Analytical and Numerical Study on Behavior of Concrete Filled Steel Tabular Columns Subjected To Axial Compression Loads

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Abstract — It has been established that CFST columns have much higher strength and other structural behavioral qualities much superior than conventional R.C.C columns and other composite columns. Owing to their superior structural qualities they have gained booming importance in construction industry across the globe especially in developed countries. Various codes deal with design specifications of the concrete filled steel tabular columns like Eurocode-4, ACI, AISC-LRFD,CECS 28:90, however Eurocode-4 and CECS 28:90 incorporates confinement effect of concrete due to steel tube in evaluating the axial compressive strength of CFST columns. In Eurocode-4 the confinement effect is related to slenderness ratio ($\bar{\lambda}$) and eccentricity (***e***) of the applied loading. In CESE 28:90 slenderness ratio and load eccentricity are taken as independent parameters governing the ultimate strength of concrete filled steel tabular columns. This paper represents an analytical and numerical study on behavior of CFST columns under axial compression loading. For this purpose the axial strength of CFST columns and their corresponding confinement factors have been evaluated using Eurocode-4 design mechanism and CESC 28:90 design mechanism. Numerical analysis has been done using three dimensional non-linear finite element software ABAQUS 6.13. The proposed finite element model is validated by comparing its results with those of corresponding experimental specimens. The analytical and numerical results obtained are compared with each other. For this study 12 circular CFST specimen having steel tubes of different thickness and in filled with different grades of concrete are chosen from the literature.

Index Terms— Confinement effect, ABAQUS, Axial load, Steel tubes, CFST columns, Slenderness ratio, Eccentricity

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1 Introduction

As the name Concrete filled steel tabular column suggests, it consists of steel tube of suitable thickness infilled with suitable grade of concrete. Since CFST columns are structurally superior to conventional R.C.C columns and other composite columns. They are being widely used in high rise buildings, bridges, flyovers and other earthquake resistant structures. The steel in the concrete filled steel tube (CFST) column acts both as longitudinal as well as lateral reinforcement. Due to which steel is subjected to biaxial stress of longitudinal compression and hoop tension. Simultaneously concrete is stressed tri-axially. In addition, the location of the steel and the concrete in the cross section optimizes the strength and stiffness of the section. In concrete filled steel tube (CFST) columns, steel lies at the outermost perimeter where it performs most efficiently in tension and in resisting bending moment. Similarly the stiffness of the concrete filled steel tube column is greatly enhanced because the steel is located farthest from the centriod, where it makes maximum contribution to the moment of inertia.

Previous studies by various scholars have revealed that axial compressive load carrying capacity of CFST columns is considerably affected by the shape of cross-section, thickness of the steel tube. Further it has been revealed that confinement effect is more in circular CFST columns than in Square CFST columns. In this study 12 circular specimens have been studied.

CFST columns have many advantages over conventional R.C.C columns. In CFST columns the steel ratio is always higher thus providing more ductility to the member locally and globally to the entire structure. The applications of form work and reinforcing bars is completely omitted as the steel tube performs the required action, consequently making structure economical as well as eco-friendly. Since the CFST columns combine the advantages of both steel and concrete, steel engulfing the concrete core not only assists in carrying axial load but at the same time confines the concrete preventing it from spalling. The concrete core in turn delays the local buckling of the steel tube.

2 Behavior of CFST columns

The interaction between steel tube and the concrete core plays pivotal role in imparting higher axial compressive strength to

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CFST columns. It is this phenomenon which determines the behavior of CFST columns under concentric axial loading. So the key issue for understanding the behavior of CFST columns under axial loading is to understand the load transfer mechanism of CFST columns via interaction between steel tube and the concrete core.

CFST columns are the composite members made of two different materials, steel and concrete. Steel and concrete are two different materials have different stress- strain compatibilities and Poisson's ratio. The difference between the properties of the above mentioned two materials makes determination of structural behavior of CFST columns a cumbersome task. The structural behavior of the CFST column is considerably affected by the difference between the Poisson's ratio of the steel and concrete. In the initial loading, Poisson's ratio for the concrete is lower than that for steel, consequently the steel tube expands radially faster than the concrete core. So the steel tube does not restrain the concrete core i.e. the steel tube has no confinement effect on the concrete at this stage of loading. The initial circumferential hoop stresses developed in steel are compressive in nature and the concrete undergoes lateral tension as shown in Fig 1. With the increase in loading concrete starts to plasticize. The lateral deformation of the concrete core races to catch up with steel. As the longitudinal strain increases the lateral expansion of the concrete core gradually becomes greater than the expansion of the steel tube. At this stage steel tube restrains concrete core and the hoop stresses which were compressive initially becomes tensile as shown in Fig 2. At this stage concrete core is stressed tri-axially and steel tube bi-axially. It the point when the confinement effect plays its role in increasing the axial compressive strength of the CFST column.

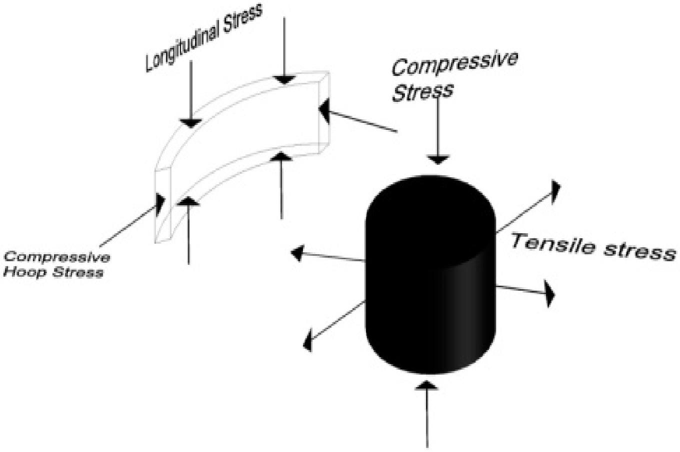


Fig 1

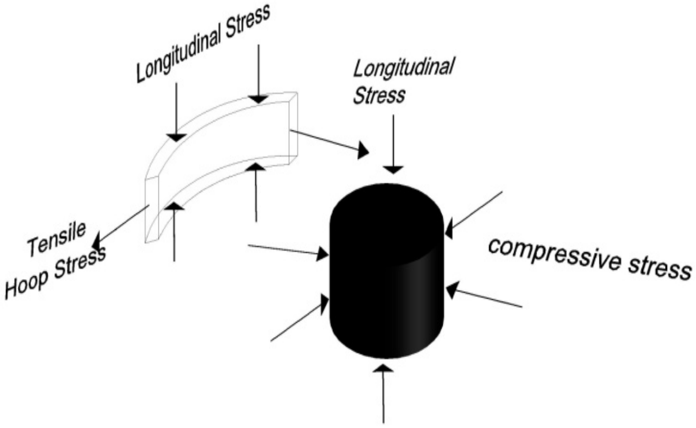
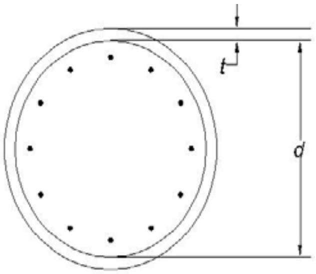


Fig 2

3 European Committee for Standardization Eurocode-4

Eucocode-4 is the most recently developed, internationally acclaimed guidelines adopted for design of composite columns. The design theory proposed by the code is based on the rigid plastic method of analysis which assumes fully yielded steel and fully crushed concrete. In eurocode-4 the confinement effect is related to slenderness ratio ($\bar{\lambda}$) and eccentricity (e) of the applied loading. Eurocode-4 includes design mechanism for both concrete encased and steel filled tabular columns. Eurocode-4 gives ultimate axial force equations for both square and circular concrete filled tabular columns. To check local buckling of circular CFST columns limiting values of the specimen are governed by the equation given in table 1

TABLE 1

Cross section	Shape	Max (d/t), max (b/t)
Circular hallow steel section		$\frac{d}{t} \leq 90\frac{235}{f_y}$

The ultimate axial strength of the concrete filled tabular column is given by

$$N_{pl,Rd} = A_s f_{y\,+} A_c f_c$$

For circular sections, Eurocode-4 considers confinement effect provided relative slenderness ($\bar{\lambda}$) has value less than 0.5 and (*e*/d) < 0.1. Relative slenderness ($\bar{\lambda}$) is defined as

$$\bar{\lambda} = \sqrt{\frac{N_{pl,Rd}}{N_{cr}}}$$

N_{cr} is defines as the Euler buckling strength of the composite column, mathematically given by

$$N_{cr} = \frac{\pi^2 \left(EI_{eff}\right)}{l^2}$$

Further

$$EI_{eff} = E_s I_s + 0.81 E_{eff} I_c$$

Where 0.81 is an empirical multiplier and E_{cm} is the secant modules of concrete.

To consider the effect of long term elastic flexural stiffness, we have

$$E_{eff} = \frac{E_{cm}}{\gamma_c}$$

γ_c is the safety factor equal to 1.35

$$EI_{eff} = E_s I_s + 0.6 E_{cm} I_c$$

So the ultimate load carrying capacity of a circular concrete filled tabular column is calculated by

$$N_{pl,RD} = \eta_2 A_s f_y + A_c f_c \left(1 + \eta_1 \frac{t}{d}\frac{f_y}{f_c}\right)$$

η_1 and $\eta_2$are the factors considering the confinement effect, for members without eccentricity

$\eta_1 = \eta_{10}$ and $\eta_2 = \eta_{20}$

Confinement effect are determined by relative slenderness as

$$\eta_1 = 4.9 - 18.5\,\bar{\lambda} + 17\,\bar{\lambda}^2$$

$$\eta_2 = 0.25\left(3 + 2\,\bar{\lambda}\right)$$

χ is termed as column resistance reduction factor used to diminish the value of compressive resistance of a composite column.

$$\chi = \frac{1}{\emptyset + \sqrt{\emptyset^2 - \bar{\lambda}^2}}$$

Where $\emptyset$ is a parameter depending up on the internal reinforcing bars.

$$\emptyset = 0.5\left[1 + 0.21\left(\bar{\lambda} - 0.2\right)\bar{\lambda}^2\right]$$

4 Chinese code (CECS 28:90)

The Chinese code (CECS 28:90) is based on unified theory that considers the CFST column as a composite member instead of separate components. The properties of CFST columns depend on the properties of the steel and concrete, and their dimensions. The composite indices and geometric properties are then used directly to obtain the ultimate strength. The Chinese code differs from both the Eurocode4 and the code ACI 318. The code also includes shear and torsion, in addition to bending and axial load. Code CECS (28:90) recommends some basic requirements for CFST members as

a) D ≥ 100 mm
b) t ≥ 14 mm
c) $\xi = \frac{f_y}{A_a} \Big/ \frac{f_c}{A_c}$
d) $0.3 \geq \xi < 3$
e) D/t should be in the range of (15 ~85)$\sqrt{235/f_a}$
f) l/D should not exceed permissible limit (20 for CFST columns)

The ultimate axial load carrying capacity of CFST columns is calculated by

$$N_u = \varphi_1 \varphi_2 N_0$$

φ_1 and φ_2 are the reduction factors incorporating the eccentric loading effect and slenderness influence respectively.

For concentric loading $\varphi_2 = 1$

And $\varphi_1 = 1 - 0.115\sqrt{l_e/D - 4}$ for $(l_e/D) > 4$

Or $\varphi_1 = 1$ for $(l_e/D) \leq 4$

N_0 is ultimate axial load carrying capacity of the short CFST columns given by

$$N_0 = f_c A_c \left(1 + \sqrt{\xi} + \xi\right)$$

Where ξ is the confinement factor explained by Han and Yang, mathematically given by

Where $\xi = \frac{A_a f_y}{A_c f_c}$

Therefore

$$N_0 = f_c A_c + f_y A_a + \sqrt{(f_c A_c)(f_y A_a)}$$

ξ is an important factor which determines the effect of confinement on the axial strength of the concrete filled tabular column. Keeping tensile strength of steel and compressive strength of concrete constant the valve of the confinement factor depends up on the area of steel. Which implies when diameter of the steel tube is kept constant and thickness is varied, the greater the thickness greater will be the confinement factor. The values of the confinement effect may be higher for the columns of different geometric properties, but neither the corresponding strength nor the axial load capacity will be higher. It should be also noted that confinement factor does not imply to the compressive strength of the concrete and the ductility of the column. The confinement factors calculated are listed in the table 2 (See appendix).

5 Numerical modeling

The interaction between the steel tube and the concrete core is the phenomena responsible for increased axial strength of the CFST columns under axial loading. It is this phenomenon that makes CFST columns structurally batter than Conventional R.C.C columns. Therefore to effectively replicate the inherent advantages of the CFST columns, it is necessary that the composite action between the steel tube and the concrete core be modeled with utmost care besides other modeling steps.

5.1 Material modeling

In ABAQUS each part is modeled separately i.e. steel tube is model as one part and concrete core is modeled as other part, then the separate parts are assembled together using interference option provided in the ABAQUS.

a) **Steel tube—**an elastic-perfectly plastic model is modeled to simulate the steel tube in ABAQUS 6.13. The poison's ratio is taken as 0.3. other geometric and material details are given in the Table 3 (see appendix)

b) **Concrete core—**the concrete core is modeled using The Drucker Prager model available in ABAQUS to describe the plastic stress strain behavior of the confined concrete. The poison's ratio is taken as 0.2. Other geometric and material properties are given in the Table 3 (See appendix)

5.2 Interference

The confinement provided by the steel tube to the concrete core is the key factor to incorporate the advantages of CFST columns. Therefore it is pertinent that the steel tube and the concrete core must behave as a single member and not merely as a combination of two different materials. To overcome this problem the contact between the steel tube and the concrete core is provided by introducing friction, using interference option available in ABAQUS 6.13. The co-efficient of friction m is chosen as m=0.25. Hard contact is provided between the two surfaces only when there is actual contact among them. While causing the surface to separate under the influence of the tensile force.

5.3 Meshing

In ABAQUS 6.13 meshing can be done individual on parts and then assembled or vice-versa. In this analysis parts were individual meshed and then assembled for further process. The key in finite element analysis is the appropriate selection of element type. The ABAQUS standard modules consist of a comprehensive element library that provides different types of elements catering to different situations. ABAQUS 6.13 has set of solid continuum element library specially designed for composite materials like CFST columns. ABAQUS commonly provides 4-node linear tetrahedron (C3D4) elements, 6-node linear triangular prism (C3D8) elements and 8-node linear brick (C3D8) elements. In this analysis 8-noded brick elements are used for meshing of steel tube as well as concrete core. As these elements are used for analysis of complex non-linear analysis involving contact, plasticity and large deformations. The cylinder geometry generated in ABAQUS is illustrated in Fig 3.

5.4 Analysis

ABAQUS 6.13 provides various analysis procedures to analyze the behavior of different models catering different needs. In this analysis for CFST columns to study the buckling behavior of CFST columns, linear perturbation procedure of analysis is chosen. ABAQUS further provides different type of analysis procedures in liner perturbation to meet requirements for different models. In our analysis linear perturbation buckle analysis is used to obtain the buckling load of the CFST column. Linear perturbation buckle analysis provides Eigen values corresponding to buckle loads. The interface of FEM Software for assigning liner perturbation buckle analysis is shown in Fig 4.

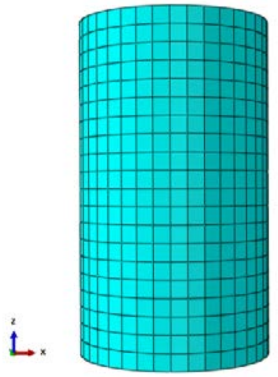
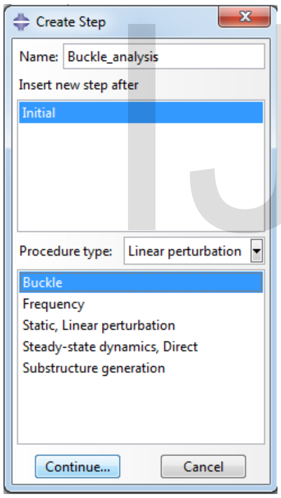


Fig 3



Name: Buckle_analysis

Procedure type: Linear perturbation

Buckle

Fig 4

5.5 Load and boundary conditions

Loads and boundary conditions must be applied to the geometry of model accurately to get the perfect result. In this analysis for each of the two ends, two different types of boundary conditions were used. The nodes of the bottom end were fixed, displacement degrees of freedom in 1, 2, 3 directions (U1, U2, U3) as well as rotational degrees of freedom in 1, 2, 3 directions were restrained to be zero. The nodes at the top are kept free in rotational degrees of freedom and translation U3 is free remaining U1, U2 are restrained. The model generated in ABAQUS is shown in Fig 5.

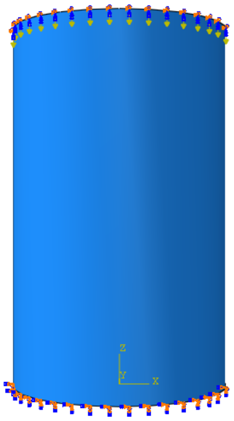


Fig 5

6 Results

The results obtained are tabulated in Table 4 (see appendix) .Fig 6 shows the final deformed shape of the circular CFST column under axial compressive loading.

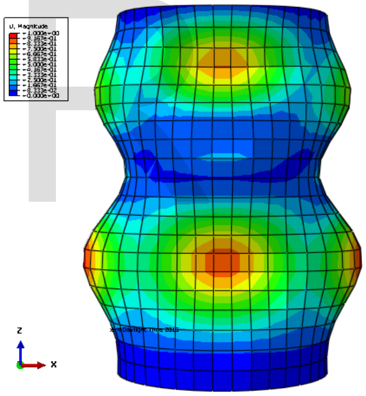


Fig 6

7 Conclusions

A non-linear 3-D finite element model was developed using ABAQUS 6.13 for the numerical simulation of circular CFST columns under a constant axial loading for a number of specimens having different geometries and material properties. The variation between experimental and numerically simulated results was within the range of ±5%. From the study following conclusions were drawn.

[1] CFST columns under axial compressive loads are not affected by the change in effective length.
[2] CFST columns with smaller diameter to thickness ratio show abrupt decrease in concrete confinement.

[3] The confinement effect increase with the increase in the yield stress of the steel tube.

[4] Comparison between Eurocode-4 and CECS 28:90 shows Eurocode-4 is more conservative in most cases.

[5] CECS 28:90 is not good for evaluating the axial strength of CFST columns having steel tube thickness less than 4mm.

[6] The confining pressure is much higher at the areas adjacent to top and bottom of the column. Further the confinement effect varies along the length of the column.

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List of symbols

A_c	Area of steel section
As	Section area of concrete
B	overall width of rectangular CFST column
CFST	Concrete filled tabular column
d	diameter
D	outer diameter
E_s	Elastic modules of steel
E_c	Elastic modules of concrete
E_{cm}	Secant modules of concrete
EI_{eff}	Effective flexure stiffness
e	Eccentricity
f_c	Specified compressive strength of concrete
f_y	yield strength of concrete
I_c	Moment of inertia of section for concrete
I_s	Moment of inertia of section for steel
l_e	Effective length of CFST column
N_{cr}	Euler buckling resistance of CFST column
N_u	Design strength of CFST column
N_0	Axial load capacity of CFST column
t	Thickness of steel tube
$\bar{\lambda}$	Relative slenderness

APPENDIX

TABLE 2

Calculation of Confinement Factors

Specimen label	Tested by	Aa (mm)	Ac (mm)	Fy (Mpa)	Fc (Mpa)	Confinement factors		
						CESC	Eurocode-4	
						ξ	h_1	h_2
7a	Gardner	2573	19806	200.2	33.4	0.7787	3.71	0.78
7b		2573	19806	200.2	33.4	0.7787	3.71	0.78
8a		2573	19806	200.2	27.9	0.9322	3.75	0.78
1-3Y6	Cheng 1988	2269	19113	254.4	33.2	0.9097	2.35	0.83
2-3Y4		1548	8658.9	271	33.2	1.4593	2.38	0.83
3-3Y3		1061.9	5089.5	232	33.2	14568	2.49	0.83
4-3Y2		621.25	2206.2	223	33.2	1.8914	2.55	0.82
5-3Y1.5		489.3	1320.2	304	33.2	3.3937	2.34	0.83
S3LA	Sakino 1985	913.1	7226	320	18.0	2.2465	3.59	0.79
S3HA		913.1	7226	320	37.4	1.0812	3.43	0.79
S6LA		1720.9	6418.3	305	18.0	4.5432	3.6	0.79
S6HA		1720.9	6418.3	305	37.4	2.1866	3.5	0.79

TABLE 3

Geometric and Material Properties of Specimen

Specimen label	Tested by	D (mm)	T (mm)	l/d	D/t	L (mm)	f_c (Mpa)	f_y (Mpa)	E_s (Gpa)
7a	Gardner	168.80	5.00	1.81	33.8	305	33.4	200.2	200
7b		168.80	5.00	1.81	33.8	305	33.4	200.2	200
8a		168.80	5.00	1.81	33.8	305	27.9	200.2	200
1-3Y6	Cheng	165.00	4.50	4.00	36.7	660	33.2	254.4	200
2-3Y4		114.00	4.50	4.00	25.3	456	33.2	271	200
3-3Y3		88.50	4.00	4.00	22.1	354	33.2	232	200
4-3Y2		60.00	3.50	4.00	17.1	240	33.2	223	200
5-3Y1.5		48.00	3.50	4.00	13.7	192	33.2	304	200
S3LA	Sakino	101.80	2.94	1.96	34.6	200	18.0	320	200
S3HA		101.80	2.94	1.96	34.6	200	37.4	320	200
S6LA		101.80	5.70	1.96	17.9	200	18.0	305	200
S6HA		101.80	5.70	1.96	17.9	200	37.4	305	200

TABLE 4

Comparison of Analytical and Numerical results

Specimen label	**Tested by**	**Test load (Mpa)**	**Eurocode-4**		**CECS 28:90**		**ABAQUS**	
			Pu (Mpa)	% error	Pu (Mpa)	% error	Pu (Mpa)	% error
7a	Gardner	1966	1501	-23.65	1760	-10.48	1923	-2.19
7b		1970	1501	-23.80	1760	-10.66	1937	-2.38
8a		1984	1397	-29.58	1601	-19.30	1951	-1.66
1-3Y6	Cheng 1988	1647	1426	-13.42	1817	+9.35	1607	-2.40
2-3Y4		1033	856	-17.13	1054	+2.00	998	-3.39
3-3Y3		602	505	-16.11	619	+2.74	623	+3.37
4-3Y2		334	261	-21.85	312	-6.58	318	-4.79
5-3Y1.5		273	236	-13.55	273	0.00	284	+3.87
S3LA	Sakino 1985	628	600	-4.46	617	-1.75	603	-3.98
S3HA		660	731	+9.71	843	+21.71	638	-3.33
S6LA		954	923	-3.24	886	-7.13	911	-4.51
S6HA		971	1039	+6.54	1120	+13.30	924	-4.84