Analytical and Numerical Study of Concrete Filled Tabular Columns

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Abstract

Concrete filled steel tabular columns have gained immense importance in recent decades due to numerous structural benefits especially in developed countries like china, Japan, U.S.A, Britain. In this paper analytical equations are put to understand the mechanism of concrete filled tabular columns under axial loading. For this purpose a comparison between design codes Eurocode -4, and AISC-LRFD has been made in evaluating the axial compressive strength of concrete filled tabular columns. This study further presents a numerical investigation in to the behavior of concrete filled tabular columns using three dimensional nonlinear finite element software ABAQUS 6.13. The proposed finite element model is validated by comparing its results with those of the corresponding experimental specimens. The analytical results obtained are compared with the numerical results obtained from ABAQUS. Both square and circular concrete filled tabular columns having steel tubes of different geometries and in-filled with different grades of concrete chosen from the literature are analyzed and the predicted axial strength obtained from different codes and by finite element analysis are compared. In this study 10rectangular specimens and 4 circular are analyzed.

Keywords: *ABAQUS, CFT column, Finite element method, theoretical equation, Effective slenderness, Eccentricity, Confinement effect.*

I. INTRODUCTION

Concrete filled steel tube columns (CFST) consists of a steel tube filled with concrete. 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.

Due to the benefit of the composite action of the two materials CFST columns provide excellent seismic event resistant properties and other structural properties like high strength, high ductility and large energy absorption capacity. The interaction of the steel tube with the concrete also prevents the local buckling of the steel tube, due to the restraining effect of concrete. The strength of concrete is increased due to the confinement effect provided by the steel tube resulting in less strength reduction, as concrete spading is prevented by the steel tube.

Because of the high seismic performance, the concrete filled steel tabular (CFST) columns are becoming more and more popular in recent years. The precise analytical calculations involve hectic non-linear three dimensional modeling of such structures. So designers prefer to adopt design mechanism provided in different codes like Eurocode- 4, ACI, AISE-LFRD, CESE etc.

According to the previous research on concrete filled steel tabular (CFST) columns by various scholars on the concentric behavior of concrete filled steel tabular columns, the ultimate axial strength of concrete filler steel tabular column is affected by the shape of the cross section, thickness of steel tube. Confining effect is less in square concrete filled tabular (CFST) columns due to tri-axial effect. Since the behavior of the concrete filled tabular columns is mostly affected by the width-to-thickness D/t ratio, slenderness Ratio L/D, and axial load, in this research the accuracy of codes is compared with detailed analytical method.

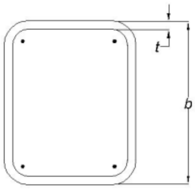
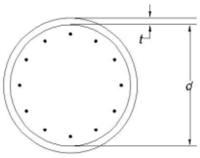
Besides concrete filler tabular columns have many advantages over conventional reinforced concrete columns which make them stronger and economical as well. In concrete filler tabular columns the steel ratio is always higher thus providing more ductility to the structure. The application of form work is completely saved resulting in faster and economical construction with less man power.

II. STRENGTH COMPARISON BY DESIGN CODES

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. The code uses a column curve to determine the effect of slenderness in CFST columns. 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 CFST columns limiting values of the specimen are governed by the equations given in table 1 below.

Table 1

Cross section	Shape	Max (d/t), max (b/t)
Square hollow steel section		$\frac{B}{t} \leq 52\sqrt{\frac{235}{f_y}}$
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 the Euler buckling strength of the composite column, mathematically given by

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

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 η_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.

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

AISC– LRDF:

Code proposes design mechanism for composite structures. According to the LRFD design mechanism it believes that composite materials in a composite structure should act together to resist bending or in other words as one i.e. monolithically. LRFD code takes confinement effect of concrete into consideration in case of circular CFST columns by increasing strength reduction factor from 0.85 in case of rectangular CFST columns to 0.95 in case of circular CFST columns. The code further suggests, the minimum steel required shall be more than 4% in composite elements.

$$\rho_{sr} > 4\%$$

To resist local buckling of steel tubes, the thickness of the steel tubes are governed by the equations

$$\frac{b}{t} = 2.26\sqrt{E/f_y} \quad for\ rectangular\ CFTC$$

$$\frac{D}{t} = 0.15\frac{E}{f_y} \quad for\ circular\ CFTC$$

The ultimate load carrying capacity of both rectangular and circular CFTC is given by

$$P_n = A_s f_y + \emptyset A_c f_c$$

For rectangular CFTC

$$P_n = A_s f_y + 0.85 A_c f_c$$

For circular CFTC

$$P_n = A_s f_y + 0.95 A_c f_c$$

Compressive strength reduction factor has been increased from 0.85 to 0.95 in case of circular CFTC to incorporate the effect of concrete confinement.

As per the ACI- LRFD slenderness ration of CFTC is calculated by

$$P_0 = A_s f_y + 0.85 A_c f_c$$

Also

$$P_e = \frac{\pi^2 (EI_{eff})}{KL^2}$$

$$EI_{eff} = E_s I_s + C_3 E_c I_c$$

Where $C_3 = 0.6 + 2\left(\frac{A_s}{A_c + A_s}\right) \geq 0.9$

$$\lambda = \left(\frac{KL}{\pi}\right)^2 \times \frac{P_0}{EI_{eff}}$$

$$F_{cr} = (0.658^{\lambda}) P_0$$

Where F_{cr} is the Flexural buckling stress

$$P_n = A_s F_{cr}$$

III. NUMERICAL MODELING METHOD

The interaction between the steel tube and the concrete core plays a vital role in making CFST columns structurally better than conventional R.C.C columns and other composite columns. Therefore to effectively replicate the inherent advantages of CFST column, it is necessary that the composite action between steel tube and concrete core be modeled carefully.

A. *Material Modeling:*

ABAQUS creates each material as an individual part and then different parts are assembled using instances option provided in ABAQUS.

B. *Steel Tube:*

In the said model, an elastic-perfectly plastic model is modeled to simulate the steel tube in ABAQUS 6.13. The poisons ratio is taken as 0.3. Other geometric and material details for both rectangular and circular CFST columns are given in table 2 and table 3 respectively.

C. *Concrete Core:*

The Drucker Prager plasticity model available in ABAQUS was adopted for specimens to describe the plastic stress strain behavior of the confined concrete. The poisons ratio is taken as 0.2. Other geometric and material details for both rectangular and circular CFST columns are given in table 2. And table 3 respectively.

D. *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 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. 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.

E. *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 and rectangular geometry generated in ABAQUS are illustrated in figure 1 and figure 2 respectively.

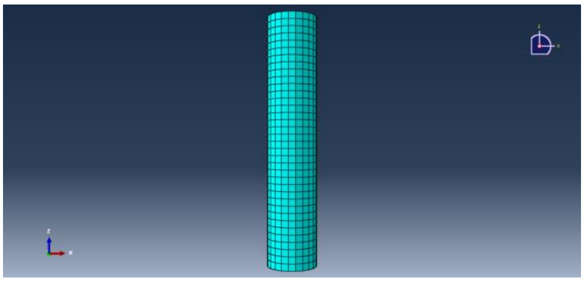


Fig 1 Meshing of Circular CFST Column

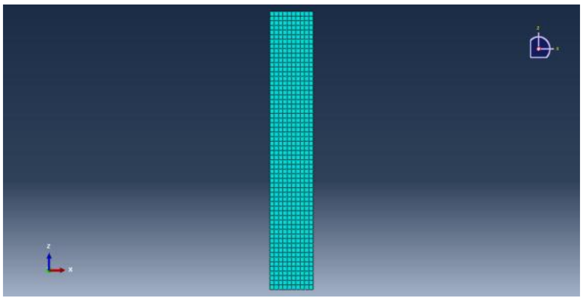


Fig 2 Meshing of Rectangular CFST Column

F. Analysis Type:

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 cater 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 figure 3.

G. 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 figure 4 and figure 5.

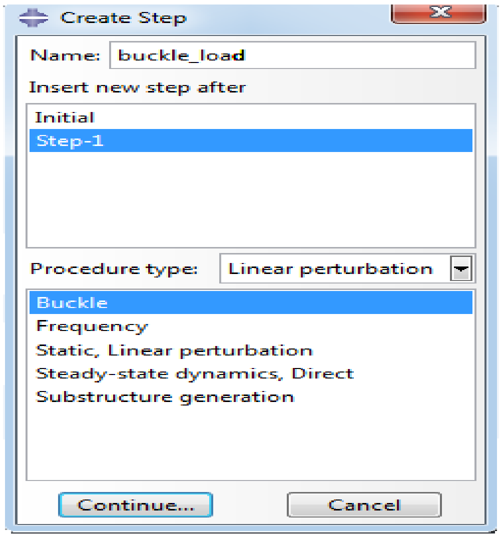


Fig 3

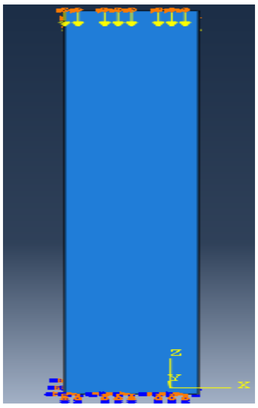


Fig 4

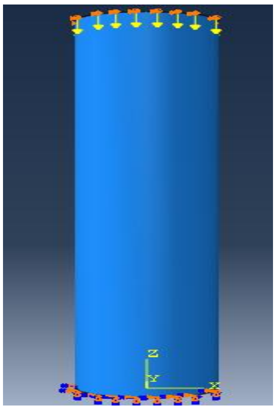


Fig 5

IV. RESULTS

The results obtained are tabulated in table 4 and 5 for rectangular CFST columns and circular CFST columns respectively. Figures 6 to 7 provide the final buckled shape of the concrete filled tabular columns simulated in ABAQUS 6.13.

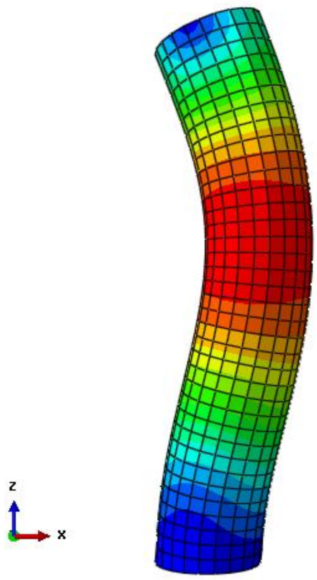


Fig 6

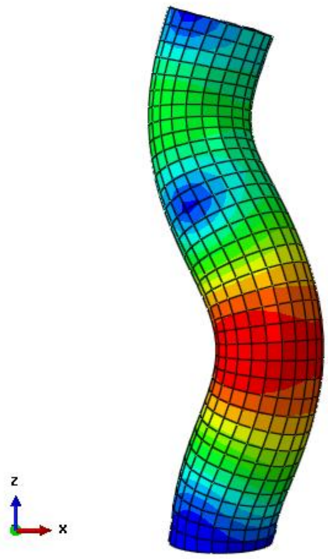


Fig 7

Table 2 Geometric and Material Details of Rectangular Specimen

Specimen label	Tested by	B (mm)	H (mm)	t (mm)	L/B	B/t	L (mm)	F_c (Mpa)	F_y (Mpa)	E_s (Gpa)
DF3	Neogi & Chapman	114.3	114.3	9.63	3.55	11.9	406	32.6	258	203
DF4		114.9	114.9	4.39	3.53	26.2	406	32.6	258	203
1A	Tomii & Sakino	100	100	2.29	3.00	43.7	300	32	194.2	206
1B		100	100	2.29	3.00	43.7	300	32	194.2	206
2A		100	100	2.2	3.00	45.5	300	21.4	339.4	214
2B		100	100	2.2	3.00	45.5	300	21.4	339.4	214
4A		100	100	2.99	3.00	33.4	300	20.6	288.4	206
3B		100	100	2.99	3.00	33.4	300	20.6	288.4	206
4A		100	100	4.25	3.00	23.5	300	19.8	284.5	226
4B		100	100	4.25	3.00	23.5	300	19.8	284.5	226

Table 3 Geometric and Material Details of Circular Specimen

Specimen label	Tested by	Dia (mm)	t (mm)	D/t	L/D	L (mm)	F_c (Mpa)	F_y (Mpa)	E_s (Gpa)
1-3Y6	Cheng	165.00	4.50	36.7	4.00	660	33.2	254.4	200
2-3Y4		114.00	4.50	25.3	4.00	456	33.2	271	200
3-3Y3		88.50	4.00	22.1	4.00	354	33.2	232	200
4-3Y2		60.00	3.50	17.1	4.00	240	33.2	223	200

Table 4 Comparison of Capacities Rectangular Specimen

Specimen label	Tested by	Test load (Mpa)	EC-4		AISC-LRFD		ABAQUS	
			Pu (Mpa)	% error	Pu (Mpa)	% error	Pu (Mpa)	% error
DF3	Neogi & Chapman	2442	1335	-45	1284	-47	2492	+2
DF4		897	868	-3	808	-10	903	+0.6
1A	Tomii &	497.4	465	-6.5	420	-15.5	482	-3.0

	sakino							
1B		498	465	-6.5	420	-15.5	482	-3.0
2A		511	488	-4.5	457	-10.5	502	-1.7
2B		510	488	-4.3	457	-10.4	502	-1.6
4A		529	517	-2.2	488	-7.7	517	-2.2
3B		528	517	-2.1	488	-7.6	517	-2.1
4A		667	629	-5.7	602	-9.7	658	-1.3
4B		666	629	-5.5	602	-9.6	658	-1.2

Table 5 Comparison of Capacities Circular Specimen

Specimen label	Tested by	Test load (Mpa)	EC-4		AISC-LRFD		ABAQUS	
			Pu (Mpa)	% error	Pu (Mpa)	% error	Pu (Mpa)	% error
1-3Y6		1647	1426	-13.4	1142	-30.6	1607	-2.4
2-3Y4		1033	856	-17.1	686	-33.6	1089	+5.1
3-3Y3		602	505	-16.1	403	-33.0	635	+5.2
4-3Y2		334	261	-21.8	206	-38.3	301	-9.9

V. CONCLUSION

1. The lateral deformation strength and the nominal squash load are enhanced by the confinement effect on concrete, this enhancement depends upon the tube strength.
2. With the increase in the length of CFST column, load carrying capacity decreases.
3. The Eurocode-4 design method considers the influence of load eccentricity and slenderness ratio on the confinement effect.
4. Load carrying capacity of CFST columns decreases with increase in D/t ratio.
5. The results shows unconfined columns buckle more than confined counterparts (CFST).
6. Comparison between Eurocode-4 and AISC-LRFD shows AISC-LRDF is more conservative.
7. Slenderness ratio plays vital role in the strength calculation of column and its behavior. As the slenderness ratio increases, the ultimate strength decreases.
8. The model is found to work equally well for thin steel tubes and thick steel tubes.
9. The variation between experimental and numerically simulated results was varying within the range of ±5% except for one circular specimen 4-3Y2 -9.9%.

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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
F_{cr}	Flexural buckling stress
I_c	Moment of inertia of section for concrete
I_s	Moment of inertia of section for steel
K	Effective length factor
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
P_n	Design axial load strength
P_0	Nominal axial load strength
r	Radius of gyration
t	Thickness of steel tube
$\bar{\lambda}$	Relative slenderness
x	Confinement effect
f1	Slenderness effect reduction factor
f2	Eccentric loading reduction factor
h_1 & h_2	Factors considering confinement effect of circular columns in EC4
r_{cr}	Steel contribution ratio
c	Column buckling reduction factor
Ø	A factor considering the influence of internal axial reinforcing bars in EC4