Impact of diameter to thickness (D/t) on axial capacity of circular CFST columns: Experimental, parametric and numerical analysis

Shaik Madeena Imam Shah, G. Mohan Ganesh*

School of Civil Engineering, Vellore Institute of Technology, Vellore 632014, Tamil Nadu, India

ABSTRACT

Twenty-four circular Concrete Filled Steel Tube (CFST) columns divided into three series based on their cross-sectional dimensions were subjected to uni-axial compression and their behaviour is studied. This paper aims to develop the volume of experimental database as there is shortage in data that can assess the guidance from the codes and enhances their accuracy in determining the ultimate capacities and the behaviour of CFST specimens subjected to uni axial compression. This study consists of CFST specimens having outer diameter of 76 mm, 89 mm and 100 mm with same wall thickness of 3 mm having four Length to Diameter (L/D) ratios of 3, 4, 5 and 6. Impact of D/t on the parameters like confinement (ξ), strength index (SI), relative slenderness ratio (λ), percentage contribution of steel and concrete and ductility index (DI) were studied. Further, the axial compressive load values were compared with the predicted design values of codes, namely, Eurocode – 4 (EC4), American code (AISC 360-10), Australian code (AS5100), Chinese code (DBJ13-51) and American Concrete Institute (ACI-318). A design equation is proposed to calculate the ultimate axial load and the predicted results are near to the test results. To check the accuracy of the proposed equation, experimental results of 63 CFST circular columns from the literatures were compared with proposed equation and found the results to be conservative. At last, finite element analysis using ABAQUS was done to study the behaviour of column buckling, axial load and displacement curves. Results showed good agreement with experimental test results.

Keywords: Concrete contribution ratio, Ductility index, Length to diameter, Overestimated, Underestimated.

1. INTRODUCTION

Concrete Filled Steel Tube (CFST) columns having the advantage of exceptional axial carrying capacity are used in modern developments of structures like bridges with long span, high rise buildings, subways, transmitting poles and other infrastructures (Feng et al., 2020). As the demand of economy is high and constructions are rapid, CFST columns have come in to play with practical applications. SEG Plaza in Shenzhen – China is one of the first structures using circular concrete filled steel tube columns in a very large scale. The diameter of circular CFST used in this construction ranged from 900 mm to 1600 mm (Zhao et al., 2010). Also, Obayshi Technical Research Institute is constructed using circular CFST columns having steel grade of 780 MPa and columns in Tokyo Sky Tree has the steel grade of 700 MPa. Both the structures are constructed in Japan. The diameters of the columns used in the structure ranged from 2000 mm to 2300 mm (Li et al., 2020). Canton Tower in China topped out in the year 2009 and opened in 2010 which has 604 m height used circular CFST columns in a very large scale. All these structures mentioned above are beyond the limit of substantial design codes such as AS5100, EC4, DBJ13-51 and AISC. The parameters in these design codes
were limited to certain ranges because of its early research developments and their results. The design capacities and parametric limits of these codes are represented in Table 1. Research and experimental work have been conducted on CFST columns having yield strength, high strength concrete and different diameter to thickness ratios. Dundu (2012) studied the behaviour of 24 CFST columns having diameter ranging from 114.85 mm to 193.7 mm with a thickness of 3 – 3.5 mm. Yield strength of steel and concrete strength considered was 345 – 488 MPa and 30- 40.3 MPa respectively. Author has concluded that, columns with higher diameter and hoop stress results in increasing the load carrying capacity. The experimental results are 8.4% and 13.6% conservative with the predicted values of EC4 codes respectively. Wang et al. (2017) studied the effect of size in circular CFST with different D/t ratios ranging from 55 - 88 under axial compression and concluded that effect of size has more impact on the columns. Ekmekeyapar et al. (2016) presented 18 CFST circular columns of various lengths having concrete grade strength between 50 MPa to 110 MPa with diameter of 114.3 mm and thickness ranging from 2.74 to 5.9 mm. It is concluded that, EC4 had better acceptance with the test results and suggested to widen the range of limits for better research and experimental works. Zeghiche et al. (2005) tested 27 CFST specimens with fy = 40 MPa to 106 MPa, having diameter ranging from 159-160 mm and thickness of 4.9 – 5.13 mm.

| Code  | D/t Limit | Steel yield strength | Concrete strength | Relative slenderness ratio | Axial capacity prediction |
|-------|----------|----------------------|-------------------|-----------------------------|--------------------------|
| EC4   | 90(\(\frac{235}{f_y}\)) | 235 \(\leq f_y\) \leq 460 | 20 \(\leq f_c\) \leq 60 | \(\lambda = \frac{\sqrt{N_{pl,kr}}}{N_{cr}} \leq 2.0\) | \(N_u = A_f \eta_a f_y + A_c f_c \left(1 + \frac{\eta_1 f_y}{d f_c}\right)\) |
| AS 5100 | 90(\(\frac{235}{f_y}\)) | 200 \(\leq f_y\) \leq 450 | 25 \(\leq f_c\) \leq 65 | \(\lambda = \frac{N_a}{N_{cr}} \leq 2.0\) | \(N_u = \phi A_f \eta_a f_y + \phi_c A_c f_c \left(1 + \eta_1 \frac{f_y}{f_c}\right)\) |
| DBJ 13-51 | 150(\(\frac{235}{f_y}\)) | 235 \(\leq f_y\) \leq 420 | 20 \(\leq f_c\) \leq 50 | - | \(N_u = f_{sc} A_{sc}\) |
| AISC 360-10 | \(\lambda_p = 0.15 \frac{f_y}{f_y}\) | \(f_y \leq 525\) | 21 \(\leq f_c\) \leq 70 | - | \(P_n = P_{no}[0.658 \frac{P_{no}}{P_e}]\) \(P_{no} \leq 2.25\) |
| ACT-318 | - | - | - | - | \(P_{ACI} = 0.85 f_y A_s + f_y A_t\) |
It is concluded that concrete having high strength intensified the column axial capacity and EC4 predictions are safe and in good accord with experimental and numerical failure loads. Similarly, Ou et al. (2011) conducted experimental study having the diameter range from 222-488 mm with steel tube thickness of 1.5 mm, all the 27 specimens used in the study had their D/t limit beyond the code provisions. The conclusions given by the author is that as eccentricity and slenderness are increasing, the load capacity of the CFST columns is decreasing. Fang and Visintin (2021) studied the structural performance of 6 square and 5 circular geopolymer CFST members having B x t of 125 x 4 mm and D x t of 140 x 3.6 mm respectively. All the specimens were subjected to compression and flexural bending. It is concluded here that, ultimate load of the specimen decreased with increasing eccentric loading. Greater structural performance can be obtained with lesser B/t or D/t and member slenderness ratios. Authors also compared the experimental test results with design codes like EC4, AS/NZS2327 and AISC 360 and concluded that these codes are safe to apply in generating the design of geopolymer CFST members. Dar et al. (2021) studied the axial strength and deformation behaviour of light weight CFS composite built up columns that are formed using GFRP and timber and showed that the axial strength improvement in the short CFS composite columns due to double GFRP is very near to that of GFRP sheets and timber plank. Many researchers have studied the axial compressive behaviour of CFST columns and disclosed that, as the length of columns are increasing, the axial capacities are decreasing. The effect of length (L) on CFST axial capacity also differs among various design codes. EC4 and AS5100 has similar approach on the design of predicting the capacity of the column, where it introduces an effective length factor (k) with idealized end restraints. While the approach in AISC is based on Euler’s formula that considers the effect of slenderness ratio. DBJ13-51 has completely different approach in predicting the capacity and there is no such parameter length (L) that influences the axial capacity. Confinement factor (ξ) is the main parameter that influences the axial capacity of the column. Based on the literature review, enormous data shows that materials are within and beyond the limit of application in design codes that effect the axial capacity of the columns. Hence, the study of parameters and size effect of column enhances the design specifications and allows to revise the method of approach in predicting the axial capacities. This paper shows the experimental behaviour and parametric analysis of CFST columns having different diameter to thickness and length to diameter ratios. In addition, the experimental results are compared to the predicted code results. The design codes used in this study are Eurocode-4(EC4), American code (AISC360-10), Australian code (AS5100), Chinese code (DBJ13-51) and American Concrete Institute (ACI - 318). The main aim of this study is to enhance the data of experimental study available with current series of test data on CFST columns under uni axial compression.

2. EXPERIMENTAL STRATEGY

2.1 Test Setup and Details

24 CFST columns having outer diameter of 76 mm, 89 mm and 100 mm with same wall thickness of 3 mm were taken for the experimental study. The specimens were divided in to three series depending on their cross-sectional dimension. Each series had 8 specimens of L/D ratio of 3, 4, 5 and 6. For each L/D ratio, two specimens were cast, exhibited for axial load compression and the average load of the two specimens were recorded. Similarly, all the series had 8 specimens of L/D ratio 3, 4, 5 and 6 and two specimens for each L/D were cast and tested in UTM recording the average ultimate load of the specimens. In order to have ease, the series were named as follows: OD76-3t, OD89-3t and OD100-3t in which, ‘OD’ and ‘t’ represents outer diameter and thickness respectively. The experimental work was completely carried out at VIT University – Vellore (India). The reason for choosing the small diameters was to study the behaviour of columns that has the load carrying capacity below 1000 kN. The available diameters from the market were chosen for the research study as the UTM had the limited capacity of 1000 kN. Fig. 1 shows the specimen placed in UTM with a dial gauge fixed beside the specimen for recording the axial deformation values.

![Fig. 1. Specimen placed in UTM for testing](image)

2.2 Properties of Materials

2.2.1 Steel Tubes

Hot rolled steel tubes were fabricated and supplied by the manufacturer available locally. Coupon test was conducted to find out the elastic modulus of the steel plate specimen which was used to fabricate the CFST columns and found the value to be 208.4 GPa, which is in the prescribed limits of steel yield strength as shown from Table 1. Steel columns had outer diameter of 76 mm, 89 mm and 100 mm with a wall thickness of 3 mm were used in the experimental study.
2.2.2 Concrete

In this study, self-compacting concrete (SCC) having M30 grade which satisfied all the prescribed mandates by the EFNARC code was used as infill in the steel hollow columns. Poly carboxylate ether (PCE) based super plasticizer named MasterGlenium SKY 8233 having pH value greater than 6 and specific gravity of 1.08 was used to obtain the mix. SCC has satisfied all the basic fresh properties like slump flow and V-Funnel. The mix proportion, limits and values of the fresh properties are summarised in Table 2. Aligned with the CFST experimental work, compressive strength of concrete ($f_c$) was carried out in 150 x 150 x 150 mm cubes. Three concrete sample cubes were cast and placed in curing tank for 28 days and the final recorded compressive strength is given in Table 3. The process of filling the concrete was so easy because it had self-flow and vibration was not necessary. The base of the hollow column was attached to a plate and the concrete was filled. All the specimens were machined to achieve smooth base in the top and bottom and painted to avoid corrosion before placing into the curing tank. Fig 2 shows the cross-sectional dimensions of the specimens that were ready for testing.

3. EXPERIMENTAL APPROACH AND RESULTS

All the CFST specimens were subjected to uni-axial compression till failure. Columns were placed vertically in UTM with the base plates at the top and bottom to have the uniform loading on steel and concrete (Fig.1). Axial load was applied 2 mm per minute to control correctly and record the experimental results accurately. After reaching the failure load, the experiment was continued till the specimen reached 85% of its peak load in order to study the ductility behaviour of the columns.

3.1 Test Results

Failure modes of each specimen was captured and registered safely. Fig. 3 shows the specimens failed after testing. The behaviour of each specimen can be represented through the load verses deflection curves for various L/D ratios for series 1, 2 and 3 as shown in Fig. 4.

| Table 2. Mix proportions and fresh properties |
|---------------------------------------------|
| Cement (kg/m³) | Fine aggregate (kg/m³) | Coarse aggregate (kg/m³) | Water-cement ratio | Super plasticizer (%) | Slump flow (mm) | V-Funnel (sec) |
| 450 | 740 | 810 | 0.46 | 0.85 | 610 | 06 |

Fig. 2. CFST specimens with cross sectional details

Fig. 3. Failure mode of specimens
In general, the specimens in all the series failed due to outward buckling of steel tube, while local buckling was observed at the mid length of the sections. Circular specimens with larger diameter and lesser L/D ratio exhibited more ductile behaviour compared to larger L/D ratios. The columns with increasing L/D ratios, showed decreasing axial compressive capacity. The values of the column capacities are summarized in Table 3. As per the ductile performance of the specimens are concerned, relatively low ductility is seen in the specimens with lesser diameter. This effect is inverse as the length is increasing. It is as expected that the capacity of the column is higher for specimens having larger area of steel and concrete.

3.2 D/T and L/D of the Columns

Fig. 5 shows the graph plotted between L/D and axial load of the CFST column for all the series of the specimens.

Since yield strength, compressive strength and thickness of the specimens are same in all the series, the effect in axial load is influenced by the diameter of the column. It can be seen from the graph that, series 3 that is OD100-3t have higher axial capacities compared to other two series of specimens. However, the axial load decreased as the L/D of the column increased which is as expected.

Series 3 which is OD100-3t having L/D ratio 3 showed 7.24% increment compared to column having L/D ratio 6. 3.66% and 0.33% increment compared to columns with L/D ratios 5 and 4 respectively.

Specimens with L/D ratio 3 in OD100-3t (series 3) showed an increment of 13.41% compared to OD89-3t (series 2) having L/D ratio of 3 and 39.45% compared to OD76-3t having L/D ratio 3. It is inferred here that, as the yield strength and thickness of the columns are same for all the specimens, influence of diameter on axial capacity of column is predominant.

![Graphs showing axial load versus axial deformation for different series](https://doi.org/10.6703/IJASE.202206_19(2).005)
3.3 Confinement Effect

As the yield strength and concrete strength of all the specimens are same, the confinement effect depends on the cross-section area of steel and concrete which differs with the diameter of the column. Confinement (ξ) is calculated using the expression given in Table 1 in DBJ13-51 section. Fig. 6 shows the plot between D/t and confinement (ξ). As the D/t of the column is increasing, the confinement effect is decreasing.

Also, confinement (ξ) has much influence on the axial capacity of the column which can be seen from Fig. 7. The axial capacity of the column increases with the increase in the cross-sectional area of steel and concrete which is the main parameter that influences the confinement (ξ). However, L/D has inverse effect on the load carrying capacity.

| Series and Title | L/D | f_y (MPa) | f_c (MPa) | A_s (mm^2) | A_c (mm^2) | N_e (kN) | P_e% | P_c% | λ | ξ | SI | δ (mm) | DI |
|------------------|-----|-----------|-----------|-------------|-------------|----------|------|------|----|----|----|-------|----|
| OD76-3t          | 3   | 255       | 38.6      | 688.01      | 3848.4      | 424.5    | 41.3 | 58.6 | 0.118 | 1.181 | 1.405 | 2.16  | 2.54 |
| OD76-3t          | 4   | 255       | 38.6      | 688.01      | 3848.4      | 394      | 44.5 | 55.4 | 0.158 | 1.181 | 1.313 | 2.27  | 1.46 |
| OD76-3t          | 5   | 255       | 38.6      | 688.01      | 3848.4      | 376.5    | 46.6 | 53.4 | 0.197 | 1.181 | 1.256 | 2.32  | 1.51 |
| OD76-3t          | 6   | 255       | 38.6      | 688.01      | 3848.4      | 364.5    | 48.1 | 51.8 | 0.237 | 1.181 | 1.193 | 2.41  | 1.60 |
| OD89-3t          | 3   | 255       | 38.6      | 862.55      | 5358.6      | 522      | 42.1 | 57.8 | 0.119 | 1.063 | 1.319 | 1.84  | 2.68 |
| OD89-3t          | 4   | 255       | 38.6      | 862.55      | 5358.6      | 516      | 42.7 | 57.2 | 0.159 | 1.063 | 1.299 | 2.04  | 2.02 |
| OD89-3t          | 5   | 255       | 38.6      | 862.55      | 5358.6      | 496      | 44.3 | 55.6 | 0.199 | 1.063 | 1.253 | 2.19  | 1.90 |
| OD89-3t          | 6   | 255       | 38.6      | 862.55      | 5358.6      | 479      | 45.9 | 54.0 | 0.239 | 1.063 | 1.210 | 2.31  | 1.84 |
| OD100-3t         | 3   | 255       | 38.6      | 914.2       | 6939.7      | 592      | 39.3 | 60.6 | 0.122 | 0.870 | 1.285 | 1.56  | 2.96 |
| OD100-3t         | 4   | 255       | 38.6      | 914.2       | 6939.7      | 590      | 39.5 | 60.4 | 0.162 | 0.870 | 1.280 | 1.62  | 2.14 |
| OD100-3t         | 5   | 255       | 38.6      | 914.2       | 6939.7      | 572      | 40.8 | 59.1 | 0.203 | 0.870 | 1.239 | 1.82  | 1.97 |
| OD100-3t         | 6   | 255       | 38.6      | 914.2       | 6939.7      | 550      | 42.2 | 57.7 | 0.244 | 0.870 | 1.198 | 2.09  | 1.89 |

Fig. 5. Axial capacities of CFST columns of various diameters

Fig. 6. D/t versus confinement effect

Fig. 7. Effect of confinement on axial capacities of the columns
3.4 Strength Index

Strength Index (SI) is an important parameter that is used to measure the composite action between concrete core and steel tube. It is also used to analyse the performance of columns. Equation of SI is as follows:

\[
SI = \frac{N_u}{A_s f_y + A_c f_c}
\]

where \(N_u\) is ultimate axial capacity of the composite specimen governed either by experimental data or design code value. The denominator specifies the squash load of the specimen. Where \(A_s\) and \(f_y\) are cross sectional area and yield strength of the steel tube respectively. \(A_c\) and \(f_c\) are cross sectional area and concrete compressive strength respectively. The strength index values are given in Table 3.

The values of SI for series 1 (OD76-3t) ranges from 1.405 to 1.193 while the values of other two series (OD89-3t and OD100-3t) varies from 1.319 to 1.210 and 1.285 to 1.198. Fig. 8 and 9 shows the plot between SI versus L/D and SI versus confinement (\(\xi\)) respectively. It can be observed that a general increment of L/D leads to decrease in SI. However, increase in size of diameter will increase the cross-sectional area of steel tube thereby decreases the confinement which also leads to low performance in strength index of the column. The reduction in axial capacities of CFST specimens may occur due to global imperfections.

3.5 Percentage Contribution of Steel and Concrete

The contribution of steel (\(P_s\)) and concrete (\(P_c\)) for all the specimens in the series are analysed by the equations as shown:

\[
P_s(\%) = \frac{f_y A_s}{N_e}
\]

\[
P_c(\%) = 1 - P_s
\]

for all the three series of specimens, the values of \(P_s\) and \(P_c\) are plotted which can be seen in Fig. 11(a) and (b) respectively. Also, the values are summarized in Table 3. It is observed that contribution of concrete in axial capacities of CFST specimens are around 51 – 58% for series 1, 54 – 57% for series 2 and 57 – 60% for series 3. The increment in axial capacities of the columns enhanced the concrete contribution. Considering the diameter of the specimens, it is observed that, values of \(P_s\) are generally low for the specimens with higher diameter that is for series 3 (OD100-3t). The reason here is less confinement of the specimens increases the load carrying capacity which results in less contribution of steel and more contribution of concrete to bear the load. However, as the specimen lengths are increasing, the concrete contribution values are decreasing because, the steel wall permits the specimen to deliver huge scope to support the axial load carrying capacity.

3.6 Ductility Index

It is one such parameter that is analysed by the
deformation of specimen. Generally, Ductility Index (DI) is taken from the load versus axial deformation curves. The deflection of the specimen occurred at its ultimate load and deflection corresponding to the load at the point when it comes back to 85% of its ultimate load are considered to calculate the DI values. The expression is given as follows:

\[ DI = \frac{\delta_{85}}{\delta} \] (4)

where \( \delta_{85} \) is the displacement occurred at fall of 85% in the ultimate load and \( \delta \) represents the displacement occurred at ultimate load of the specimen. The ductility index values are calculated as shown in Fig. 12 which is a load versus deformation curve for specimen having ID - OD76-3t in series 1 with L/D ratio of 3. All the DI values for three series with different L/D ratios are compared and represented graphically in Fig. 13. The DI values are higher for the specimens with greater confinement effect, and it is observed a decrement in values for increased L/D ratios in all the series. Compared to series 1 and 2, the specimens in series 3 showed smooth curves till the post peak transition particularly for L/D values 4, 5 and 6.

4. CODE PREDICTIONS AND COMPARISON

As the experimental data base on stub CFST columns are less, the design codes that are used regularly have certain limits in choosing the parametric values. The parametric limits and axial capacity predictions of the design codes can be seen in Table 1. This section manifests the precision of axial compressive test results of CFST columns having different diameters and lengths but same wall thickness is compared with the predicted design values. The approach for the CFST column design in this study is established by Eurocode – 4 (EC4), American code (AISC 360 – 10), Australian code (AS5100), Chinese code (DBJ13-51) and American Concrete Institute (ACI – 318). As the part of analysis, since the concrete compressive strength and yield strength of steel tube are known, partial safety factors in the axial capacity prediction equations are taken as unity in all the codes. The predicted axial capacity of different codes is summarized in Table 4 and represented graphically from Figs. 14 to 18.

4.1 Eurocode 4 (EC4)

The axial compressive predicted capacities \( N_{\text{EC4}} \) are shown in Table 4 along with experimental result to predicted result \( N_e/N_{\text{EC4}} \) for all the series and L/D values. EC4 code gives conservative results with a mean, standard deviation
and coefficient of variance (COV) of 1.01, 0.02 and 0.019 respectively. Two specimens, one in series 2 with L/D ratio of 3 and other in series 3 with same L/D ratio showed un-conservative result. Fig. 14 shows L/D versus \( \frac{N_e}{N_{EC4}} \) for all the three series of specimens. As L/D of the column increases, axial capacity decreases, however, the predictions of EC4 are very precise and hence showed conservative results.

### Table 4. Experimental and code comparisons of CFST axial capacity

| Series and Title | \( \frac{N_e}{N_{EC4}} \) (kN) | \( \frac{N_e}{N_{NEC4}} \) (kN) | \( \frac{N_e}{N_{ASC}} \) (kN) | \( \frac{N_e}{N_{AS5100}} \) (kN) | \( \frac{N_e}{N_{DBJ13-51}} \) (kN) | \( \frac{N_e}{N_{ACI}} \) (kN) | \( \frac{P_{N_{ACI}}}{N_e} \) (kN) | \( \frac{P_{N_{ACI}}}{N_{ACI}} \) | Mean | SD | COV |
|-----------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------------|-----------------|------|-----|
| OD76-3t         | 424                           | 404.5                         | 1.049                         | 314.77                        | 1.349                         | 292.2                         | 1.453                         | 1.034                        | 297.6           | 1.426 | 349 |
| OD76-3t         | 394                           | 386.8                         | 1.018                         | 313.38                        | 1.257                         | 284.2                         | 1.386                         | 0.960                        | 297.6           | 1.324 | 340 |
| OD89-3t         | 376                           | 371.2                         | 1.014                         | 311.61                        | 1.208                         | 276.6                         | 1.361                         | 0.971                        | 297.6           | 1.265 | 334 |
| OD76-3t         | 364                           | 354.7                         | 1.028                         | 309.45                        | 1.178                         | 269.9                         | 1.351                         | 0.888                        | 297.6           | 1.224 | 329 |
| OD93-3t         | 522                           | 528.8                         | 0.987                         | 402.72                        | 1.296                         | 380.46                        | 1.372                         | 0.977                        | 393.8           | 1.326 | 458 |
| OD93-3t         | 514                           | 506.2                         | 1.015                         | 400.88                        | 1.282                         | 370.13                        | 1.389                         | 0.962                        | 393.8           | 1.305 | 447 |
| OD93-3t         | 496                           | 486.3                         | 1.020                         | 398.54                        | 1.245                         | 360.73                        | 1.375                         | 0.928                        | 393.8           | 1.260 | 440 |
| OD89-3t         | 479                           | 469.0                         | 1.021                         | 395.69                        | 1.211                         | 352.25                        | 1.360                         | 0.897                        | 393.8           | 1.216 | 433 |
| OD100-3t        | 592                           | 610.5                         | 0.970                         | 484.4                         | 1.220                         | 435.7                         | 1.359                         | 0.963                        | 466             | 1.270 | 534 |
| OD100-3t        | 590                           | 585.8                         | 1.007                         | 482.4                         | 1.230                         | 424.74                        | 1.389                         | 0.960                        | 466             | 1.266 | 523 |
| OD100-3t        | 571                           | 564.0                         | 1.012                         | 479.5                         | 1.190                         | 414.72                        | 1.377                         | 0.929                        | 466             | 1.225 | 515 |
| OD100-3t        | 552                           | 545.2                         | 1.012                         | 475.9                         | 1.160                         | 405.63                        | 1.361                         | 0.898                        | 466             | 1.184 | 508 |

Mean  
\( 1.013 \)  
\( 1.236 \)  
\( 1.378 \)  
\( 0.947 \)  
\( 1.274 \)  
\( 1.097 \)

SD  
\( 0.020 \)  
\( 0.054 \)  
\( 0.027 \)  
\( 0.041 \)  
\( 0.064 \)  
\( 0.040 \)

COV  
\( 0.019 \)  
\( 0.044 \)  
\( 0.020 \)  
\( 0.044 \)  
\( 0.051 \)  
\( 0.036 \)

### 4.2 American Institute of Steel Construction (AISC 360-10)

The predicted values of the CFST specimens \( (\frac{N_e}{N_{ASC}}) \) and the test to code values \( (\frac{N_e}{N_{EC4}}) \) are summarized in Table 4. It is observed that the predicted axial compressive values of AISC 360-10 are lesser than experimental results and hence, \( \frac{N_e}{N_{ASC}} \) values are greater than unity which remarks that code gives underestimated results. The mean, standard deviation and COV of the specimens are 1.236, 0.054 and 0.044 respectively. Fig. 15 shows the plot between L/D and \( \frac{N_e}{N_{ASC}} \) for all the series of specimens having various L/D ratios. The predicted values vary from 16 – 34% that are lesser than the experimental results with a mean variation around 23%. Therefore, it can be mentioned that AISC 360-10 code gives underestimated results for the CFST specimens in all the three series.

![Fig. 14. Comparison of predicted axial capacities to experimental results for various L/D ratios in EC4 code](https://doi.org/10.6703/IJASE.202206_19(2).005)

### 4.3 Australian Standards (AS5100)

The axial compressive capacity calculated from the design code \( (\frac{N_{AS5100}}{N_e}) \) along with test to code \( (\frac{N_{AS5100}}{N_e}) \) for all the series of specimens are listed in Table 4. These predictions are similar to AISC 360 – 10 having greater variation than the experimental results. The mean, standard deviation and COV of the specimens are 1.378, 0.027 and 0.020 respectively. Fig. 16 shows the plot between L/D and \( \frac{N_e}{N_{AS5100}} \) for all the series of columns. The axial predicted capacities are around 35 – 38% lesser than the experimental results while one specimen in series 1 (OD76-3t) having L/D of 3 showed 45% lesser value than the experimental result. The mean variation of the predicted results of the CFST specimens are around 37% lesser than the test results which confirm that, AS5100 showed underestimated results in predicting the column capacity.
4.4 Chinese Code (DBJ13-51)

The design predicted values (N_DBU) and test to code values (N_e/N_DBU) are listed in Table 4 and the graphical representation for L/D versus N_e/N_DBU for all the specimens in the series is seen in Fig. 17. The mean, standard deviation and COV of the specimens in all the series having 0.947, 0.041 and 0.44 respectively shows over-conservative results in predicting the column capacity. All the specimens in the series show 3 – 12% higher values than the experimental results while one specimen in series 1 (OD76-3t) with L/D ratio 3 showed conservative result with N_e/N_DBU value of 1.034. The mean value of all the specimens being 0.947, code DBJ13-51 shows overestimated results.

5. PROPOSED EQUATION PREDICTIONS AND COMPARISONS

On the basis of experimental test results, a factor ‘k’ is arrived in terms of L/D ratio. From the graph plotted between k versus L/D, a best fitting curve is adopted that can predict the ultimate axial load of the CFST column irrespective of the diameter.

\[ P - N_{ACI} = k[0.85f_cA_c + f_yA_s] \]  
\[ k = 1.583 \left( \frac{L}{D} \right)^{-0.148} \]

The proposed Equation (5) is compared with the experimental test results. Table 4 shows the test to proposed equation results (N_e/P-NACI) having mean, standard deviation and COV of 1.097, 0.040 and 0.036 respectively. This shows the proposed equation predicted the results very near to the experimental test results and hence, the proposed equation gave conservative results. Fig. 19 shows the comparison of N_e versus N_{ACI} and N_e versus P-N_{ACI}. It can be seen that all the points in P-N_{ACI} fall in a straight line with R² value being 0.98 while the points of N_{ACI} having R² value of 0.9023.
Further, to check the accuracy of the proposed equation, comparison is done with the experimental test results obtained from the literatures. Table 5 shows the experimental test results of 63 CFST specimens from references Wang et al. (2017), Li et al. (2020) and Ahamed et al. (2020) that are compared with EC4, AS5100, DBJ13-51, ACI – 318 and Proposed N-ACI. The mean of EC4 predictions is 1.079 which shows conservative results while AS5100 and ACI – 318 codes having the mean value of 1.648 and 1.398 respectively which are unconservative.

DBJ13-51 gives the mean value of 1.179 which is again unconservative by 17%.

However, the proposed N-ACI gives the mean, standard deviation and COV of 1.097, 0.096 and 0.094 respectively. Hence, it is inferred here that the predictions of proposed equation are very near to accuracy and shows conservative results. It is reminded here that the agreement of axial load test results is not end in itself, but in this case, the Equation (5) proved the accuracy in determining the axial capacity.

| Table 5. Comparison of literature experimental results to predicted results |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Ref. | $N_e$ (kN) | $N_{EC4}$ (kN) | $N_{AS5100}$ (kN) | $N_{DBJ13-51}$ (kN) | $N_{ACI}$ (kN) | $N_{Proposed ACI}$ (kN) |
| 4234 | 1260 | 1241.81 | 1.015 | 868.20 | 1.451 | 1294.62 | 1.879 | 2253.85 | 1.879 | 2537.52 | 1.669 | 2602.11 | 1.627 |
| 4245 | 1660 | 1469.23 | 1.130 | 1051.53 | 1.579 | 1504.02 | 1.163 | 1175.77 | 1.412 | 1615.52 | 1.027 |
| 1785 | 1569.82 | 1.079 | 1105.24 | 1.529 | 1695.99 | 1.018 | 1301.36 | 1.299 | 1789.19 | 1.038 |
| 1390 | 1571.96 | 1.079 | 1256.03 | 1.505 | 1843.43 | 1.012 | 1426.10 | 1.340 | 1938.92 | 0.975 |
| 1450 | 1508.21 | 1.06 | 1302.77 | 1.338 | 1637.10 | 0.886 | 1326.09 | 1.093 | 1823.18 | 0.795 |
| 1789 | 1724.12 | 1.038 | 1216.76 | 1.470 | 1847.09 | 0.969 | 1444.36 | 1.385 | 1991.90 | 0.689 |
| 1980 | 1850.17 | 1.076 | 1319.04 | 1.509 | 1981.55 | 1.004 | 1518.28 | 1.311 | 2087.42 | 0.953 |
| 1600 | 1972.12 | 1.211 | 1159.07 | 1.691 | 1643.11 | 1.193 | 1254.09 | 1.563 | 1724.20 | 1.137 |
| 1690 | 1379.39 | 1.225 | 955.99 | 1.768 | 1471.90 | 1.148 | 1190.68 | 1.419 | 1637.02 | 1.032 |
| 1900 | 1600.84 | 1.243 | 1137.10 | 1.750 | 1681.90 | 1.183 | 1317.10 | 1.511 | 1810.83 | 1.099 |
| 1850 | 2185.00 | 1.267 | 1127.10 | 1.750 | 1659.19 | 1.193 | 1435.95 | 1.522 | 1974.33 | 1.107 |
| 2397 | 1838.47 | 1.304 | 1311.43 | 1.828 | 1964.55 | 1.220 | 1505.70 | 1.592 | 2070.12 | 1.158 |
| 1700 | 1369.99 | 1.241 | 950.01 | 1.789 | 1458.82 | 1.165 | 1180.77 | 1.440 | 1623.40 | 1.047 |
| 1900 | 1591.84 | 1.250 | 1131.27 | 1.759 | 1669.81 | 1.192 | 1307.47 | 1.522 | 1797.58 | 1.107 |
| 2135 | 1721.63 | 1.240 | 1235.29 | 1.728 | 1804.27 | 1.183 | 1379.89 | 1.547 | 1897.16 | 1.125 |
| 1890 | 1660.82 | 1.287 | 1097.51 | 1.722 | 1757.97 | 1.075 | 1425.17 | 1.326 | 1959.40 | 0.969 |
| 2100 | 1814.69 | 1.157 | 1270.01 | 1.647 | 1967.96 | 1.067 | 1545.16 | 1.359 | 2124.38 | 0.989 |
| 2230 | 1938.19 | 1.151 | 1376.11 | 1.621 | 2102.42 | 1.061 | 1612.63 | 1.383 | 2217.14 | 1.006 |
| 1940 | 1621.75 | 1.196 | 1109.46 | 1.749 | 1782.15 | 1.089 | 1444.98 | 1.343 | 1986.65 | 0.977 |
| 2100 | 1832.83 | 1.146 | 1286.65 | 1.632 | 1992.14 | 1.054 | 1654.44 | 1.342 | 2150.88 | 0.976 |
| 2250 | 1955.83 | 1.150 | 1387.52 | 1.622 | 2126.60 | 1.058 | 1631.50 | 1.379 | 2243.08 | 1.003 |
| 1625 | 1854.36 | 1.210 | 933.05 | 1.724 | 1425.57 | 1.140 | 1152.70 | 1.410 | 1584.80 | 1.025 |
| 1950 | 1566.37 | 1.245 | 1114.75 | 1.749 | 1635.56 | 1.192 | 1280.16 | 1.523 | 1760.04 | 1.108 |
| 2010 | 1965.87 | 1.285 | 1219.10 | 1.649 | 1770.02 | 1.163 | 1353.16 | 1.485 | 1860.40 | 1.069 |
| 1880 | 1387.23 | 1.355 | 960.98 | 1.956 | 1481.98 | 1.269 | 1198.94 | 1.568 | 1648.37 | 1.141 |
| 2140 | 1608.34 | 1.331 | 1141.96 | 1.874 | 1691.97 | 1.265 | 1325.13 | 1.615 | 1821.87 | 1.175 |
| 2200 | 1737.66 | 1.266 | 1245.77 | 1.766 | 1826.43 | 1.205 | 1397.19 | 1.575 | 1920.94 | 1.145 |
| 1700 | 1476.75 | 1.151 | 1017.80 | 1.670 | 1596.81 | 1.065 | 1293.06 | 1.315 | 1777.78 | 0.956 |
6. FE MODELLING OF CFST WITH ABAQUS

Abaqus/CAE – 6.14 tool was used to develop the model of all 24 CFST specimens subjected to axial loading. Buckling of columns, failure modes and axial load versus deformation curves were generated through FE modelling and compared with experimental test results. Deformable and homogeneous element shell was used in modelling and developing the steel tube. While, deformable and solid element was used for concrete core.

Material properties of steel and concrete in the tool were defined as same as the experimental test results. ‘Full Newton’ estimation was selected to run the program using nonlinear geometry solvers. Only axial deformation along the length of the specimen was permitted in boundary condition. Formation of reference points at the ends of column was confirmed to concentric loading, fixed end boundary condition was applied to all the specimens and to reduce the variation of mesh conversion, a structured type of mesh control was used.

In the procedure of CFST modelling, displacement was applied in vertical direction. Load versus displacement curves for all the columns were generated after the analysis. The best comparisons of experimental and FE test results are seen for columns having L/D of 4 and is shown in Fig. 20. Experimental and FE axial test results of all the CFST specimens are listed in Table 6. FEA results showed a difference of 6 - 10% from experimental results. However, few specimens (OD89-3t-5, OD100-3t-6) exhibited 19% difference which identified few geometrical imperfections.

Fig. 21 shows the comparison of deformed shapes of FE models and experimental failure specimens. All the specimens showed outward local bucking.

7. CONCLUSIONS

The effect of confinement due to outer diameter and effect of axial capacity due to various L/D ratios (3,4,5,6) and ductility were studied for all the 24 CFST specimens. Then, design code predictions on axial capacities were compared to the experimental results. Based on this, design equation is proposed for determining the ultimate axial capacities. The conclusions are drawn below.

Local buckling mode of failure is observed in all the CFST specimens. Less ductility is seen in the columns having outer diameter of 76 mm with L/D ratio of 3. The strength index (SI) of the CFST specimens can be increased with increasing the effect of confinement (ξ). However, the axial capacities are decreased with increasing the slenderness of the column.

The experimental study fulfilled the statement that using greater outer diameter steel tubes immensely increased the concrete contribution ratio with increasing L/D.
and ACI-318. Correlation showed that EC4 gives greater traditional outcomes. AISC 360 – 10 and AS5100 showed underestimated results, which is similar in ACI – 318 as well. DBJ13 – 51 showed overestimated results as the fact being that the parameter L/D has no significance in the design procedure of column in the code.

The predicted ultimate axial load results obtained from the proposed equation agreed well with the experimental test results as well as with the experimental results from the literature.

FE models using ABAQUS for all the CFST specimens were developed in this study. Good agreement is observed in axial test results, buckling pattern and axial deformation curves for both experimental and FE model’s output.

### Table 6. Experimental and FEA model comparisons of CFST axial capacity

| Series | Title | L/D | \(N_e\) (kN) | FEA (kN) | \(N_e/\text{FEA}\) |
|--------|-------|-----|-------------|----------|------------------|
| 1      | OD76-3t | 3   | 424.5       | 440.14   | 0.964            |
|        | OD76-3t | 4   | 394         | 417.73   | 0.943            |
|        | OD76-3t | 5   | 376.5       | 378.37   | 0.995            |
|        | OD76-3t | 6   | 364.5       | 375      | 0.972            |
| 2      | OD89-3t | 3   | 522         | 578.14   | 0.903            |
|        | OD89-3t | 4   | 514         | 554.61   | 0.927            |
|        | OD89-3t | 5   | 496         | 593.42   | 0.836            |
|        | OD89-3t | 6   | 479         | 517.05   | 0.926            |
| 3      | OD100-3t | 3  | 592         | 683.05   | 0.867            |
|        | OD100-3t | 4  | 590         | 690.31   | 0.855            |
|        | OD100-3t | 5  | 571         | 665.57   | 0.858            |
|        | OD100-3t | 6  | 552         | 657.08   | 0.840            |
|        | Mean   |     |             |          | 0.970            |
|        | SD     |     |             |          | 0.053            |
|        | COV    |     |             |          | 0.058            |

**Fig. 21.** Buckling patterns of CFST columns in ABAQUS and tested specimens

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