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Nonlinear 3D Finite Element Model for Round Composite Columns under Various Eccentricity Loads

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HIGHLIGHTS

- The results of ABAQUS show that increasing eccentricity for applied loads causes the decreasing loads to fail for composed columns.
- The ultimate load of hollow composite sections under eccentricity is lower than solid composite sections under different eccentricity loads. Also, the same results indicated an increased number of steel layers.
- The increase in compressive strength of concrete enhanced the composite column's stiffness.
- The finite element results are in good agreement with the experimental results.

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Eccentricity; CFSP (concrete filled steel pipe); FEM; loading; compressive strength.

ABSTRACT

Composite columns are often used in constructing high-rise structures because they can reduce the size of a building's columns while increasing the usable area in the floor plan. This research aimed to develop a nonlinear 3D finite element analysis model using the ABAQUS, version 6.13-4, of various round composite column designs with varied multi-skin of tubes for solid and hollow columns subjected to various eccentricity loads (90, 180 mm). Extended data to another 12 specimens of composite columns by numerical method, based on six references experimental data of composite columns. The results of ABAQUS data in this study show that; increasing eccentricity for applied loads causes a decrease in loads to fail for composed columns. The ultimate load of hollow composite sections under eccentricity is lower than solid composite sections under different eccentricity loads. Also, the same results indicated fort eccentricity loads. The same results indicated an increased number of steel layers. The stiffness of concrete is greatly influenced by its strength. When the concrete strength rises, the stiffness of the composite column rises as well. The ratios of concrete compressive strength values according to the reference column (CC1S00 with fc'=31.96 MPa) were (-4.4, 3.1, and 6.5) percent for the specimen (CC1S00) with (fc'=25, 35, and 40) MPa, respectively. The method utilized is in the nonlinear analysis, and the finite element results are in good agreement with the experimental results.

1. Introduction

Steel-concrete composite structures have become common in the past few years because of their greater load-caring capacity and stiffness. Due to its strong structural performance could be used in bridges, high-rise buildings, viaducts, and electrical transmission towers compared to steel or classic concrete constructions [1], [2]. The advantages of both steel and concrete elements are optimally combined in the composite structure. Composite columns are extensively utilized in developing high-rise structures because they can decrease the size of the building's columns while maximizing the floor plan's usable space. Furthermore, the composite column improves the building's overall rigidity. It provides excellent shear resistance against powerful earthquakes and other lateral stresses [3]. Finite element modeling in ABAQUS 6.13-4 is a 3D nonlinear analysis technique that applies numerical solutions to simulate and detect faults in composite structural elements [4]. The most effective nonlinear finite element model for evaluating hollow and solid composite columns with multi-layers of HSS (hollow steel structure) steel pipe under compression is studied in this work. Alaa Mahdi Al-Khekany et al. test findings will be used to validate the ABAQUS 6.13-4 software results. Then, based on the results of that correction factor obtained as a result of the finite element software and experimental data by Alaa Mahdi Al-Khekany et al., we expanded the data of the composite

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column under different eccentricity loads (90, 180mm) and various compressive strengths of concrete by 3D nonlinear analysis. ABAQUS 6.13-4 software [5]. Previously, many researchers have studied composite columns, such as Yonas T.Y. et al. [6] ABAQUS/static general analysis was used to model 18 different reference columns. The steel tube thickness, steel reinforcement ratio, column length, and depth to thickness ratio of 18 different reference columns varied. The results show that a composite column with a smaller eccentricity, a larger cross-sectional area, and a larger steel tube thickness may support a more load. The load-carrying capacity reduces as eccentricity increases, and the mid-height displacement increases as the length increases. In Beiranvand et al.[7], this work proposes a nonlinear 3-D finite element model for eccentrically loaded (10 number) concrete encased steel composite columns based on numerical simulations using the ABAQUS program. The interaction between the steel segment and the concrete was considered in the model. Different column dimensions, structural steel sizes, concrete strengths, and steel yield stresses are considered. When the eccentricity is reduced, increasing the ultimate acceptable load in the section by increasing concrete strength will have a considerable effect.

Thunga Kartheek & T. Venkat Das [3] the ABAQUS simulation of fully encased composite columns was compared to reinforced concrete columns of various concrete strengths. Axial load capacity deformation, stress, and strain patterns are determined for reinforced concrete and composite columns with I-section steel confinement. ABAQUS software can be used to determine the behavior of composite and reinforced concrete columns using the finite element method. According to the findings, reinforced concrete columns are less resistant to ultimate axial load than fully encased composite columns. Mohamed et al.[8] The experimental test results and nonlinear finite element modeling of an experimental test program on concrete-filled steel tube CFST columns with longitudinal stiffeners as a proposed method to enhance CFST capacity are presented in this research. The validated numerical model is used to expand the study to include additional parameters affecting the design of CFST columns. The results show that adding longitudinal stiffeners increases load-carrying capacity slightly, which may stimulate the use of such a system to improve the load-carrying capacity of existing CFST columns. Mohammed Salem and Muhammad Shekaib [9] propose a mathematical model for analyzing uniaxial and biaxial reinforced concrete columns. This proposed model is a rapid and straightforward method for analyzing and designing reinforced concrete columns that do not require interaction charts. Computer software is also used to analyze the analyzed columns. The average difference between the mathematically derived values and the finite element software is less than 10%, indicating promising computational results.

The overall goal of this study was to create a nonlinear 3D finite element analysis model of various round composite columns with varying multi-skin of tubes for solid and hollow columns subjected to different eccentricity loads. Also, investigate the effect of the compressive strength of concrete on the modeling of composite columns.

2. Materials and Methods

The ABAQUS 6.13-4 version was utilized in this work, and all simulations were run using ABAQUS 6.13-4 standard/explicit model 3D Nonlinear Analysis. The steel tube was modeled by shell homogeneous Quad-dominated (Element Type for Meshing process), and the concrete infill was modeled by solid homogeneous Hex (Element Type for Meshing process) as shown in Figures (1, 2) [10].

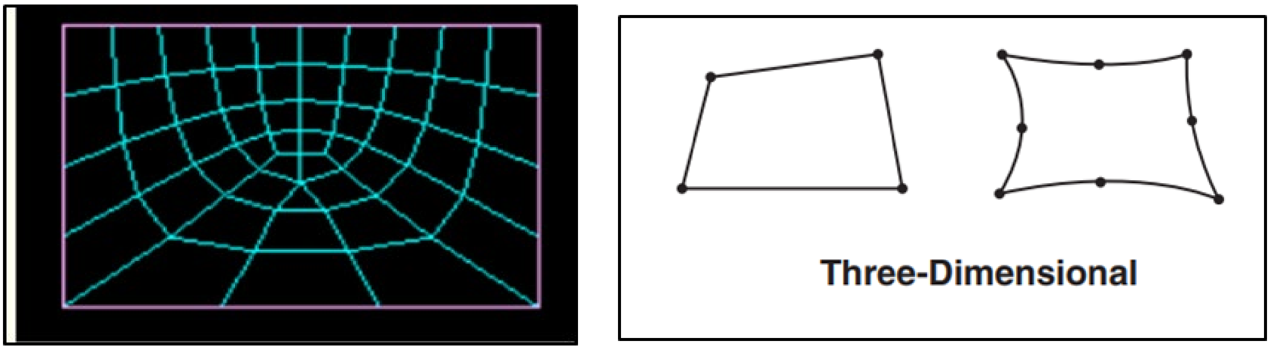

Figure 1: Element shape (Quad-dominated) for Meshing steel tube.[10]

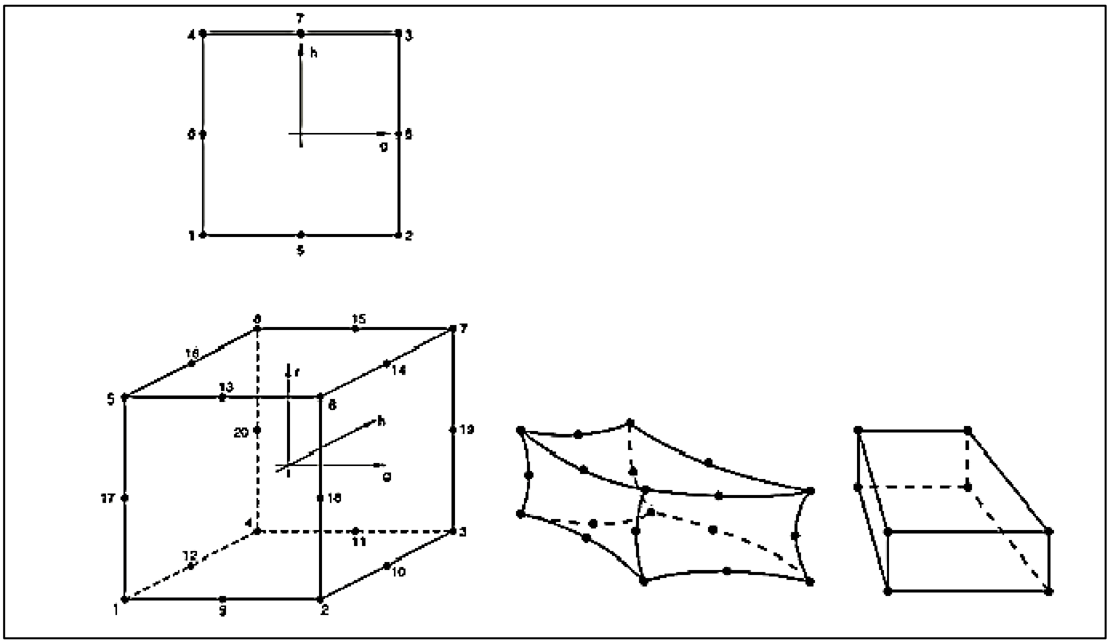

Figure 2: Element shape (Hex) for Meshing Concrete. [10]

A discrete rigid element was used to model the rigid supporting plates at the top and bottom of the samples. The plastic behavior of materials, as defined in this study, and model concrete with deteriorated plasticity was used. From the equation (1,2,3,4 and 5), the stress-strain curve can determine the mean compressive strength fcm can be used to draw the curve; also, the stress-strain relation for concrete and steel under uniaxial load for tension and compression can be illustrated in Figure(3, 4) [11]. Based on Experimental results by Alaa Mahdi Al-Khekany et al. [5]. The following are the input data for the ABAQUS 6.13-4 damage plasticity model as shown in Tables (1, 2, and 3).

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

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

$$\sigma = f_c\,(k\eta - \eta^2)/(1+(k-2)\eta) \quad (3)$$

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

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

where: f_{cm} is in MPaE_{cm} is the longitudinal modulus of elasticityε_{c1} is the strain at the average compressive strength ε_{cu} is the ultimate strain (3.5%)

The compressive behavior of concrete with the tensile behavior of steel tube is shown in Figures (2 and 3).

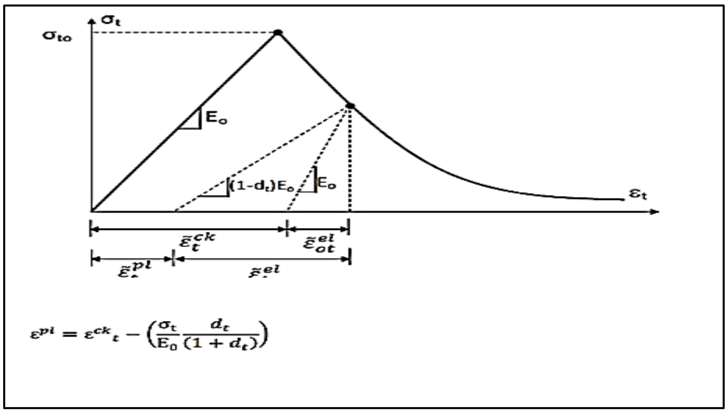

Figure 3: Tension behavior for concrete in ABAQUS [11]

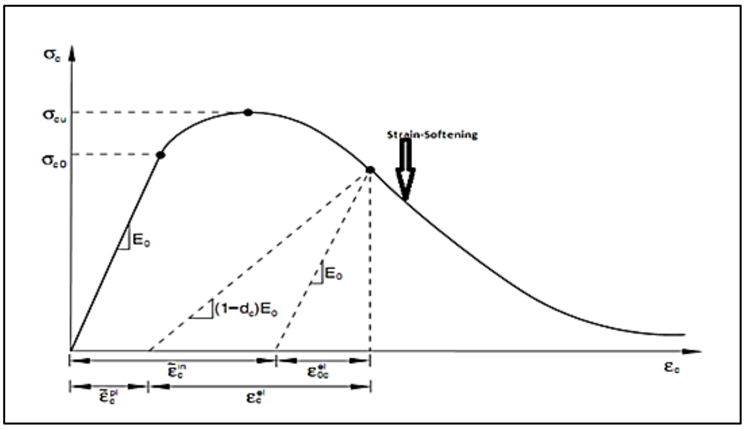

Figure 4: Compression behavior for concrete in ABAQUS [11]

Table 1: Concrete property material data

Property	Amount
Density (ɣ)	24000 N/m^3
Compressive strength of concrete (f'_c)	31.96E6 N/m^2
Young's modulus (E)	20000 N/m^2
Poisson's ratio (ɳ)	0.2
Dilation Angle	30
Flow potential Eccentricity (Ɛ)	0.1
* f_{b0}/f_{c0}	1.16
K	0.667
Viscosity parameter	0

* f_{b0}/f_{c0} is a ratio of the strength in the biaxial state to the strength in the uniaxial state

* k can be defined as a function of the void ratio.

Table 2: Steel tube property material data

Property	Amount
Density (ɣ)	78500 N/m^3
Young's modulus (E)	200000 N/m^2
Poisson's ratio (ɳ)	0.3
Thickness (t)	4mm

Table 3: Plastic behavior of steel tube property data

Tensile strength of steel (MPa)	Elongation (mm)
50	0
260	0.25

3. Investigation of Program

The structural behavior of solid and hollow composite columns reinforced with multi-layers of HSS (Hollow Steel Structure) steel pipe under compression is investigated using data of Al- Khekany et al. [5]. Al-Khekany tested six specimens in the laboratory of the Engineering college-Al-Qadisiyah University as part of this research. There are one non-composite and five composite samples. The composite samples were made out of composite standard strength concrete and HSS steel sections with various HSS layers, as shown in Figure 5. The column height in all specimens was 1000mm, and the diameter of the columns was (150mm). The non-composite samples were designated as (CN1H) while the composite samples were (CC2H, CC3H, CC1S, CC2S, and CC3S). The initial letter (C) denotes a round specimen's cross-section. The second letter (C or N) indicates whether the part is composite or non-composite, HSS's layered number is denoted by numbers (1, 2, and 3), and the last letter (S or H) denotes a Solid or Hollow segment. Figure 5 shows the attached specimens.

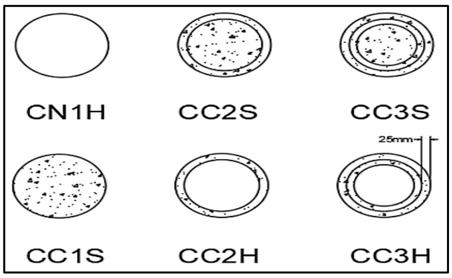

Figure 5: Specimens details [5]

4. Finite Element Modeling

Experimenting with a composite column specimen is both costly and time time-demanding. However, the influence of various parameters on the behavior of such columns can be better understood using finite element analysis. By applying finite element code, ABAQUS 6.13-4 is used to create a numerical model of composite columns. The finite element model incorporated geometric and non-linearity materials.

The composite column cross-section was fixed at 150mm round diameter. Based on six references of composite columns that were tested in the laboratory under concentrically loaded by Al- Khekany et al. and modeled by the ABAQUS 6.13-4 program, therefore compare experimental data with numerical results is shown in Figures (6,7,8,9,10 and 11), provided the correction factor as shown in Table (4). After that, comprehensive data to another Twelve specimens of a composite column by the numerical method were modeled with two varying eccentricity loads (90, 180) mm, different layers of steel layers, and solid and hollow composite columns, as shown in Figure (12, 13, 14, 15, 16, and 17).

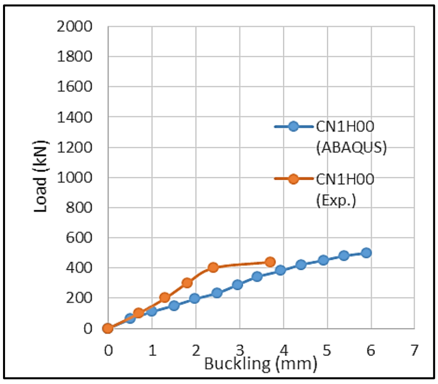

Figure 6: Load-Buckling Curve (CN1H00)

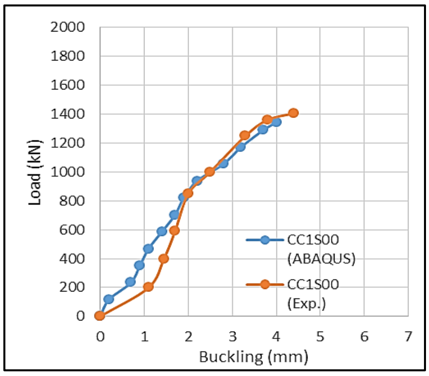

Figure 7: Load-Buckling Curve (CC1S00)

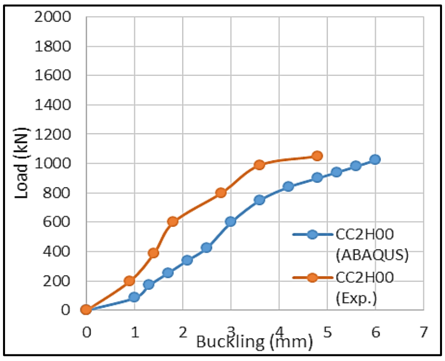

Figure 8: Load-Buckling Curve (CC2H00)

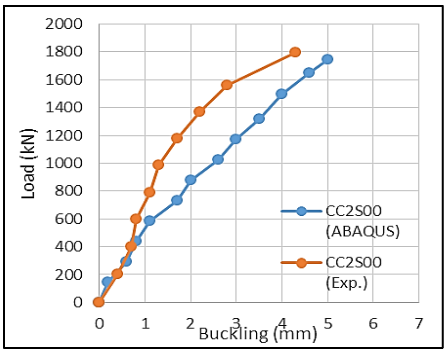

Figure 9: Load-Buckling Curve (CC2S00)

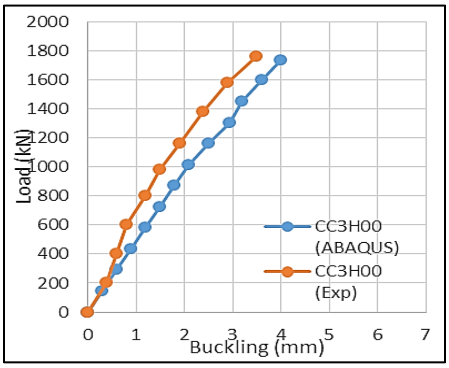

Figure 10: Load-Buckling Curve (CC3H00)

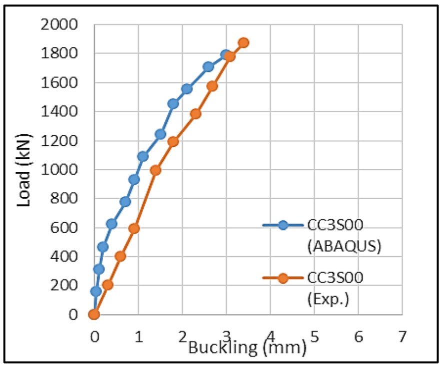

Figure 11: Load-Buckling Curve (CC3S00)

Table 4: Experimental vs. Numerical Results

Specimens	Ultimate loads (kN) Experimental	Ultimate loads (kN) ABAQUS	Difference (%)= (Exp.-ABAQUS.)/Exp.
CN1H00	468	421	10
CC1S00	1406	1344	4.41
CC2H00	1054	980	7.02
CC2S00	1797	1700	5.40
CC3H00	1758	1650	6.14
CC3S00	1875	1680	10.40

*00 refers to the eccentricity of loads as zero.

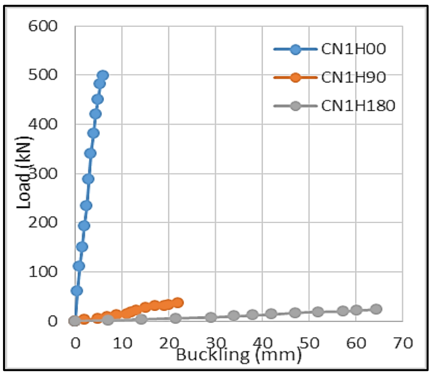

Figure 12: Load-Buckling Curve for CN1H

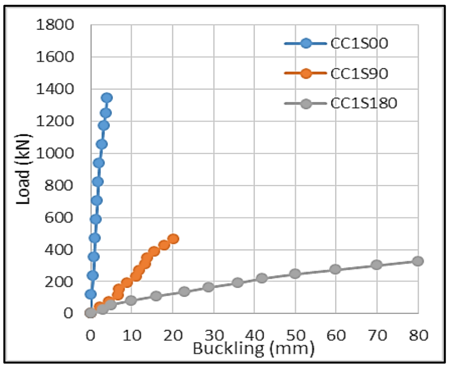

Figure 13: Load-Buckling Curve for CC1S

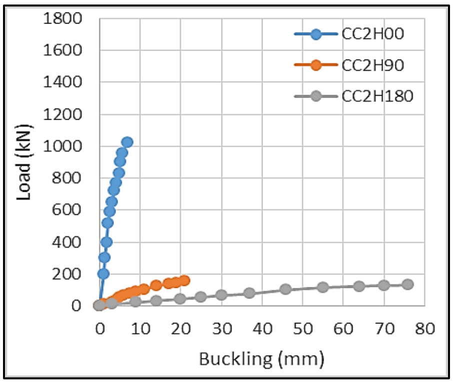

Figure 14: Load-Buckling Curve for CC2H

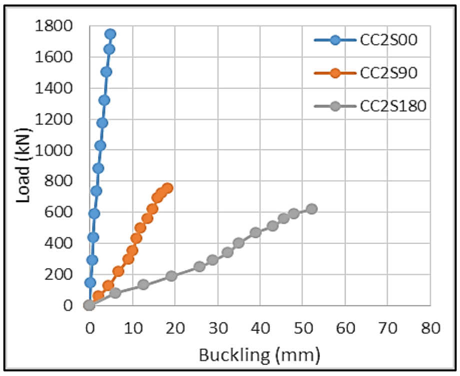

Figure 15: Load-Buckling Curve for CC2S

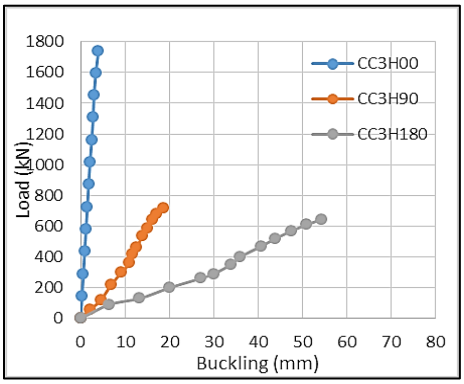

Figure 16: Load-Buckling Curve for CC3H

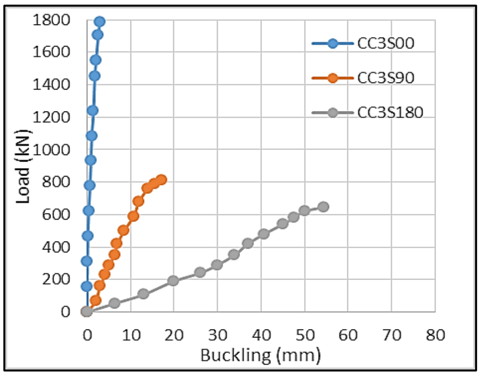

Figure 17: Load-Buckling Curve for CC3S

5. Finite Element Results and Discussion

The numerical results obtained from ABAQUS 6.13-4 program were recorded in Figures (12, 13, 14, 15, 16, and 17), presenting the failure patterns for composite columns tested under eccentricity loads. All specimens failed due to local buckling failure, similar to the laboratory's experimental work by Al- Khekany et al. The tube is filled with concrete, and the section's strength and ductility are increased. As a result, the steel tube's local buckling failure is delayed. In addition, the steel tube confines the concrete inside it. Due to the restraining effect of concrete, the concrete avoids local buckling failure of hollow steel tubes. The modeling failure of the specimen (CC2H) under eccentricity is shown in Figures (18, 19, and 20).

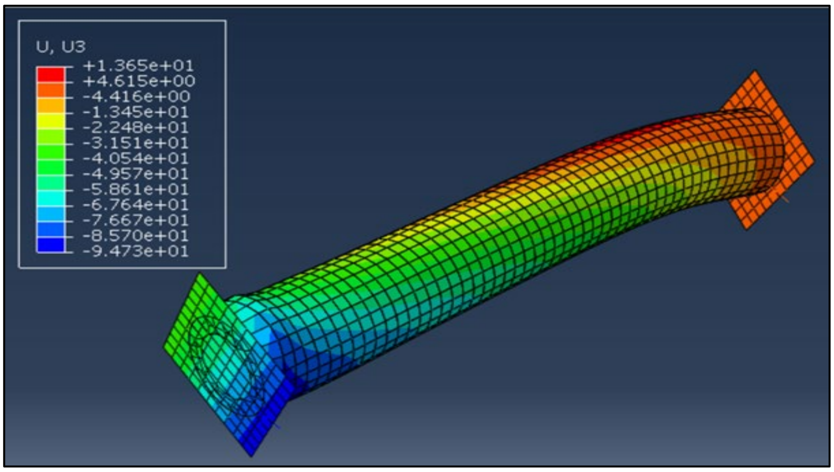

Figure 18: Column(CC2H) failure under eccentricity 180mm

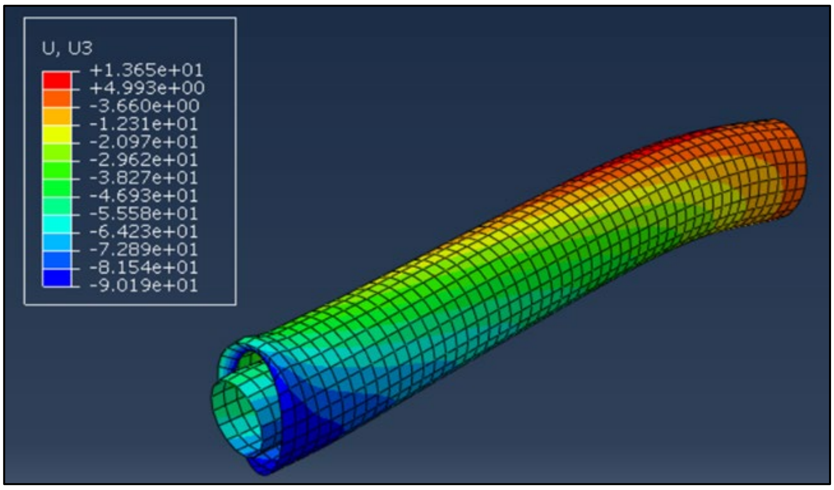

Figure 19: Steel tube (CC2H) failure under eccentricity 180mm

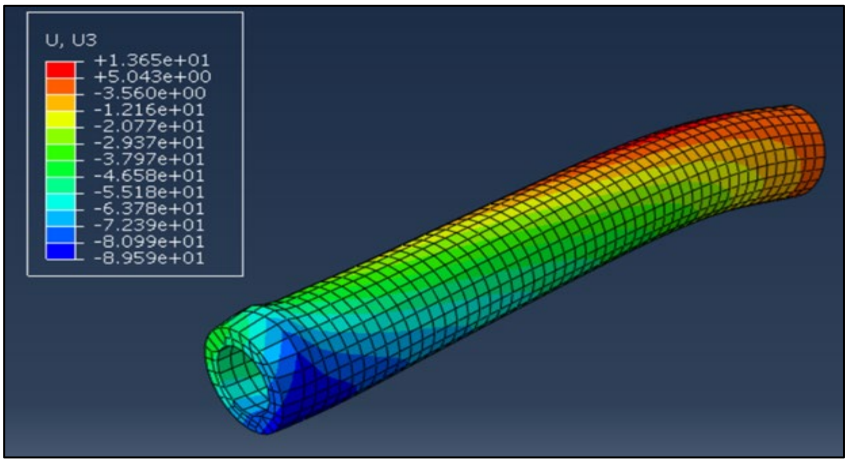

Figure 20: Concrete (CC2H) failure under eccentricity 180mm

5.1 Eccentricity Effect

Table (5) shows that increasing eccentricity for applied loads causes a decreasing amount of loads to failure composed columns. i.e., The stiffness of the column reduces, leading the structure to lose stability more quickly. Also, increasing eccentricity causes increasing buckling in composite columns. The ABAQUS results show that the difference ratio of ultimate loads varies from (9.84, 15.26, 17.64, 20.47, 29.36, and 35.22) percent for the specimen (CC3H, CC2H, CC2S, CC3S, CC1S, and CN1H) respectively. It is Also illustrated in Figures (12, 13, 14, 15, 16, and 17).

Table 5: Effect of difference Eccentricity

Specimens	Ultimate loads (kN) for e= 90mm	Ultimate loads (kN) e= 180mm	Difference (%)= (load90-load180)/load90
CN1H	34.18	22.14	35.23
CC1S	483.89	341.8	29.36
CC2H	159.23	134.93	15.26
CC2S	776.51	639.52	17.64
CC3H	723.36	652.15	9.84
CC3S	852.49	677.98	20.47

5.2 Void Size Effect

The comparison of numerical data for the specimens, as given in Tables (6 and 7), illustrates the effect of void size on composite column behavior. The ultimate load of hollow composite sections is less significant than solid composite sections with the same number of steel layers by a ratio of (92.94, 79.49, and 15.15) percent and (93.52,78.90, and 3.81) percent for one, two, and three-layer hollow steel tubes with eccentricities of 90mm and 180mm, respectively. The influence of void ratio on ultimate strength is shown in Table 8, and it can be seen that the ultimate strength of hollow sections increases as the void size decreases.

Table 6: Effect of void size for 90mm eccentricity for specimens

Specimens	Ultimate loads (kN) ABAQUS	Difference (%)= (SCH-SCS)/SCS
CN1H90	34.18	-92.94
CC1S90	483.89	
CC2H90	159.23	-79.49
CC2S90	776.51	
CC3H90	723.36	-15.15
CC3S90	852.49	

Table 7: Effect of void size for 180mm eccentricity for specimens

Specimens	Ultimate loads (kN) ABAQUS	Difference (%)= (SCH-SCS)/SCS
CN1H180	22.14	-93.52
CC1S180	341.8	
CC2H180	134.93	-78.90
CC2S180	639.52	
CC3H180	652.15	-3.81
CC3S180	677.98	

Table 8: Effect of void ratio on ultimate strength

Specimens	Void ratio*(%)	Ultimate load (kN) for 90mm	Ultimate load (kN) for 180mm
CN1H	89.61	34.18	22.14
CC2H	44.44	159.23	134.93
CC3H	11.11	723.36	652.15

*Void ratio (%) = (area of opening / area of cross section) X 100

5.3 Number of Steel Layers Effect

A variable number of steel layers were utilized to reinforce the adopted composite columns to test their structural behavior using ABAQUS. The Show comparison of the numerical data results for the adopted specimens in Tables (9 and 10) are shown. The ultimate strength climbed as the number of steel layers increased as the area of steel contributing to the resistance column to the applied load increased.

Table 9: Effect of Steel layers for 90mm eccentricity

Specimens		Ultimate load (kN)	Difference (%)= $(C_N-C_{(N-1)})/C_{(N-1)}$
Solid section	CC1S90	483.89	0
	CC2S90	776.51	60.47
	CC3S90	852.49	9.78
Hollow section	CN1H90	34.18	0
	CC2H90	159.23	365.86
	CC3H90	723.36	354.29

Table 10: Effect of Steel layers for 180mm eccentricity

Specimens		Ultimate load (kN)	Difference (%)= $(C_N-C_{(N-1)})/C_{(N-1)}$
Solid	CC1S180	341.8	0
section	CC2S180	639.52	87.10
	CC3S180	677.98	6.01
Hollow	CN1H180	22.14	0
section	CC2H180	134.93	509.44
	CC3H180	652.15	383.32

5.4 Effect of Concrete Compressive Strength

The specimen (CC1S00) was simulated under vertical loading in this section; the main variation is the concrete strength (25MPa, 35MPa, and 40MPa) compared with reference compressive strength (31.96MPa). The ABAQUS results were verified. According to the research, Concrete strength has a significant impact on stiffness. It has been demonstrated that when concrete strength improves, column stiffness increases. The ratio of concrete compressive strength values according to the reference column (CC1S00 with fc'=31.96 MPa) was (-4.4, 3.1, and 6.5) percent for the specimen (CC1S00) with (fc'=25, 35, and 40) MPa, respectively. As illustrates illustrated in Figure 21.

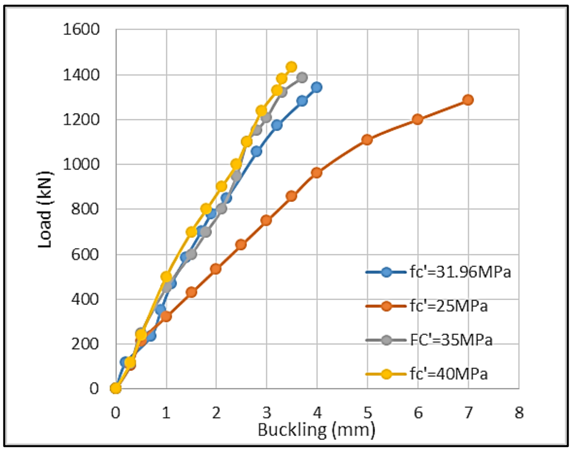

Figure 21: Load-Buckling Curve for CC2S00 for various *f'c*

6. Conclusions

This paper compares the experimental and software ABAQUS 6.13-14 findings of the composite column with different layers of steel tube under compression loads. The following are the key conclusions of this study:

1) The proposed ABAQUS 6.13-4 models used in this study are suitable for predicting the behavior of composite column specimens. Throughout the whole range of behavior, the numerical results were in good agreement with the experimental load-buckling curve.
2) The proposed model's results show that increasing eccentricity for applied loads from 90mm to 180mm, causes a decreasing amount of loads in the strength of the composite columns. When the eccentricity of the load is applied away from the column, the stiffness of the column reduces, causing the structure to lose stability quicker.
3) Predicted nonlinear finite element models; show that the ultimate loads of hollow composite sections are lower than solid composite sections due to an increase in the cross-section area of the concrete core, which contributes to the section's resistance to the applied load.
4) The ultimate strength of the resistance column to the applied eccentricity load increased as the number of steel layers increased because of the increased steel area that adds to the resistance column to the applied load.
5) The stiffness of concrete is greatly influenced by its strength. When the concrete strength rises, the composite column's stiffness also rises. The stiffness of concrete is primarily determined by its strength. When the concrete strength increases, so do the composite column's stiffness. The ratio of concrete compressive strength values according to the reference column (CC1S00 with fc'=31.96 MPa) were was (-4.4, 3.1, and 6.5) percent for the specimen (CC1S00) with (fc'=25, 35, and 40) MPa, respectively.
6) Additionally, increased eccentricity promotes buckling in composite columns due to the loss of rigidity.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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