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Finite Element Analysis of Slender Composite Column Subjected to Eccentric Loading

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Abstract

In recent times, steel-concrete composite construction being widely used to meet performance and functional requirements of mid to high-rise structures as well as large span structures. These structures acquire the structural and constructional advantages of both concrete and steel. A steel-concrete composite column is a compression member which can be found either as concrete filled tubular steel section or a concrete encased steel section. This paper discusses the behavior of slender concrete filled steel tube column subjected to eccentric loading using finite element analysis. Finite element package ABAQUS 6.13-1 is used to analyze the load carrying capacity of the composite columns. A general non-linear procedure is adopted for the prediction of mid height deflection and axial load carrying capacity with varying eccentricity. The study considers square concrete filled steel tube cross-sections with different lengths (from 4.5m to 9m), length to depth ratios (slenderness ratios of L/D, from 27.41 to 57.92) and thickness of the steel tube (from 2.7mm to 7.1mm), steel reinforcement ratio (from 1.5 to 4) and depth to thickness ratio (D/t, from 23.13 to 56.74). All columns are isolated, laterally braced with 150 mm internal diameter and axially loaded with eccentricity (from 0 mm to 164.2 mm). The result shows composite column with smaller eccentricity, large cross-sectional area and large thickness of steel tube can carry higher maximum load. Due to the increment of eccentricity (from 0 mm to 157 mm) the load carrying capacity decreases (from 0% to 32.71%).

Key words: concrete steel tube, eccentric loading, ABAQUS, material non-linearity, Finite element Analysis

INTRODUCTION

During the last few years, steel-concrete composite elements became widespread systems in high rise buildings due to their higher load-carrying capacity and stiffness. Compared to steel structures or traditional concrete, composite steel-concrete construction has gained more advantages such as high load carrying capacity, admirable structural integrity, excellent structural and dimensional stability.

In multi-story commercial buildings and factories the most important and frequently encountered combination of construction materials is that of steel and concrete, with applications in vast areas. Structural steel has high strength, high ductility, high stiffness (modulus of elasticity), faster erection speed and very good floor finishing. Reinforced concrete provides high rigidity, excellent fire resistance, low cost, Greater workability and durability.

Several configurations of composite columns exist. The most basic and common are steel –encased concrete column (SRC) and concrete-filled steel tubes (CFT). Steel –encased concrete column (SRC) is a steel shape which is enclosed with a concrete column and concrete-filled steel tubes (CFT) is an outer tube which is filled with concrete. Concrete-steel tubes are generally designated by the shape of steel tube such as rectangular concrete-filled steel tubes (RCFT), circular concrete-filled steel tubes (CCFT) or partially encased sections (steel sections partially covered by concrete).

The interactive and integral behavior of concrete and the structural steel elements makes the composite column a very cost-effective and structurally efficient member.

In this research concrete-filled steel tubes (CFT) are considered because they result in material with excellent performance because of the confining effect of steel on the concrete and they can also be employed in construction easily. The steel tube in CFT is used as longitudinal and confining reinforcement so that usual reinforcement for a composite column may not be used because these steel tubes serve as a form work for the concrete.

Composite columns can be made up of various configurations. They have been classified in to two general types in terms of the position of steel and concrete as follows

- Encased or steel reinforced concrete elements, where the steel section is embedded or encased by the concrete; in other words, the concrete section is reinforced by a rolled or a built-up steel section.
- Concrete-filled steel tube, where the steel is a rolled or built-up hollow section filled with concrete.

Figure 1: Concrete encased section

Figure 2: Concrete filled hollow section

OBJECTIVE OF WORK

The general objective of this research was to simulate a non-linear 3D finite element analysis model of various sizes of composite columns with different slenderness ratio and steel reinforcement ratio subjected to eccentric loading. The expected outputs of this analysis are in the form of charts where different cross section of composite columns with different eccentricity loading are compared.

SCOPE

The presented research is limited to eccentric loading character of slender column which is steel tube filled by concrete. The scope will extend to cover the analysis only by using FEM method and it discuss only point load carrying capability of slender column which is steel tube filled by concrete. Furthermore there is no physical testing concrete filled steel tube column.

LITERATURE REVIEW

Ellobody et al [4] studied the responses of concrete encased steel composite columns to eccentric loads acting along the major axis. Many variables that influence the response, such as the concrete strength, the steel section yield stresses, eccentricities, column dimensions and structural steel sizes were investigated. A three dimensional finite element analysis using ABAQUS was developed and validated against experimental result. Eccentric load-concrete strength curves, axial load-moment curves, and ultimate capacity were obtained. The results showed that the increase in steel section yield stress had significant effect on the strength of composite column under small eccentric loads with concrete lower than 70 MPa compressive strength. A conclusion was drawn after comparing the results based on Euro code 4 that the eccentric loads were predicted correctly but the moment values were overestimated.

Furthermore, **Ellobody & Young [2]** investigated the effect of varied slenderness ratios, concrete strength and steel yield stress on strength and behaviour of pin-ended axially loaded concrete encased steel composite columns. Their 3D nonlinear finite elements analysis results have been validated against actual tests results. The results demonstrated that the effect of increasing steel yield stress on the composite strength for slender columns is less pronounced because of the flexural buckling failure mode.

On the other hand,**Dundu [3]** conducted an experimental study to investigate the behaviour of concrete-filled steel tube columns,which consisted of a test of 24 specimens loaded concentrically in compression to failure. In this study,slenderness ratio and the strength of materials were considered as main variables.The result has shown that the columns having larger slenderness ratios failed by overall flexural buckling. Whereas the composite columns that have lower slenderness ratio failed by crushing of the concrete and yielding of the steel tube. The test results were compared with Eurocode 4 and the South Africa code and it was observed that the codes are conservative.

MATERIALS

For this study ABAQUS 6.13-1 version was used and all simulations were completed with ABAQUS Standard/ Static General Analysis.

The concrete infill and the steel tube were modeled using solid C3D8R (an 8-node linear brick, reduced integration, hourglass control) element. The loading and supporting rigid plates at the top and bottom of the sample were modeled using a discrete Rigid Element R3D4 (A 4-node 3-D bilinear rigid quadrilateral)

For the analysis a nonlinear behavior of concrete was considered. In this study, plastic behavior of materials was defined and damaged plasticity for model concrete was used.

When no test results are available to determine the stress-strain curve for the concrete, one can use the mean compressive strength f_{cm} to plot the curve. Other quantities needed in order to determine the points on the graph are [5]

$$E_{cm} = 22(0.1\, f_{cm})^{0.3} \quad (1)$$

$$\varepsilon_{c1} = 0.7(\, f_{cm})^{0.31} \quad (2)$$

$$\sigma = f_{cm}\frac{k\eta - \eta^2}{1+(k-2)\eta} \quad (3)$$

$$k = 1.05 E_{cm}\frac{\varepsilon_{c1}}{f_{cm}} \quad (4)$$

$$\eta = \frac{\varepsilon_c}{\varepsilon_{c1}} \quad (5)$$

Where:

f_{cm} is in MPa

E_{cm} is the longitudinal modulus of elasticity

ε_{c1} is strain at avarage compressive strength

ε_{cu} is the ultimate strain (3.5 %)

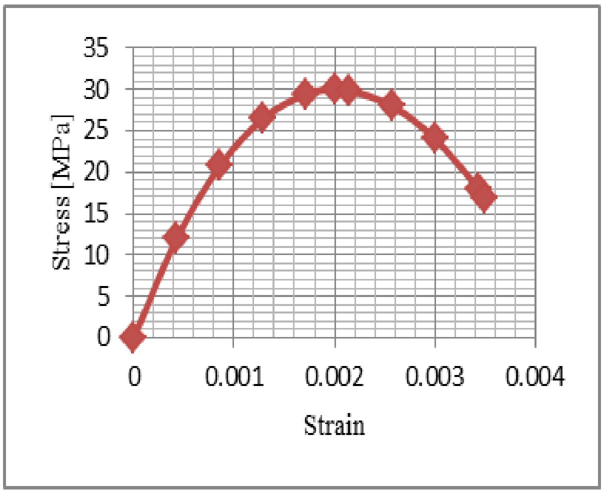

Figure 3: Material curve for compressive behavior of the analyzed concrete

The post-failure behaviour is simulated with tension stiffening by applying a fracture energy cracking criterion. To determine the stress-strain curve for tension, a bilinear crack opening curve is used [6].

$$f_{ctm} = 0.3 f_{ck}^{\frac{2}{3}} \qquad (6)$$

$$f_{cm} = f_{ck} + 8 \qquad (7)$$

$$G_f = 73 f_{cm}^{0.18} \qquad (8)$$

Where f_{cm} is the mean concrete strength [MPa]

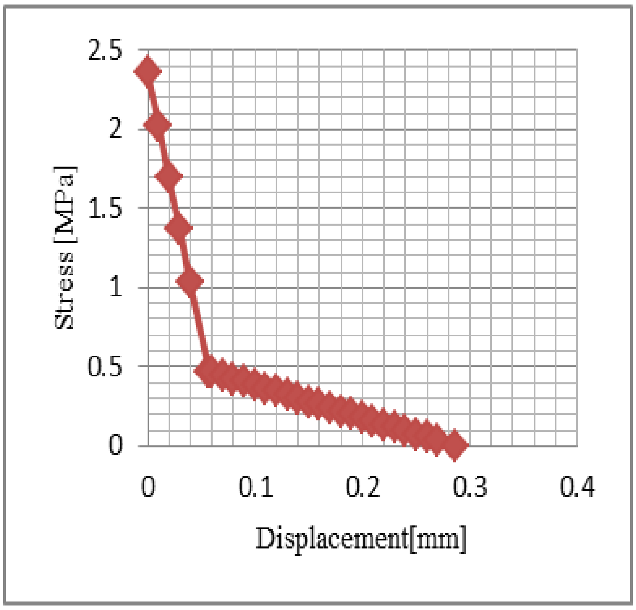

Figure 4: Material curve for tensile behavior of the analyzed concrete

The input variables used in the damage plasticity model in ABAQUS are as follows.

Table 1: input material data for concrete

Density	2400 kg/m^3
Young's modulus	30.58 GPa
Poisson's ratio	0.2
Dilation angle	36
Flow potential Eccentricity (ε)	0.1
f_{bo}/f_{co}	1.16
k	0.667
Viscosity parameter	0

Table 2: Input material data for steel tube

Density	7800 kg/m^3
Young's Modulus	200 GPa
Poisson's ratio	0.3

Table 3: Input values for plastic behavior of structural steel tube

True Stress	Plastic strain
355 MPa	0
355 MPa	0.2

The main characteristics of the finite element model can be summarized as:

- Use of the elastic and plastic properties of material with the Von mises yield criterion in the modeling of steel tube.
- Use of the concrete damaged plasticity model offered by ABAQUS/CAE in modeling of concrete.
- Modeling of both the concrete and steel tube with 8 node solid elements with reduced integration.
- Load increment process governed by static general analysis, while the iterative equation solving is based on Full Newton –Raphson methods.
- All the loads are applied using displacement control

MODELING OF CFST COLUMN

Design of parametric study

The column cross-section for concrete core was fixed at 150 x 150 mm.18 numbers of reference columns were modeled with varying steel tube thickness, steel reinforcement ratio, length of column and depth to thickness ratio.

The global stability of the column is controlled by the overall slenderness ratio. 18 numbers of different slenderness ratio (27.41-57.92) were employed in the parametric study to cover the wide range of slender columns. The study also considered square concrete filled steel tube cross-sections with different lengths (4.5m-9m) ,thickness of steel tube (2.7mm-7.1mm), steel reinforcement ratio (1.5-4) and depth to thickness ratio (D/t, 23.13-56.74).

All cross-sections have been done by using finite element software ABAQUS. Cross-sectional properties of the columns are taken from universal column table, hollow square section properties and all steel tube thickness less than 40mm as specified in Euro code.

The geometry of the model consists of four independent components, as shown in Figure 5., the interaction of which is idealized using tie constraints. The square steel tube, with the thickness t, length L and the square concrete core with depth, width and length, with two rigid plates at the top and bottom. No clearance exists between the concrete core and steel tube. The purpose of placing the rigid plates on the top and bottom is to simulate the real conditions of the composite column.

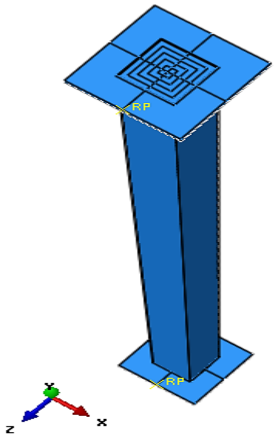

Figure 5: Three-dimensional square concrete filled steel tube

During the initial steps, boundary conditions were defined and static general step loading was used. Large strains and displacements were considered in the analyses in order to include second-order effects. Total time period was set to 1. Different time increments were tested awaiting convergence. Apart from the interaction between the inner surface of the steel tube and the outer surface of the concrete core, tie constraints are defined. In general eight tie constraint pairs are set.

1) Bottom part of the upper loading discrete rigid plate with top part of steel tube
2) Bottom part of the upper loading discrete rigid plate with top part of concrete block
3) top part of the bottom discrete rigid plate with bottom part of steel tube
4) top part of the bottom discrete rigid plate with bottom part of concrete block
5) exterior surface of concrete block with interior surface of steel tube in 1^{st} face
6) exterior surface of concrete block with interior surface of steel tube in 2^{nd} face
7) exterior surface of concrete block with interior surface of steel tube in 3^{rd} face
8) exterior surface of concrete block with interior surface of steel tube in 4^{th} face

Pinned-pinned condition were modeled by restraining reference points in the displacement in x, and z-directions but allowing for the displacement in the y direction.

The interface between steel and concrete was assumed to be fully bonded and hence tie constraints were adopted.

In order to decide on how to apply the load, comparison is made between loading control and displacement control, as shown in Figure 6 and 7 respectively. It is observed that when the load is applied as a point load, it is not possible to obtain a displacement with respect to the peak load. However, when a point displacement is applied the peak load and the corresponding displacements are easily obtained and there is a softening behavior following the post peak load.

This may be explained by the modified Newton-Raphson solution technique used, which only captures a minimum of zero tangent stiffness of the system. Figure 8. shows a close look at the two methods for an eccentricity of 15 mm.

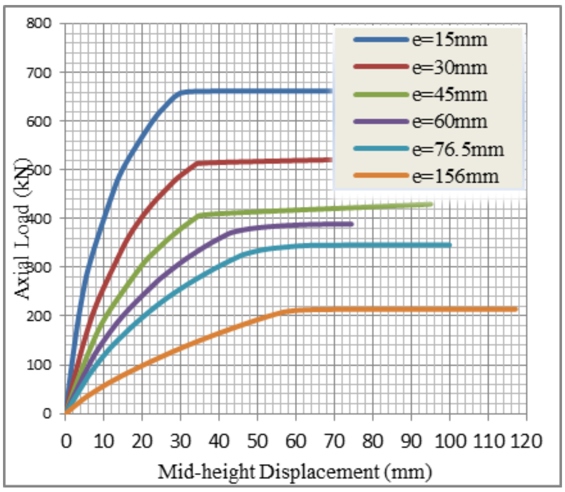

Figure 6: Load-Displacement curve for (H=4500mm, D=156mm, d=150mm, ω=1.5, t=3mm, Loading plate=312mm,Base plate=312mm,(Applied Load=4000kN)

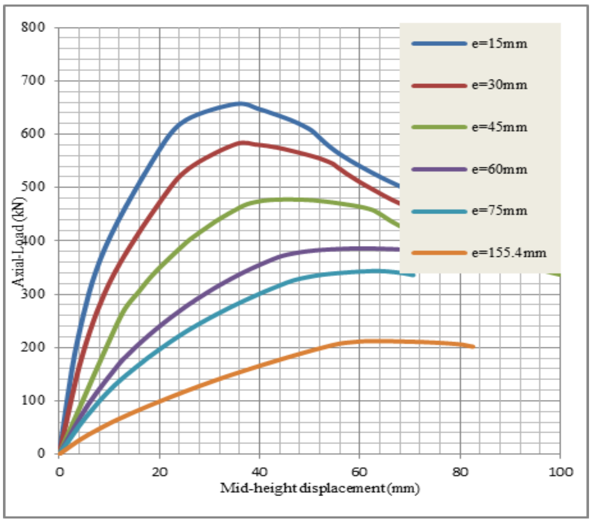

Figure 7: Load-Displacement curve for (H=4500mm,D=155.4mm,d=150mm,ω=1.5,t=2.7mm,Loading plate=310.8mm,Base plate=310.8mm,Applied Load(displacement=100mm)

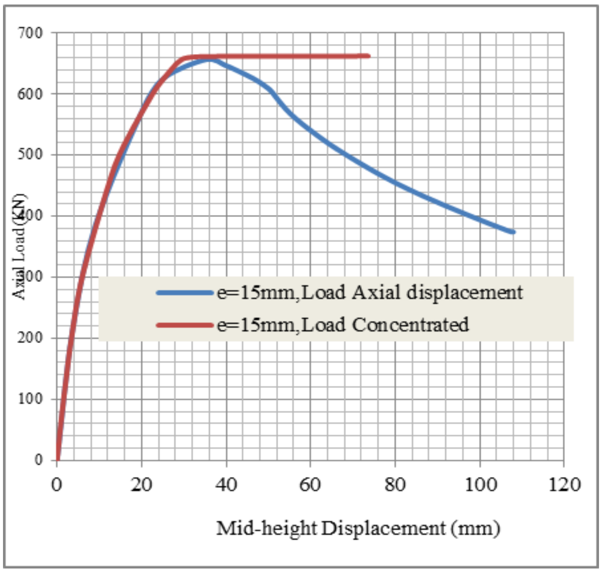

Figure 8: Comparison of ABAQUS result in terms of Application of Load, Concentrated Load with Axial displacement.

In the analysis presented in this document, the element type C3D8R was used for meshing of concrete and steel tube. The element type R3D4 was used for meshing of loading and supporting plates which are found at the top and bottom of the sample.

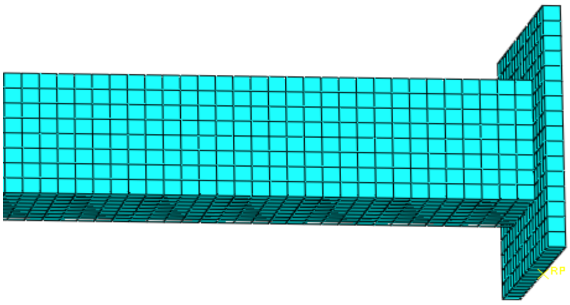

Figure 9: Diagram of sample column which is meshed

To get an accurate result similar mesh size was used for all elements. The mesh size was chosen based on a convergence analysis, and was set at 0.02m. This element size gives a relative accurate result, combined with reasonable running time for the model.

VALIDATION OF THE MODEL:

The analytical model was validated in comparison to an experimental research on Axial capacity of circular concrete filled steel tube columns done by Georgis Giakoumelis and Dennis Lam[12]. A difference of 12%-15% was noted in the validation results which occurred mainly due to the difference in mix standards practiced in different countries.

RESULTS AND DISCUSSION

In this study five results have been discussed: the Von mises stresses, concrete compression damage, concrete tension damaged, and the reaction at the top/bottom boundary and mid height displacement of square concrete filled steel tube.

The results presented in the figure 10. are taken from finite element analysis with a mesh size of 0.02m. In these sections the finite element results discussed are yield stress of steel tube, compression and tension damage of concrete and the mid height displacement of square concrete filled steel tube.

Figure 10. shows that the von mises stress of square composite column when eccentricity equal to 15 mm. As expected the maximum stress at the center and the von mises stresses have reached yield stress of steel tube.

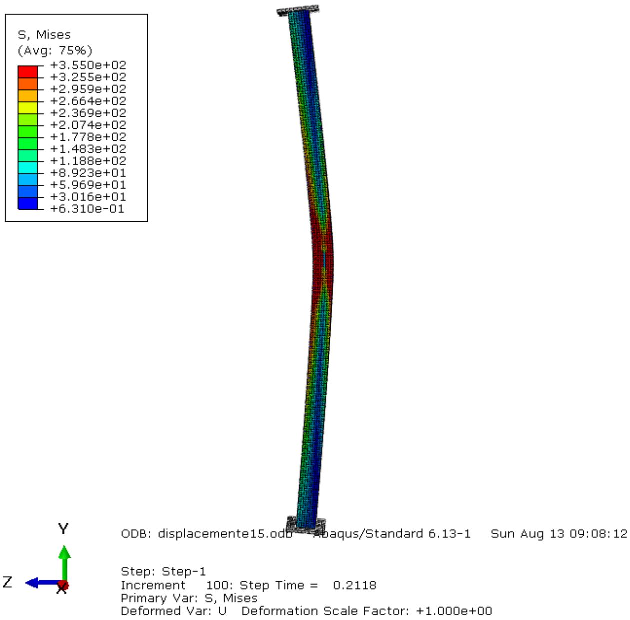

Figure 10: Stress components and invariants

In the damage plasticity model used in this study, tensile cracking and the compressive crushing failure mechanisms are used. Concrete fails by both compressive and tensile damage. Figure 11, shows that the crack appeared at mid height of column the failure is compression damaged, this results decreasing of the carrying capacity of the concrete, which results in early failure.

As it is seen in Figure 12, the mid height of composite column was damaged by tension. In addition to this, Figure 13, shows the load-mid height deflection square concrete filled steel tube column. The maximum horizontal displacement occurs at the mid height of the composite column which is expected since the support condition pin-pin ended.

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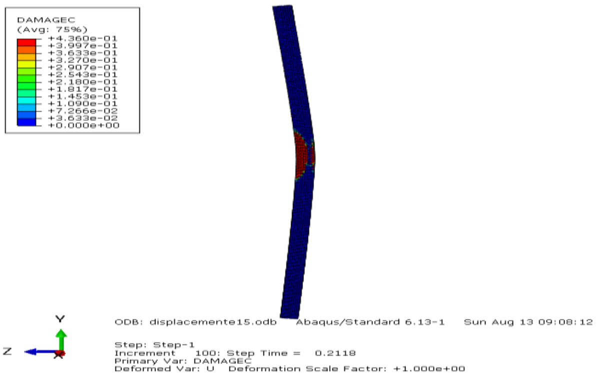

Figure 11: Crack pattern, compression damage

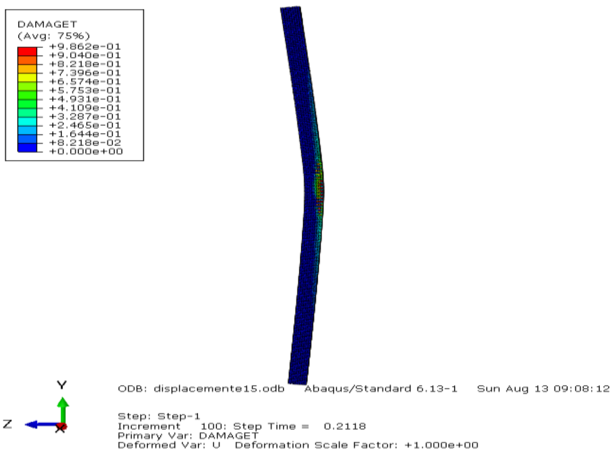

Figure 12: Crack pattern, tensile damage

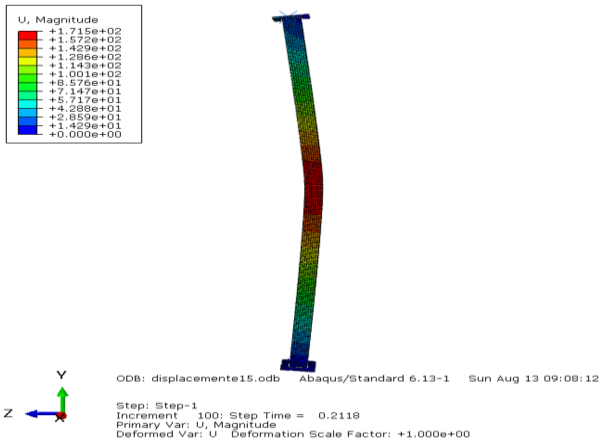

Figure 13: Visualization of mid height deflection

Finite Element Results of All Square CFST

18 squares CFST columns with different cases are modeled with a total of 144. All 18 columns were modeled with the same material input data for both steel and concrete. Also the same discretization technique is used for mesh, analysis technique and loading and boundary conditions. The load – displacement diagram for each case is monitored, a typical of which is shown in Figure 14.

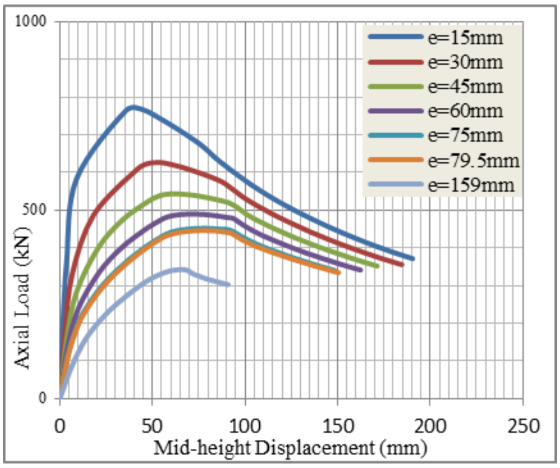

Figure 14: Load-Displacement curve for (H=6000mm,D=159mm,d=150mm,ω=2.5, t=4.5mm,Loading plate=318mm,Base plate=318mm

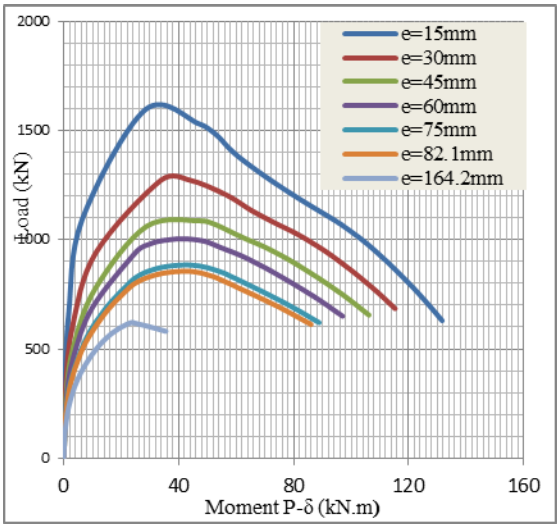

Figure 15: Axial load with moment curve for SC-6 column.

Effect of Selected Parameters on Column Response

The independent variables can significantly affect the behavior of slender CFST columns. These include overall column slenderness ratio, length of column, steel tube thickness and steel reinforcement ratio.

Effect of column slenderness effect (L/D) on SCFST column

The global stability of the column is controlled by the overall slenderness ratio, Figure 16, shows the effect of overall column slenderness (L/D) ratio on the load-displacement response of the column. When overall slenderness ratio increases, the ultimate load capacity is reduced by 33.8% to 67.1%, respectively for L/D of 38.61 and 57.92. This Figure 16, shows while the overall slenderness increases to decreases strength of the CFT column.

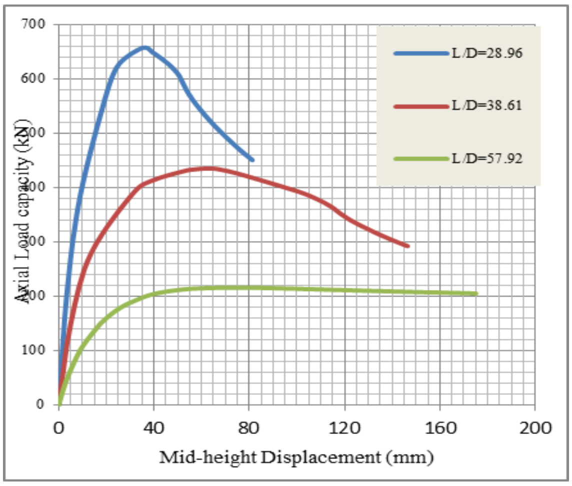

Figure 16: Load-Mid height displacement curve of selected square composite column with e=15mm

Effect of length of column on SCFST column

The size of CFT columns may have a significant effect on the strength of such columns. Figure 17, shows that length of column to increases, mid height displacement increases and the strength of the column decreases. Figure 18, shows for the same load location (eccentricity) the stiffness of the system decreases as the length increases resulting in large displacement at peak load.

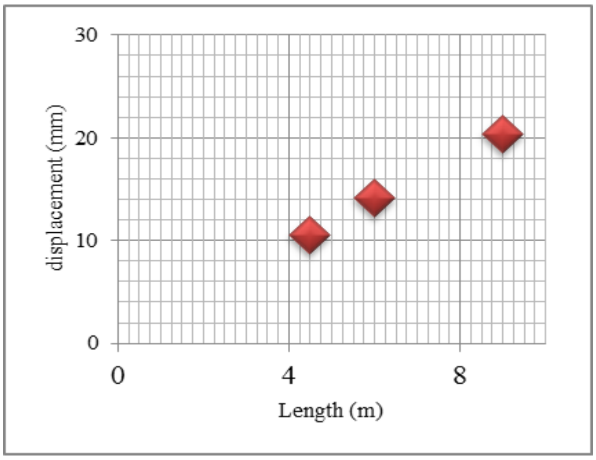

Figure 17: End displacement with length, e=0

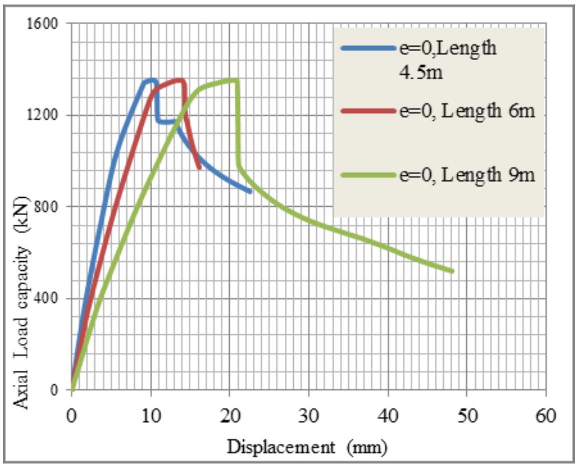

Figure 18: Axial load capacity variation with column length and displacement.

CONCLUSION

The results were first standardized by comparing with the results from experimental study conducted by other researchers and Euro code.

From the results the following conclusions were derived:

- In this study a total of 144 different square concrete filled steel tube composite column with large slenderness ratio (L/D>15, 27.41-57.92) were analyzed. The load carrying capacity decreases with increase in slenderness ratio.
- The result shows composite column with smaller eccentricity, large cross-sectional area and large thickness of steel tube can carry higher maximum load.
- Due to the increment of eccentricity (from 0 mm to 157mm) the load carrying capacity decreases (from 0% to 32.71%).
- While length increases (from 4.5 m to 9m) the mid height displacement increases from 0% to 48%.
- When the eccentricity is fixed (e =0 mm) and cross sectional area is the same, but the length vary from 4.5m to 9m , the axial load carrying capacity of composite column vary from 0 to 0.4%.

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