$

β can be taken as 1.2 for circular columns and ξ_c is the confinement factor defined as,

$$\xi_c = \frac{A_s \cdot f_y}{A_c \cdot f_c'} \qquad (8)$$

Where, A_s is area of steel tube; A_c is area of concrete core. E_c, modulus of Elasticity of Concrete is taken from the code ACI 38-11 and is given as:

$$E_c = 4730\sqrt{f_c'} \qquad (9)$$

$$f_c' = \left(0.76 + 0.2 \times \log_{10}\left(\frac{f_{cu}}{19.6}\right)\right) \times f_{cu} \qquad (10)$$

Where f_{cu} is cube strength of concrete.

IV PROPOSED MODEL FOR SOFTENING OF CONFINED CONCRETE IN CIRCULAR STUB CFST COLUMN

A wide range of specimens was considered in this study to investigate the post-peak behavior of CFST circular stub columns. The equations proposed in the previous chapter were used to predict the load–displacement curves of these columns. The peak load values obtained from the equations were also compared with experimental results and Eurocode 4 (EC4) predictions. Since EC4 is widely adopted for designing composite structures in European countries, this comparison allows for the assessment of the accuracy and reliability of the proposed equations for practical design applications. A nonlinear regression analysis was used to develop an equation for confined concrete in circular CFST column.

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The final equations that were developed given below. The stress in the descending branch is given as

$$\sigma = \left[f_r + (f_c' - f_r)\, exp\left[-\left(\frac{\varepsilon - \varepsilon_{cc}}{\alpha}\right)\right]\right] \times \left[-1.258 \cdot 10^{-1}x - 2.548 + \left({}^{5.397}/_{x}\right) + 2.168\, ln(x)\right] \quad (11)$$

and the parameter α that controls the slope of the descending curve is modified as

$$\alpha = \left[2.3395 \cdot 10^{-1e^{-7.099133 \cdot 10^{-2x}}} + 3.6542060 \cdot 10^{-2} e^{2.49965/x}\right] - \frac{0.036}{1+e^{6.08\xi_c - 3.49}} \quad (12)$$

Using the equations proposed a final comparison was shown between the Load-Displacement curves of circular CFST stub columns under axial loading.

V STEEL TUBE CONSTITUTIVE MODEL

Different stress–strain models have been proposed for the steel tube in CFST columns, including the elastic-perfectly plastic model and models incorporating linear or multi-linear strain hardening. In circular CFST columns, the steel tube is subjected to biaxial stress due to axial compressive load, and hoop tensile stress induced by the lateral expansion of the confined concrete core. The presence of hoop tension reduces the effective longitudinal yield stress of steel. To account for this interaction, an idealized linear, rounded- linear stress–strain curve is used, as illustrated in Fig. 1. This approach provides more accurate representation of reduced longitudinal stiffness, confinement-induced strain interaction, and gradual yielding of the steel tube under combined biaxial stress states.

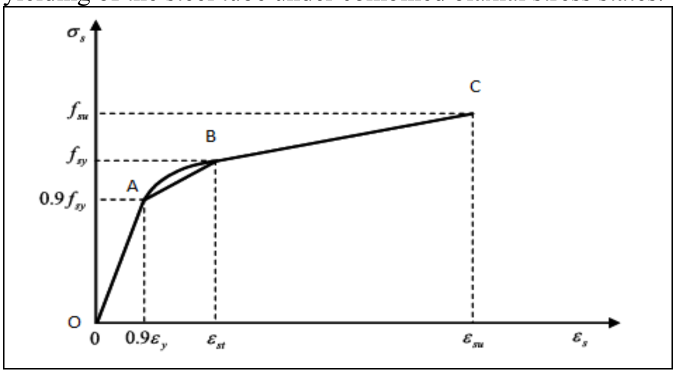

Fig. 1 Stress-strain curves for structural steel.

A schematic diagram of this model is shown in Fig. 1 , where only four parameters, i.e. yield strength (f_{sy}), ultimate strength (f_{su}), hardening strain (ε_{st}) and modulus of elasticity (E_s), are required to determine the full-range stress–strain curve. If the value of E_s and ε_{st} was not reported for a test specimen, it was taken as 200,000 MPa and 0.005 respectively. In the modelling, the following equation proposed by Tao *et al.*, 2013 was used to determine f_{su} with the help of f_{sy} if f_{su} was not available.

f_{su} is the ultimate strength of steel tube, which can be calculated as given below:

$$f_{su} = (1.6 - 2 \times 10^{-3} \times (f_{sy} - 200)) \times f_{sy} \quad \text{when} \quad 200 \le f_{sy} \le 400 \quad (13)$$

$$f_{su} = (1.2 - 3.75 \times 10^{-4} \times (f_{sy} - 400)) \times f_{sy} \quad \text{when} \quad 400 \le f_{sy} \le 800 \quad (14)$$

For Region OA,

$$\sigma_s = \left(\frac{f_{sy}}{\varepsilon_y}\right)\varepsilon_s \qquad 0 \le \varepsilon_s \le \varepsilon_y \quad (15)$$

For Region AB, (Straight line Region)

$$\sigma_s = 0.1 f_{sy} \times \left(\frac{\varepsilon_s - 0.9\varepsilon_y}{\varepsilon_{st} - 0.9\varepsilon_y}\right) + 0.9 f_{sy}\,, \quad \varepsilon_{st} < \varepsilon_s \le 0.9\varepsilon_y \quad (16)$$

The steel tube in a circular CFST column experiences biaxial stress due to the confinement effect imposed by the surrounding concrete core. The induced hoop tension reduces the effective longitudinal yield stress of the steel. This behavior is represented by an idealized linear–rounded–linear stress–strain curve, as shown in Fig. 1. For high-strength steel, the rounded portion of the curve is replaced by a straight line, reflecting the reduced strain-hardening effect. The rounded (parabolic) portion of the stress–strain curve can be expressed using the equation proposed by Liang (2008):

$$\sigma_s = f_{sy}\left(\frac{\varepsilon_s - 0.9\varepsilon_y}{\varepsilon_{st} - 0.9\varepsilon_y}\right)^{\frac{1}{45}} \qquad \varepsilon_{st} < \varepsilon_s \le 0.9\varepsilon_y \quad (17)$$

For Region BC,

$$\sigma_s = (f_{su} - f_{sy}) \times \left(\frac{\varepsilon_s - \varepsilon_{st}}{\varepsilon_{su} - \varepsilon_{st}}\right) + f_{sy} \quad (18)$$

when $\varepsilon_{st} \le \varepsilon_s < \varepsilon_{su}$

The confinement provided by the steel tube is a critical factor influencing the structural behaviour of CFST columns. In the initial stages of loading, the confinement effect can be neglected because the Poisson’s ratio of concrete is smaller than that of steel, causing the steel tube to expand faster radially than the concrete core. Consequently, the steel tube does not restrain the concrete, and it experiences primarily compressive stresses without any separation from the core. However, as the applied load approaches the uniaxial compressive strength of the concrete, microcracking occurs, and the lateral expansion of the concrete becomes significant. At this stage, the steel tube is engaged, providing effective confinement to the concrete core. This interaction enhances the ultimate capacity of the CFST column, making it greater than the sum of the individual resistances of steel and concrete.

VI RESULTS AND DISCUSSION

The specimens listed in Table 1 were evaluated using the developed numerical model for confined concrete, and their responses were expressed through axial load–displacement curves. These results were compared with the corresponding experimental findings reported by various researchers, as summarized in Table 1. The comparison indicates a strong agreement between the numerical predictions and

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Table 1. Details of specimens for the validation

Name of Specimens	(D) (mm)	(t) (mm)	D/t	L/D	f_y (MPa)	(f_{cu}) (MPa)	P_{exp} (kN)	P_{model} (kN)	P_{model} / P_{exp}	Reference
C8	115.04	4.92	23.30	2.60	343	104.9	1341.1	1344.3	1.002	[1]
C3 (G &L)	114.43	3.98	28.70	2.62	343	31.4	997.4	1002.3	1.004	[1]
C-60-3D	114.30	3.35	34.12	3.00	287.3	67.7	935.9	953.8	1.019	[7]
D4M4F1	112.56	2.89	38.95	3.00	360	35.5	765.1	753.4	0.984	[16]
C3	114.43	3.98	28.75	2.62	343	38.6	1007.3	1009	1.001	[21]
C-30-3D	114.30	3.35	34.12	3.00	287.3	40.0	736.2	720.50	0.978	[7]
C-100-3D	114.30	3.35	34.12	3.00	287.3	115.5	1457.6	1462.6	1.003	[7]
CC4-A-4-1	149.00	2.96	50.39	3.00	308	40.5	1060.8	1059.5	0.998	[19]
C7	114.88	4.91	23.39	2.61	365	34.5	1351.8	1349.2	0.998	[1]
C10A-2A-3	101.80	3.03	33.59	3.00	371	29.2	730.4	728.3	0.997	[22]
C30-1	100.00	1.90	52.63	3.00	404	101.9	1048.8	1055.8	1.006	[4]
CS1	219.00	6.90	34.76	2.73	300	172.0	6946.0	6939.7	0.999	[20]
								Mean	0.999	

Where D is outer diameter, t is wall thickness of steel tube, f_y is Yield strength of steel, f_{cu} is cube strength of concrete, P_{exp} is experimental load capacity and P_{model} is predicted load capacity by model.

experimental results, particularly in the post-peak behaviour of circular CFST columns.Moreover, the ratio of the peak load obtained from the numerical model to that from the experimental data shows very good consistency, demonstrating the reliability of the proposed model.

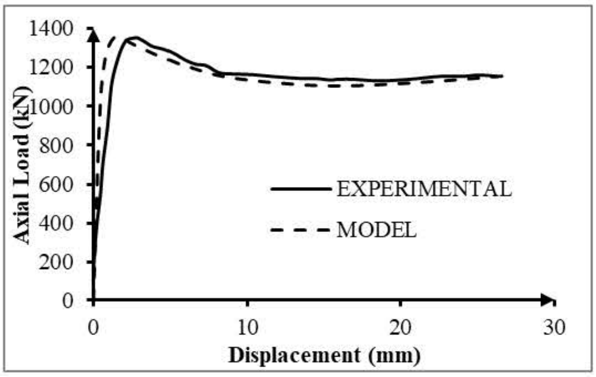

Fig. 2.1 Specimen C8

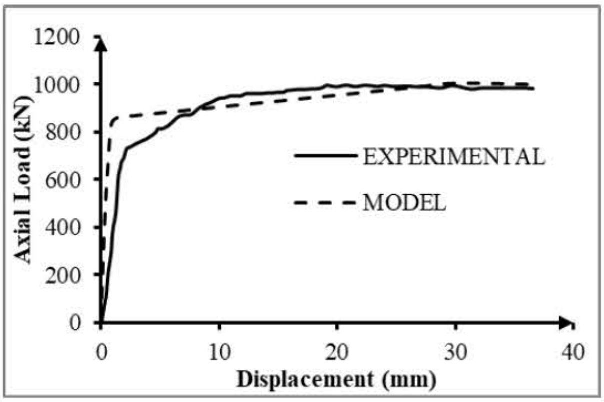

Fig. 2.2 Specimen C3 (G & L)

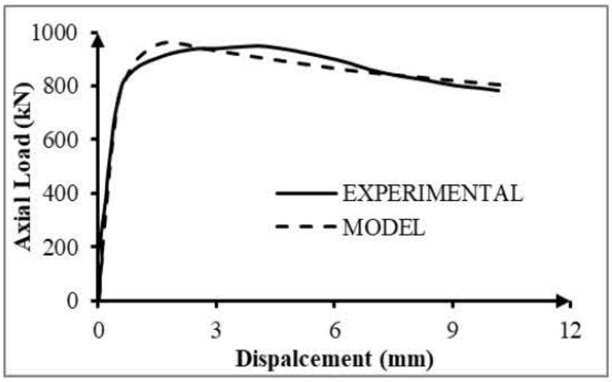

Fig. 2.3 Specimen C-60-3D

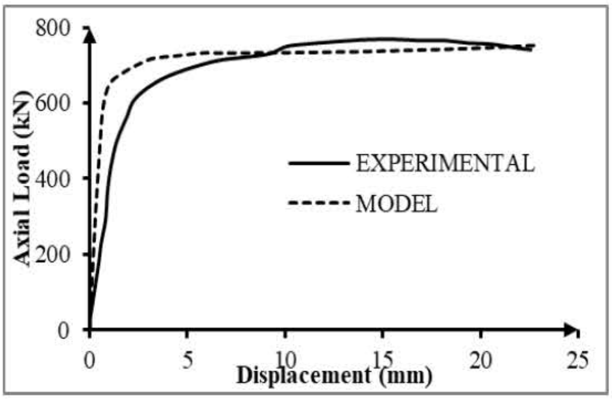

Fig. 2.4 Specimen D4M4F1

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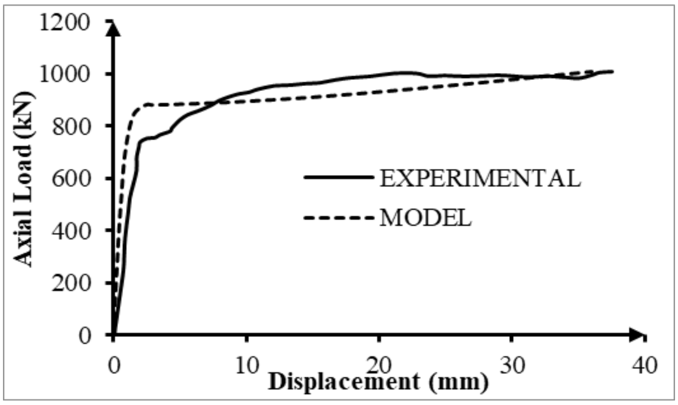

Fig. 2.5 Specimen C3

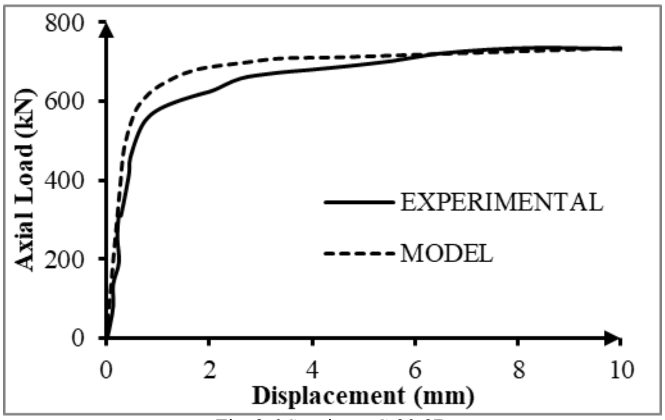

Fig. 2.6 Specimen C-30-3D

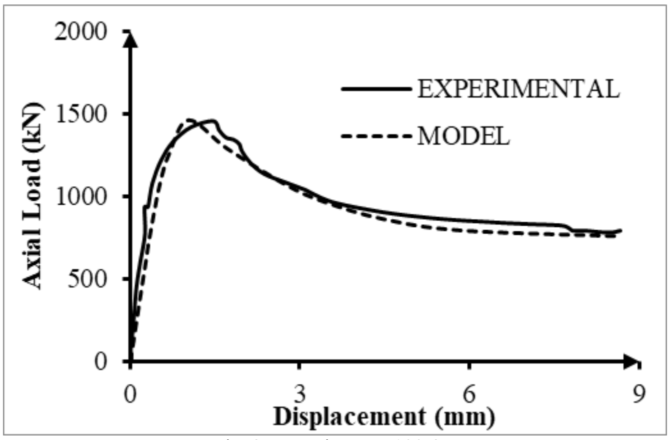

Fig. 2.7 Specimen C-100-3D

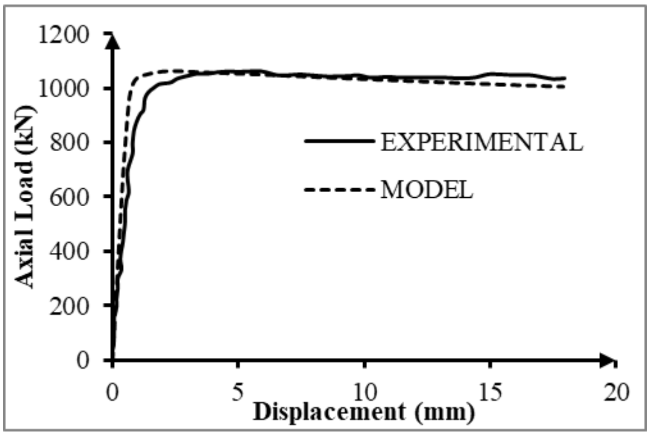

Fig. 2.8 Specimen CC4-A-4-1

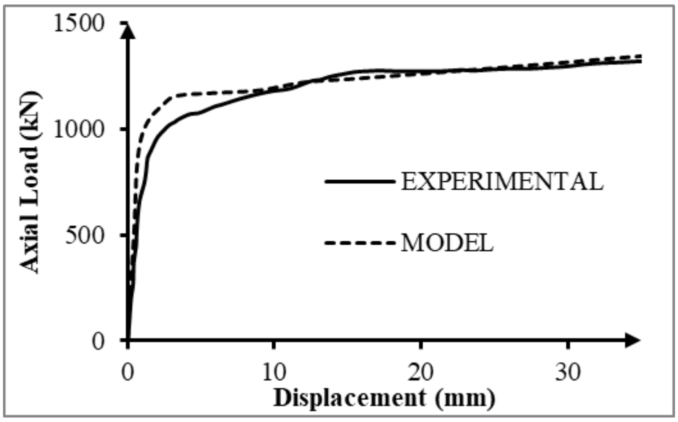

Fig. 2.9 Specimen C7

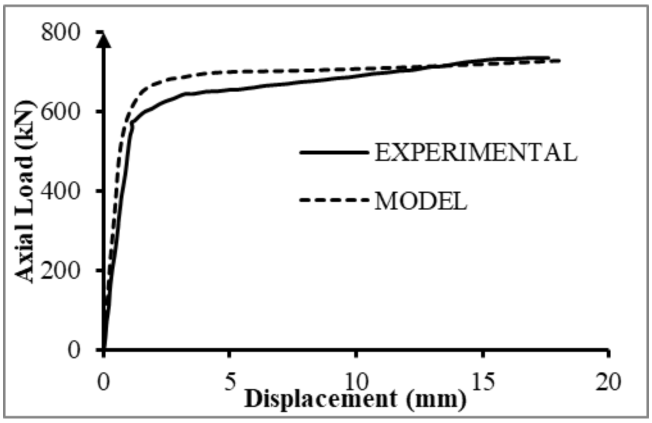

Fig. 2.10 Specimen C-10A-2A-3

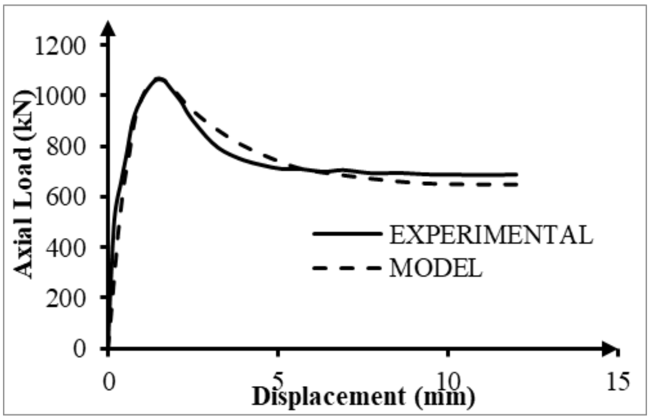

Fig. 2.11 Specimen C30-1

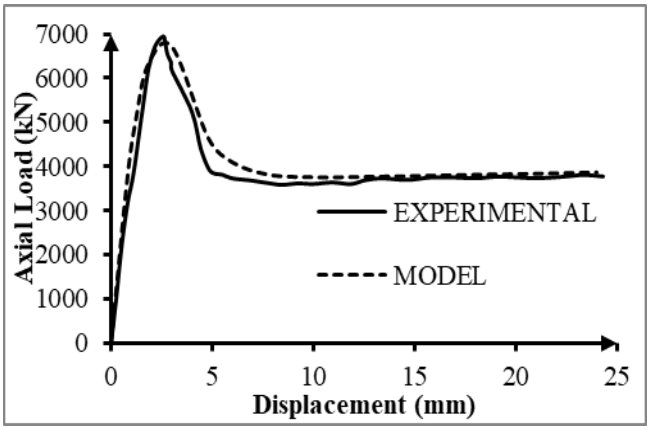

Fig. 2.12 Specimen CS-1

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VII CONCLUSIONS

The following major conclusions in the study of stub circular CFST columns under axial compression can be drawn from this study:

- Both the experimental results and the predictions obtained from the proposed equations showed good agreement, demonstrating the reliability of the developed model.
- Based on the post-peak behaviour of the specimens, it was observed that CFST columns incorporating normal-strength concrete exhibited hardening after reaching the peak load. In contrast, specimens with high-strength concrete displayed softening behaviour after the peak load was attained.
- For some specimens (C8, D4M4F1, and C30-1), an initial convexity was observed at the beginning of the load–displacement curve. This behaviour is attributed to the absence of a seating load, which is the initial load applied to stabilize the CFST specimen and ensure correct alignment before further loading. Without this seating load, slight initial movement occurs, resulting in the observed convexity.

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