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Behavior assessment of concrete filled slender steel tube columns under axial compression

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ABSTRACT

In recent years, the use of slender steel tube columns filled with concrete (SCFST) has been developed due to their good performance. This study evaluates the ultimate strength of slender steel tube columns filled with concrete under axial compression using the three-dimensional finite element method. The effect of some parameters on the ultimate strength, such as the compressive strength of concrete, the yield stress of steel, and the slenderness ratio on circular cross-section, was studied. Concrete's damage plasticity was adopted, while steel elastic-plastic was considered perfectly. The study showed that increasing the strength of concrete leads to an increase in the bearing capacity of the column, but at the same time, it causes a decrease in ductility. From the results obtained, increasing the yield stress leads to an increase in the ultimate strength of the column while causing a decrease in ductility. When the slenderness ratio is increased, (which means an increase in the length) leads to a decrease in the ultimate capacity of the column and decreasing this percentage causes an increase in the ultimate capacity of the column.

Key words; slender columns SCFST, 3D analysis, ABAQUS.

1. **INTRODUCTION**

One of the important things in making engineering decisions is how to choose materials that can been used in engineering facilities. The controlling side in this matter is the type of facility and the economic aspect with achieving the best performance for the facility. The two main structural material used in the world are steel and concrete, as the benefits of using both materials are well known. Concrete is stiff, cheap and good for fire-resistant while steel is strong, ductile and lightweight. The intelligent combination of these two materials results in a structural system that is more efficient than the use of the component individually. The composite system of these two materials has been successful in the works of columns, bridges and slabs. In recent years, concrete-filled slender steel tubes (SCFST) has been increasingly used in high-rise buildings and other types of structures such as bridges because of their advantages compared to ordinary steel or reinforced concrete columns. Due to the positive influence of the composite, and compensate for defects of the use of two different materials.

A number of researchers carried out experimental and analytical studies to investigate the response of CFST columns under different loading conditions. These studies provided extensive data for some design codes in order to develop design approaches and applications of composite columns such as the EC4[1] and the AIC code[2]. The finite element method has the ability to effectively simulate the behavior of the columns, making the results close to reality. However, the finite element method is greatly affected by the modeling method for each of the materials used in the column composition, such as steel and concrete.

Schneider [3] in 1998 investigated the effect the shape (circular, square and rectangular) on the behavior of the short concrete filled steel tube columns CFST under concentric load in compression to failure. The results obtained showed that the composite circular columns provide better confinement, stiffness and ductility compared to square and rectangular columns. Giakoumelis and Lam (2004) [4] presented an experimental study on the behavior of steel columns filled with concrete with different concrete resistance under axial load taking into account the bonding strength between concrete and steel as well as the confinement that steel tube provides on concrete. The study concluded that the effect of increasing the strength of concrete makes the bond strength between concrete and steel tube more critical. Gupta et al. [5] (2007) presented an experimental and analytical study on behavior of the Center-loaded Circular CFST Columns. They produced a nonlinear FEM to estimate the ultimate capacity of such columns. They found that when the diameter to thickness (D/t) ratio is small, the steel tube provides good confinement on the concrete and the bearing capacity of the column decreases with the increase of the D/t ratio. In addition the CFST columns that fail mainly with local buckling, the increase in the strength of the concrete lead to a decrease in the impact of confinement on the concrete core. Dundu [8] in 2013 study the behavior of 24 specimens of concrete filled steel tubes CFST columns experimentally loaded concentrically under compression to failure. He compared his experimental results with those was predicted by the South African Code (SANS10162-1) and EC4, shows that the Codes are conservative by 8.4% and 13.6% respectively . Tao et al. [9] 2013 using a wide range of experimental data to develop refined FE models to simulate CFST stub column under axial compression by using ABAQUS program version 6.12. The simulation system is based on the damaged plasticity material for concrete found in the ABAQUS program. The ultimate strength obtained by previous researchers was compared with that obtained using the finite element program. Whereas conservative predictions were obtained from the finite element model but with reasonable accuracy. Bahrami and Kouhi [12] 2020 studied the compressive behavior of steel tubes filled with concrete with circular, rectangular and square cross-sections. Where they used nonlinear three-dimensional analysis of finite elements to simulate the behavior of columns with the help of the ABAQUS program. They found that the axial-strain-load curves of the columns obtained from finite element analysis are remarkably close to the experimental tests. Saleh and Al-abboodi [13] 2021 studied three-dimensional finite element analysis to assess the response of stub columns when subjected to axial stress using the ABAQUS program. The effect of some parameters of concrete and steel tube confinement has been verified numerically. Eighty columns equally divided into circular and square cross sections were used in the analysis under axial compression. The parameters that taken into account in the nonlinear analysis were the concrete strength, the yield stress of steel, the thickness of the steel tube, and cross-sectional shape (circular and square). All columns were of the same diameter, which is 125 mm, with two values of D/t ratio of 25 and 50.

It was noted that there is very rare research on slender steel tube columns filled with concrete, which made obtaining accurate information few. In the current study, the three-dimensional finite element method was used to assess the strength of a slender steel tube column filled with concrete under axial pressure using the ABAQUS software.

2. FINITE ELEMENT MODELLING AND VERIFICAT

2.1 General

In this study, the nonlinear analysis of the finite elements of slender steel tube columns filled with concrete was studied using the ABAQUS software version 2019. The steel tube is modeled using 4 nodes of shell elements. It was decided to use the S4R elements, a four-node component, for the general purpose of the shell element and to reduce the degree of integration. While concrete is modeled using 3D- 8 nodes soled elements. The solid elements used in the concrete model were C3D8R, an 8-node for the element with a reduced first integration rank. Several tries was made to select the size of mesh by comparing the results with experimental ones. A fixed size of the mesh was used in present study is 21mm for D(diameter) equal to 150mm and 40mm for D equal to 250mm . The meshing samples for circular columns shown in fig.1 The concept of surface-to-surface contact, presented by Tao et al. (2011)[7], has been used to simulate the interaction between the concrete and steel. The default friction model in ABAQUS was selected as a friction coefficient equal to 0.6. In addition, the shear stress is scheduled to be the connection between the concrete and the steel tube, which is like the conduct of the connection between concrete and normal reinforcement.

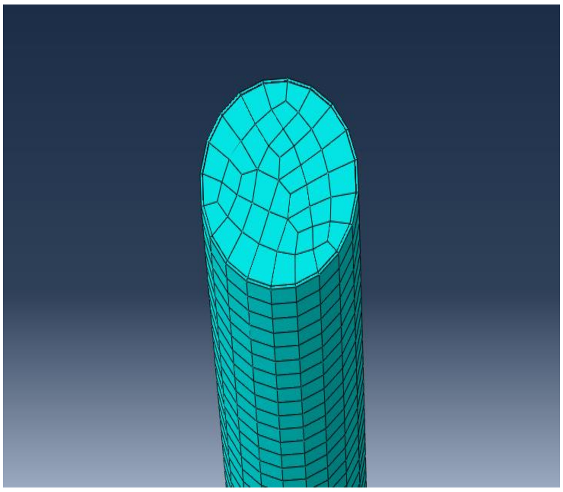


Figure 1. Sample mesh for circular SCFST column

It was decided to use hard-contact to model the normal behavior of the steel-concrete interface and the default friction model of ABAQUS .The hard contact relationship reduces the penetration of the slave surface into the master surface at the constraint location and does not allow the transfer of tensile stress across the interface as shown in figure 2.

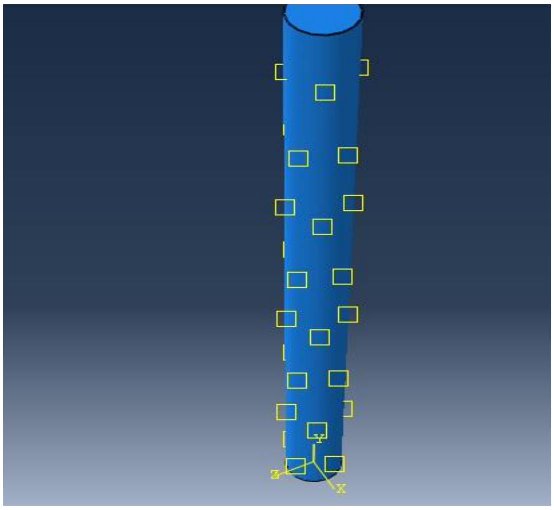


Figure 2. Sample hard contact between surfaces.

2.2. Material Modelling

In the current study, the constitutive behavior of the steel was considered as an elastic perfectly plastic material, with a modulus of elasticity equals to 200 GPa and a Poisson’s ratio of 0.3. The Concrete damaged plasticity (CDP's) model was adopted to model the concrete material. The empirical formula recommended by ACI 318 (2011) to calculate the modulus of elasticity of the concrete, which is a function of the concrete compressive strength (f’c) as follows:

$$Ec=4700\sqrt{f'c} \text{ --}$$

Where f’c in MPa

Poisson’s ratio of 0.2 for concrete. Given that the SCFST columns are axially loaded, the concrete expands laterally, but the presence of steel on the outer perimeter provides confinement to the concrete core and prevents this expansion. Because of this confinement on the concrete core, an increase in strength and ductility can be generated. The constitutive stress-strain relationship of concrete and corresponding parameters of the damaged concrete model was considered as suggested by Tao et al. 2013 [9].

2.3 Loading and Boundary Conditions

For the boundary conditions, most researchers used end plates when testing SCFST columns to minimize any effect on the end condition, Therefore, it is appropriate to use the clamping of the ends at the lower and upper surfaces of the structural member. The lower surface of the column is modeled as fixed and there are no transmissions towards X, Y, Z-axes. The upper surface is fixed to x and z and allows vertical movement towards the Y during loading. Displacement control mode was considered to simulate the applied axial compression at the top end of the modelled SCFST columns.

2.4 Validation of finite element software (ABAQUS 19)

In order to confirm that the finite element method using the ABAQUS software gives the best results for the maximum axial load and displacement of the CFST columns. It must be ensured that the ABAQUS program for the finite elements gives results identical to the experimental results before going to the modeling and giving results and recommendations. For this reason, through an extensive search of the previous literature, different researchers studied 16 models and similar models are made in the ABAQUS software for circular, square and rectangular sections. The verification of their results was compared and the results obtained were summarized in Table No. 1. The same parameters that were used in the practical and experimental tests were used in the ABAQUS program. As shown in a table, the maximum load was extracted using the ABAQUS program and those results were compared with the previous results. We also noted that the maximum load was calculated in two ways, by the method of finite elements and experimental methods, and the results were identical in a very large percentage.

Table 1. Validations of ABAQUS on experimental results

No.	Researcher	Dimensions mm			F’c MPa	Fy MPa	Load KN ABAQUS	Load KN test	PA/Pt
		L	D or B	T					
1	Dundu	1500	114.85	3	32	355	768.11	690	1.11277
2	Dundu	1000	114.85	3	32	355	773.08	805.56	0.9596
3	Abdulaziz	1500	153.6	3	16	239	1030	1126.96	0.91400
4	Ammar	1000	160	2.8	30	368	1229.13	1340	0.91726
5	Ammar	1500	160	2.8	30	368	1220	1290	0.94573
6	Walter	1143	114.3	3.35	32.7	287.3	681.276	596.583	1.14196
7	Walter	1143	114.3	3.35	58.7	287.3	713	607.44	1.17380
8	Walter	800	114.3	3.35	32.7	287.3	904.907	812.765	1.11336
9	Guanguan	1600	110*150	2.92	69.6	340.7	1570	1661.56	0.9449
10	Guanguan	1600	1108150	2.92	69.6	340.7	1630	1580	1.01316
11	Mohanad	2800	134*134	3	65	269	1230	1054	1.1668
12	Tao Zahang	1200	150	1,2	32.9	375	847.576	885.542	0.95712
13	Yonas	4500	155.4	2.7	50	355	1210	1220	0.99180
14	Yonas	6000	159	4.5	50	355	1540	1349.88	1.14084
15	E. K. Mohanraj	900	76	3	25	260	312	265.789	1.174084
16	E. K. Mohanraj	900	76	2	25	260	287.176	271.05	1.059483

3. RESULTS AND DISCUSSION

The assessment of the slender concrete filled steel tubes SCFST columns were adopted by taking different parameters that may effect on the behavior and strength of such columns. These parameters were divided as geometric properties and material properties. In this study, ABAQUS (version 19) program has been used to model 96 circular specimens loaded to failure under axial compression. The concrete compressive strength (fc'), the steel yield stress (fy), the steel tube wall thickness (t) and slenderness ratio were considered the main parameters. The thickness of steel tube was selected as 4mm, while the length 1500mm, 2500mm and 3500mm.The diameter of circular section is selected as150mm and 250mm as shown in table 2. The figure 3. shows the dimensions for circular sections. In addition, material properties of concrete and steel as shown in table 3.

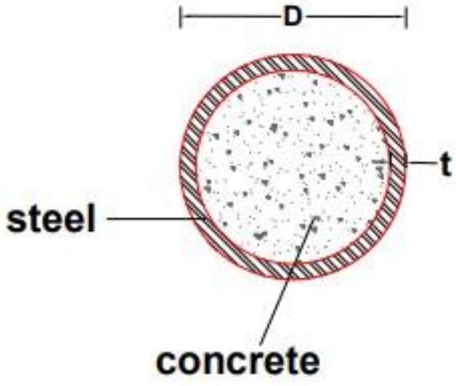


Figure 3. Schematic view of the cross-sections columns models

Table 2. Geometric properties of slender CFST columns.

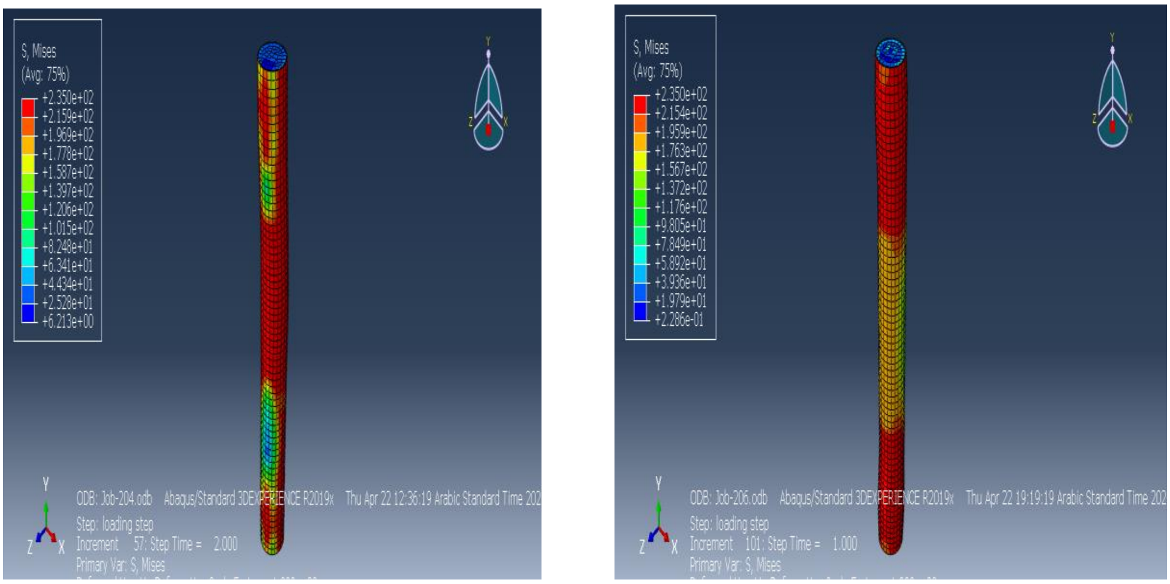
Steel tube	Dimensions in mm		
	D outer	Thickness t	Length L
circular section	150	4	1500 2500 3500
circular section	250	4	1500 2500 3500

Table 3 material properties of concrete and steel

Concrete				Steel		
f'c MPa	Ft MPa	Ec GPa	Poison's ratio	Fy MPa	Es GPa	Poison's ratio
20	2	21.019	0.2	235	200	0.3
30	3	25.743	0.2	275	200	0.3
45	4.5	31.529	0.2	355	200	0.3
60	6	36.406	0.2	425	200	0.3

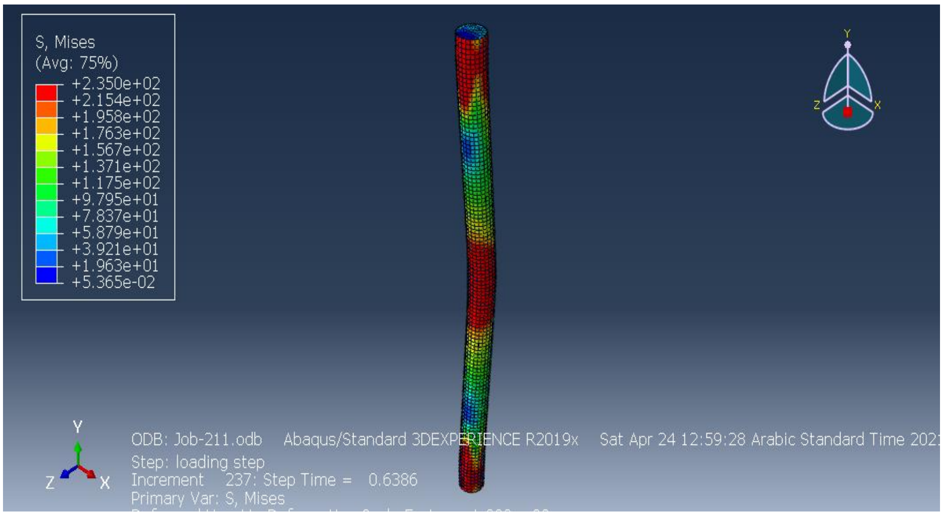
3.1 Modes of failure

Different failure patterns were observed for the analyzed SCFST columns depending on the geometric and material properties of these columns. Figure 4-a shows the mode of failure of the circular SCFST column of slenderness ratio 40 with the compressive strength of concrete 20 MPa and steel yield strength 235 MPa. It was noted that the failure mode is characterized by the global buckling at the mid-height of the column. However, this buckling is not large, but rather like a small wave. When using concrete strength 60 MPa with the same previous parameters, the failure mode was in the form of a local buckling near the end of the column, as shown in Figure 4-b. For SCFST columns having a slenderness ratio of about 66.67(D=150mm, L=2500mm) with a concrete compressive strength 20 MPa and yield strength of steel 235 MPa.. It is observed that the failure mode is a global buckling at the middle of the column, as shown in Figure 5-a. This pattern is the same when using the same previous parameters except for the strength of concrete 60 MPa as shown in figure 5-b. This means that increased resistance to concrete does not change the form of failure in columns.

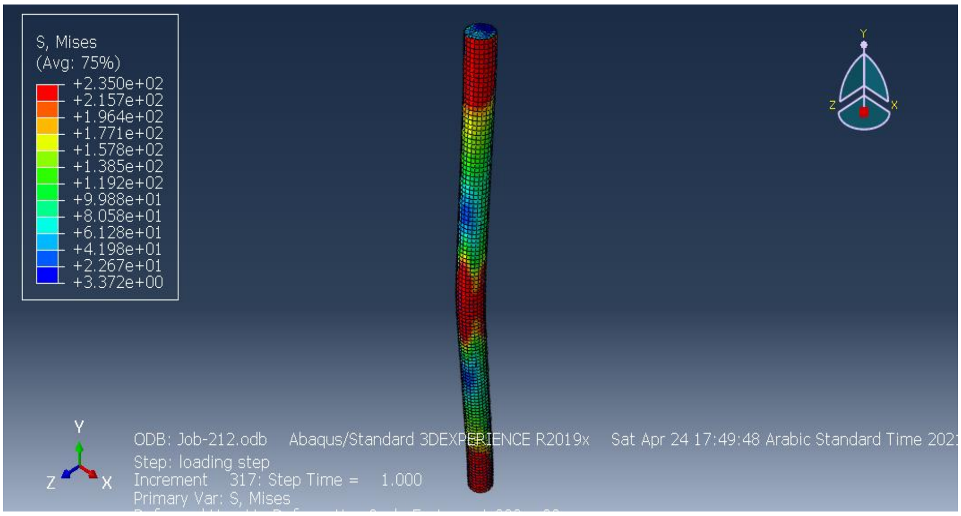


a- F’c=20 MPa b- fc=60 MPa

figure 4-circular with length=1500mm ,D=150mm, t=4mm,fy=235MPa,



a-circular with length=2500mm ,D=150mm, t=4mm,fy=235MPa, fc=20MPa

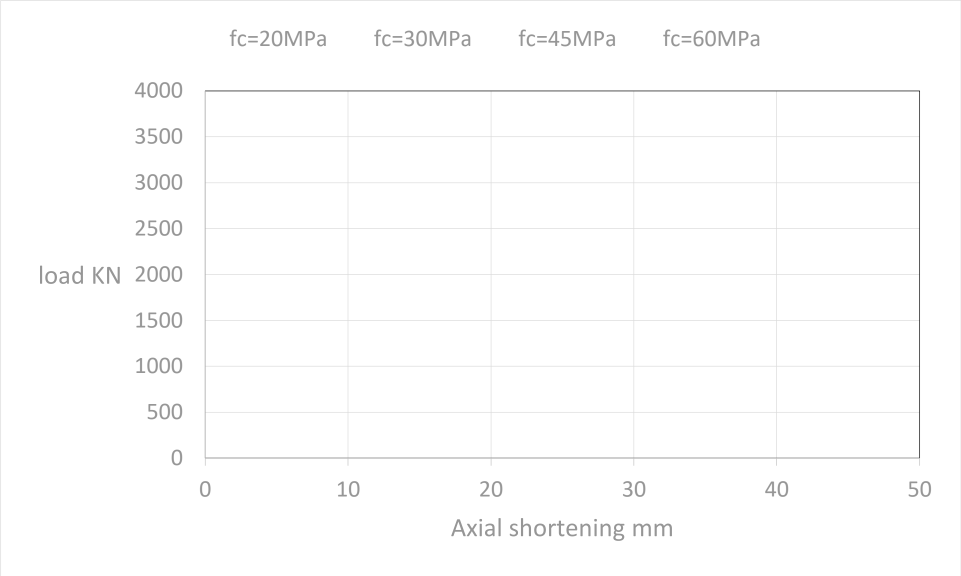


b-circular with length=2500mm ,D=150mm, t=4mm,fy=235MPa, fc=60MPa

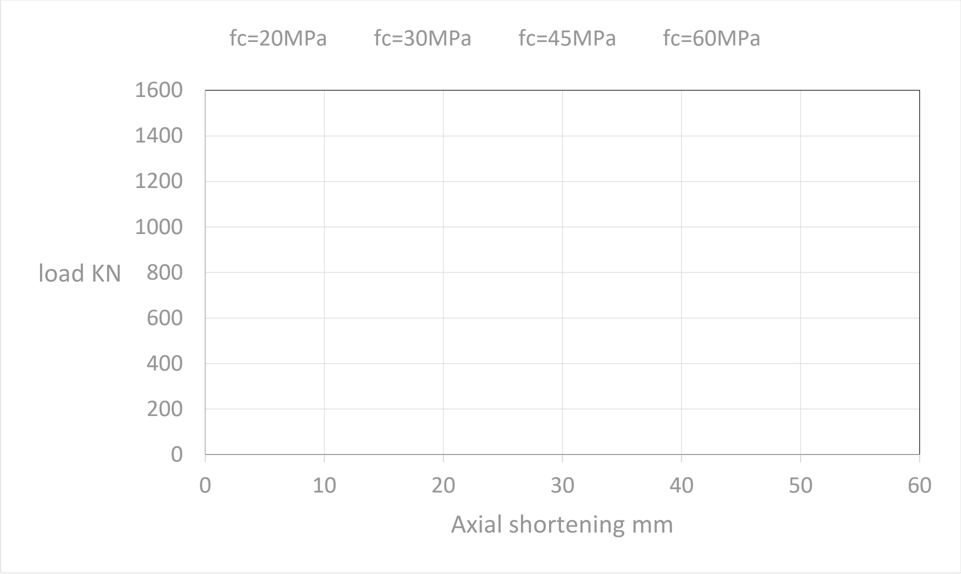
figure 4 failure modes of SCFST colimns

3.2 Behavior Assessment of SCFST columns

The present study focused on the behavior of SCFST columns for a circular and square cross-section. The columns are analyzed using the ABAQUS program. Modeling was validated compared to previous results and experiments. The consideration of a group of parameters was taken and influence statement on the behavior of SCFST columns under axial compression such as concrete strength and steel yield strength and other parameters. Through the current work, it was observed that increased concrete compressive strength has a positive impact on the capacity of the column. The impact of increased length is a negative effect on the column capacity. From the observation of figures 6, where the axial compression versus the axial displacement, as the shapes are similar until the ultimate load was reached. Then the difference can be clearly seen due to the influence of some parameters taken into consideration. At first elastic linear relationship, then followed by a non-linear relationship when the steel begins to yielding (Dundu2012) [8]. From these diagrams, it can be noted that columns with a length of 1500mm give higher ultimate capacity and greater ductility, and in general, the ductility decreases with increasing length for all columns.



D/t=62.5.5, fy=235MPa, L=2500mm, D=250 mm



D/t=62.5.5, fy=235MPa, L=1500mm, D=150 mm

Fig. 6 Axial load – axial shortening relationships for analyzed circular SCFST columns

3.2.1 Ductility

Ductility can be defined as the ability of structure to preserve the deformation behind the elastic limit at the same time, maintaining a sensible load carrying capacity to total failure. One of the methods used to determine ductility is the use of ductility index DI. A number of researchers have used the definition of ductility index based on load-deformation or load-axial strain curves. Tao et al. (1998) [14] suggested the definition of ductility as follow:

$$DI = \frac{\varepsilon_{85}\%}{\varepsilon_u} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.10$$

Where, DI=ductility index

ε_{85} = the strain when the load falls to 85% of the ultimate load

ε_u = is the strain at the ultimate load

Equation above was used to calculate ductility index in this research, and the results were tabulated in Tables 4-3, 4- 4, for different shapes and lengths.

It can be observed that the increase of concrete compressive strength produce a reduction in the SCFST columns ductility as shown in figure 7.

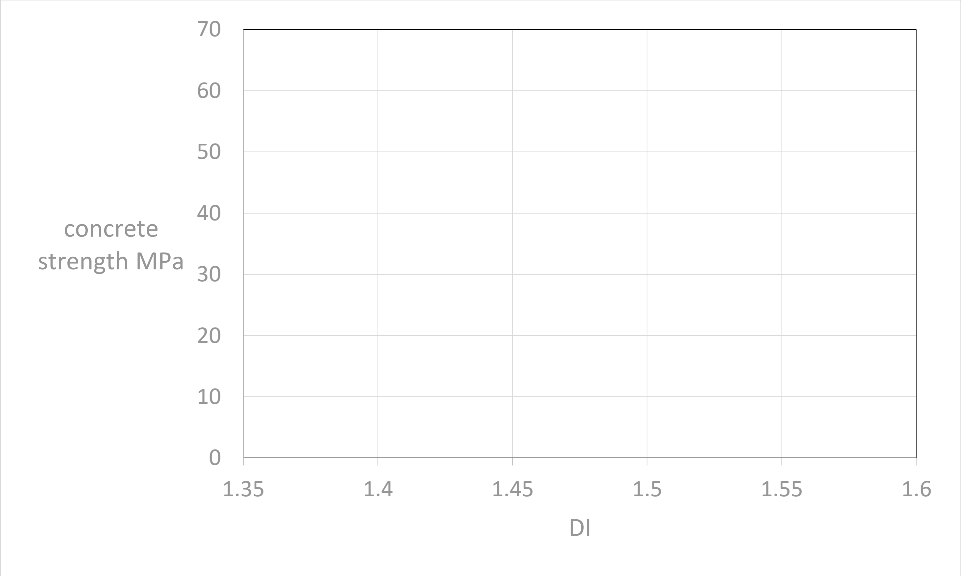


Fig. 7 concrete strength –ductility index of circular SCFST column with diameter=150mm, t=4mm, length=1500mm

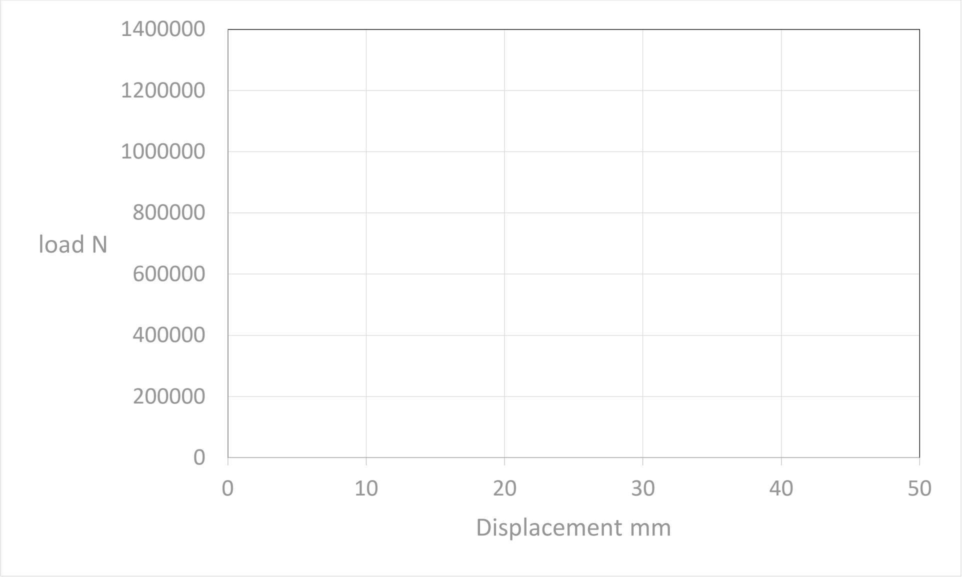
Table 4. Details of analyzed circular SCFST columns

No.	D/t	Length mm	fy(MPa)	fc(MPa)	Load (KN)	DI
1	37.5	1500	235	20	873.4	1.57
2				30	1040	1.55
3				45	1260	1.42
4				60	1480	1.376
5	37.5	1500	275	20	956.5	1.8035
6				30	1050	1.4338
7				45	1360	1.229
8				60	1580	1.175
9	37.5	1500	355	20	1130	1.285
10				30	1300	1.18
11				45	1550	1.16
12				60	1650	1.1246
13	37.5	1500	425	20	1250	1.275
14				30	1450	1.236
15				45	1700	1.21
16				60	1930	1.0836
17	62.5	1500	235	20	1890	2.71
18				30	2350	1.81
19				45	3090	1.754
20				60	3730	1.69
21	62.5	1500	275	20	2040	1.86
22				30	2510	1.70
23				45	3230	1.68
24				60	3890	1.61
25	62.5	1500	355	20	2360	2.085
26				30	2810	2.061
27				45	3490	1.996
28				60	4200	1.93
29	62.5	1500	425	20	2570	2.00
30				30	3080	1.98
31				45	3750	1.80
32				60	4430	1.797

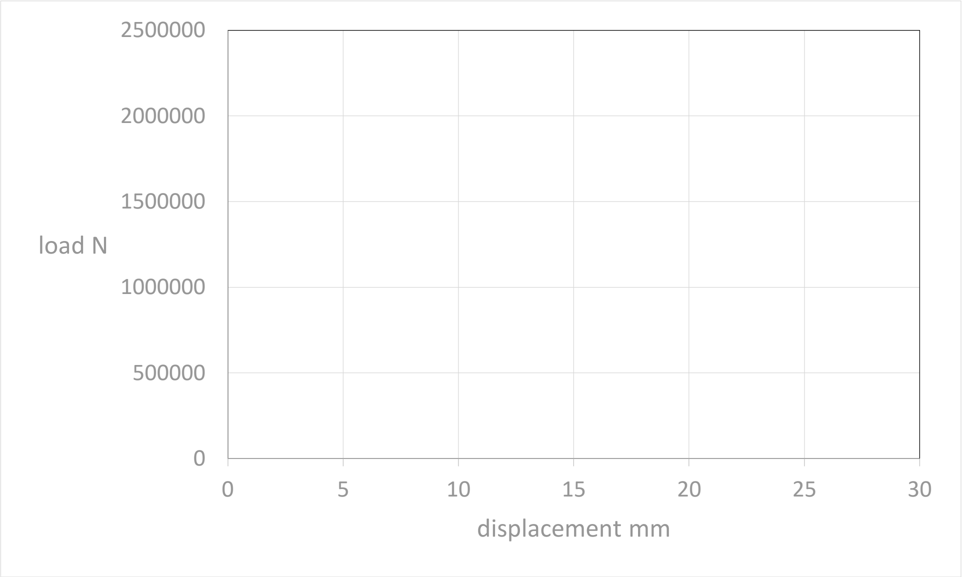
From the comparison of Figures 7, we notice that the ductility in circular SCFST columns is higher, because circular columns provide better confinement on concrete core. It was noted that when using concrete compressive strength 20 MPa, it gives higher ductility when using concrete compressive strength 60 MPa while fixing other properties. When observing the results in Tables 4 noted that increasing the length of the SCFST columns leads to a decrease in ductility, and this is due to the columns with a length of 3500 mm, the effect of confinement is less than that of columns with a length of 1500 mm. Which causes a decrease in the ductility of those columns.

3.2.2 Load and Displacement

The results shown in Figure 8 represent the relationship between load and vertical displacement for two samples of the models used in the research. It was noted that the load-displacement curves have three stages. In the first part of the curve, where the relationship is almost linear until it reaches to about 80% of the ultimate capacity of the column. After this stage, the second stage begins; the relationship is non-linear for the circular column and is clearly increasing until reaching the ultimate capacity of the column. The second stage begins when the stress in the concrete reaches the critical limit so that the lateral deformation of the concrete be hidden in the steel tube. Where the confining pressure provided by the steel tube is effective and this stage is called the stage of the initial stiffness of the specimens (Mohammed 2010) [6].In the last section of the curve, the steel tube begins to yield and the axial strength of the specimen starts to decrease gradually with respect to the circular SCFST column. That distinguishes the last part of the curve is that the axial strength is a function of the concrete compressive strength, the thickness of the steel pipe, and the slenderness ratio.



Load-displacement for circular SCFST column with L=1500mm, D=150mm,t=4mm



Load-displacement for circular SCFST column with L=3500mm, D=250mm,t=4mm

Fig.8

3.3 Strength assessment of slender SCFST columns

Many parameters effect on strength of SCFST columns. The variation of SCFST columns ultimate strength with the various adopted parameters are showing in the following:

3.3.1 Effect of steel yield strength

It was noted that there was an increase in the bearing of the CFST column when the yield strength of steel is increase. From observed the results shown in table 4 for circular SCFST column, it was noted that with D/t equal to 37.5(where D is the diameter of the column and (t) thickness of steel wall) and compressive strength of concrete 20 MPa. The ultimate capacity of column increase about by 31% when the steel yield strength increase from 235 to 425 MPa. . However, the increase percentage reaches to 24% when concrete strength 60 MPa. . When use D/t=62.5 for same properties of the column expected the diameter of the column (250mm) the ultimate capacity increase about by 26% when increase the yield strength of steel from 235 to 425 MPa .

3.3.2 Effect of concrete strength

Four values of concrete compressive strength ranging from 20 to 60 MPa were used to examine the columns under the same conditions to show the effect of this parameter on the ultimate capacity of SCFST columns. It can be seen from tables 4 that the ultimate capacity of SCFST columns increase when the concrete strength is increased. It was noted that when concrete compressive strength increased from 20 to 60 MPa for circular SCFST column w slenderness ratio D/t=37.5 and steel yield strength 235 MPa the ultimate capacity increased about by 40%. For the same column with the same properties but using the yield strength of steel 425 MPa the ultimate capacity of column increased about by 35%. When using D/t=62.5 and steel yield strength 235 MPa the ultimate capacity of SCFST column increase about by 50% when concrete strength increased from 20 to 60 MPa. For the same condition but using steel yield, strength 425 MPa the ultimate capacity increased about by 42%. Concluding from that the increasing in concrete strength gives a good increasing ratio in the column capacity.

3.3.3 Effect of slenderness ratio on ultimate capacity

In this section, the effect of slenderness ratio on the ultimate capacity of steel tube columns filled with concrete SCFST was investigated. Through the results obtained in this research which shown in tables 5 that increasing the length(increasing the slenderness ratio) leads to reduce in the ultimate capacity of the SCFST column, and vice versa, the reduce the length (reduce the slenderness ratio) causes increase in the ultimate capacity of the column under the same conditions and properties.

Table 7 results of analyzed circular SCFST columns

No.	D mm	L mm	Slenderness ratio λ	fy MPa	f'c MPa	Load KN	D=250mm, t=4mm	
							λ	Load KN
1	150	1500	40	235	20	873.4	24	1890
2					30	1040		2350
3					45	1260		3090
4					60	1480		3730
5	150	1500	40	275	20	956.5	24	2040
6					30	1050		2490
7					45	1370		3230
8					60	1580		3890
9	150	1500	40	355	20	1130	24	2360
10					30	1300		2810
11					45	1540		3490
12					60	1650		4200
13	150	1500	40	425	20	1250	24	2570
14					30	1450		3080
15					45	1700		3760
16					60	1930		4430
17	150	2500	66.67	235	20	741.5	40	1860
18					30	970		2230
19					45	1120		2970
20					60	1360		3680
21	150	2500	66.67	275	20	946	40	2010
22					30	1070		2520
23					45	1350		3100
24					60	1480		3950
25	150	2500	66.67	355	20	1070	40	2280
26					30	1220		2660
27					45	1460		3500
28					60	1770		4280
29	150	2500	66.67	425	20	1100	40	2610
30					30	1360		2870
31					45	1680		3680
32					60	1920		4500
33	150	3500	93.3	235	20	609	56	1850
34					30	1010		2140
35					45	1050		3080
36					60	1190		3790
37	150	3500	93.3	275	20	923	56	1990
38					30	1020		2470
39					45	1130		3120
40					60	1340		3940

It was noted from the results of circular SCFST columns shown in table 5. That the use of yield strength of steel 235 MPa and compressive strength of concrete 20 MPa and the thickness of steel tube wall is 4 mm, increasing the slenderness ratio from 40 to 93.3 leads to a decrease in the ultimate capacity of the column about 30%. When the strength of concrete is increased to 60 MPa with use the same previous properties, the amount of decrease in the ultimate capacity of column reaches about 20%. When changing the yield strength of steel to 425 MPa and concrete strength 20 MPa, the ratio of decreased in the bearing capacity of the column does not exceed 4%. However, when the diameter of the column have been increased to 250 mm with use the same previous characteristics, the decrease is very small and cannot be taken into account, where it does not exceed 1%. It was noted that there is a decrease in the ultimate capacity of the column when the slenderness ratio increases.

3.3.4 Effect of thickness steel tube (D/t ratio)

Two steel tube wall thickness were adopted in the present study for all the modeled SCFST columns. For circular SCFST column when using the yield strength of steel 275 MPa and compressive strength of concrete 60 MPa with changing the D/t ratio from 75 to 37.5 the increasing ratio of the ultimate capacity about by 14%. When using the same properties but with yield strength of steel 355 MPa the increasing ratio in the ultimate capacity about 12%. The figure 9 shows the effect of increasing the thickness of steel tube for circular SCFST column. This indicates that increasing the amount of steel at the outer circumference of the column leads to an increase in column capacity. Thus, it provide better confinement of the concrete core and enhances the strength of the concrete, and leads to an increase in the bearing capacity of the column.

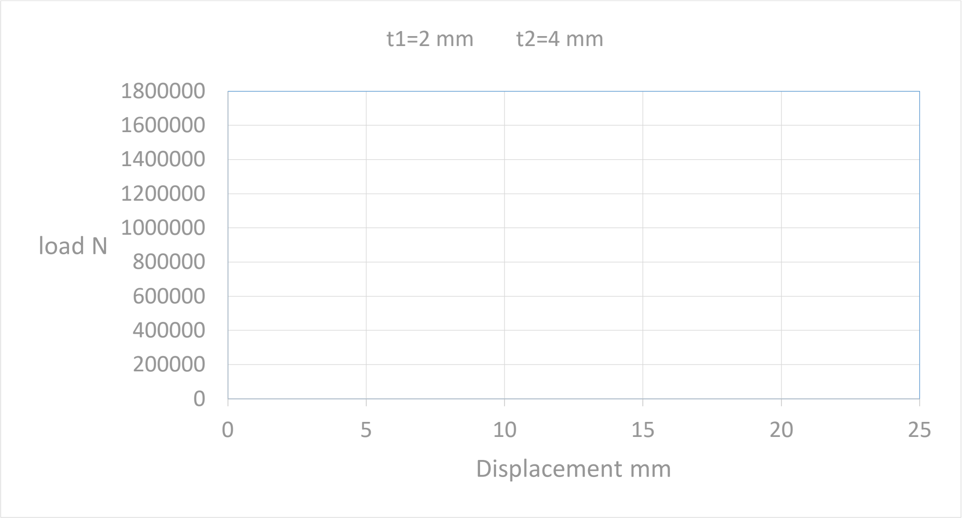


Figure 9 the effect of thickness on the ultimate capacity of circular SCFST column with L=1500mm, D=150mm, fy=275MPa, fc=60M

4.2 Conclusion

A simplified and reasonable finite element model of steel tube columns filled with concrete to investigate and verify the bearing capacity of the column using FE software and accordingly the effect of geometric nonlinearity was taken into consideration. The results obtained from finite element analysis were validated by the results obtained from previous researches, where the bearing capacity of the column is reasonably and acceptable.

From the results of this research, the following conclusions were drawn:

1- The failure mode a largely global buckling with no sign of local buckling. The pattern failure was due to the slenderness ratio is big for columns.
2- The increased of concrete strength caused an increased in the ultimate strength of the SCFST columns, but the ductility reduction with increased the concrete strength.
3- The increased of steel yield strength leads to increase the ultimate capacity of the SCFST columns.
4- The increased the amount of steel at the outer circumference of the column leads to an increased the ultimate capacity of the SCFST columns.in other hand the increased the D/t ratio leads to decreased the ultimate strength.
5- Circular columns with diameter of 250 mm and thickness of 4 mm gave higher strength than other dimension with the use the same lengths. This difference in bearing capacity is because the hoop stress and circumferential stress are higher which results in higher strength.
6- All the steel tube columns filled with concrete showed ductility, but the ductility was more noticeable in columns with length 1500mm comparison with length 3500mm when using a low strength of concrete.
7- In general, the slender CFST columns with a circular section showed higher ductility.
8- The increased of slenderness ratio leads to decreased the ductility for circular SCFST columns.

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