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Research Article

Study on Buckling of Concrete-filled double skin steel tubular columns

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Abstract:

The concrete-filled double skin steel tubular columns (CFDST) are regarded as one of the composite columns consisting of double steel tubes with square or circular hollow sections and the space between two skins is filled with concrete. These columns possess several advantages, including a proper performance during loading, smaller dimensions, cost-effectiveness, protection of the concrete surface against the damage, others compared to conventional columns. In this paper, the buckling of the concrete-filled double skin steel tubular columns subjected to the axial compression was assessed using finite element software, ANSYS. For further investigation of the various types of this novel column system, the nonlinear behaviors of the 3D model of the double skin sections with various cross-section shapes of the section were compared and the influence of the support condition was studied Moreover the buckling of the columns filled with self-compacting concrete, which is required due to the difficulty in the pouring in the confined space, was scrutinized. The results for the short CFDST columns indicate that the column with square-outer-section and circular-inner-section tubes exhibited high buckling critical load and better ductility. Variations in the support conditions do not have significant influence on the columns.

Keywords: *Concrete-filled double skin steel tubular columns, CFDST, Buckling, Self-compacting Concrete*

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1. Introduction

Concrete and steel are regarded as the most important materials which are applicable in the field of construction and structures. The advantages of the afore-mentioned materials are obvious to everyone. The smart and proper combination of concrete and steel is considered to lead to more efficient system than systems consisting only of each material. The composite system or double system are used for example as beams, columns, and slabs of medium to large size buildings and bridges.

The composite columns not only possess numerous advantages for construction industry (specially speed and economical privileges), but also these columns lead to a considerable improvement in the mechanical properties of the structural members, compared to the members of the reinforced concrete and steel. The above-mentioned advantages of this type of columns, including construction speed, no need for frame, reduction in the loads exerted on foundation, increase in the useful space, fast transportation and assembling, protection of the concrete surface against the damages, reduction on the expense associated with construction and maintenance leads to increase in their usages.

The composite columns are divided into two general groups, in terms of placement location of the concrete and steel:

1) Concrete-filled steel tube (CFT)
2) Steel reinforced concrete (SRC) sections, where steel section is encased in concrete.

The concrete-filled double skin tubular (CFDST) columns which is derived from CFT columns, consisted of two steel skins with circular or square hollow section concentrically and they are assembled concentrically, and the space between two skins is filled with concrete. These CFDST columns don’t only have typical advantages of the composite columns, but also present characteristics such as light weight, high ductility and high load-bearing capacity. The CFDST are used in the offshore structures, base of a bridge with large spans, nuclear ducts of the plants, and most recently there are utilized in the skeleton of the high structures in Japan. The numerical and experimental study on the behavior of the CFDST columns is accomplished by various scholars, among which Tao et al. (2004) have focused on the behavior of CFDST columns with a circular outer and inner sections [1]. Zhao et al. (2002) performed experiments on the concrete-filled double steel skin tubular columns with square outer and inner hollow sections in order to investigate the structural behavior of these columns [2]. Han et al. (2011) studied the behavior of CFDST columns subjected to the long-term sustained loading condition [3]. Yang et al. (2015) studied these columns behavior when they were subjected to the lateral loads of 90 degrees and 45 degrees angles [4]. Li e al. (2012) investigated the behavior of CFDST columns with axial pre-loading, while they also applied loading on the outer skin and steel tubes [5]. Moreover, Li et al. (2012) conducted a numerical study on these columns on the basis of finite element analysis of the tapered CFDST columns, under compressive load with various conditions for tapered angle and section specifications [6]. In 2013, they investigated the same tapered columns subjected to the loading, but with different load eccentrics [7]. Han et al. (2009) and Huang et al. (2010) developed numerical models for studying the static and cyclic behavior of the double skin CFDST columns and they focused on the interaction between concrete and outer and inner steel tubes [8, 9]. A series of studies are also reported by Yang and Han in 2008 and Lu et al. in 2010, with a main focus on the thermal performance of the CFDST columns subjected to the heat [10, 11]. In 2014, Pagoulatou et al. studied the behavior of CFDST columns subjected to compressive load which was centralized at the center of the columns through numerical modelling and they obtained a formula to evaluate the strength of the double-skin specimens [12]. In 2015, Li et al. attempted to predict the structural behavior of the CFDST column under the pre-loading condition and sustained load, while the external pipe was exposed to chloride using finite element analysis, and they discussed the difference between the specimens with and without considering the factors [13]. In 2015, Zhang et al. conducted an empirical research on the CFDST columns filled with high efficient concrete, which was subject to the blast load [14].

It is essential necessary to investigate the buckling of CFDST columns, since the columns experience instability during the loading phase and this critical load is capable of bending the columns, even without forming a moment for bending, that is, it would lead to buckling of the columns and the columns will be susceptible to increase in load under critical load conditions, in such a way that adding a slight load, can lead to a high lateral deflection in the column. Feng and Xu (2018) have proposed an efficient fiber beam-column elements for RC structures which are subjected to cyclic loading throughout the experiments. According to the obtained results, it was observed that the developed element is capable of predicting the cyclic responses of RC structures, and it can be employed as a reliable tool for analyzing of RC structures. The element was developed on the basis of conventional displacement-based Timoshenko beam theory [18]. Zhou et al. (2016) have carried out elastic distortional buckling Analysis of I-Steel concrete composite. For Zhou et al. (2016), torsional” and “lateral” restraint stiffnesses of the bottom flange of the beam are among the factors which are effective on the kind of buckling. This paper investigates the equivalent lateral and torsional restraint stiffnesses of the bottom flange of the ISCCB under the gradient of negative moment. Based on the findings, they proposed a new method for appraising the buckling of the elastic-foundation beam, by which the related factors are considered: (1) The coupling effect between the applied forces and lateral/torsional restraint stiffness of the bottom flange of the beam, (2) the effect of gradient of a moment and (3) the effect of shear deformation of the web [19]. Yang et al. (2008) have attempted to scrutinize the behavior of concrete-filled double skin steel tubular columns subjected to axial compression and they have plotted some curves of load-strain of steel tubes and confined concrete, while the bearing capacity of members were illustrated. They declared that the bearing capacity of the columns incorporating octagonal section is greater than that of with square section and is smaller than that with circular section [20]. Liu and Qian (2009) have sought to study the Moment-curvature relationship of FRP-concrete-steel double-skin tubular members. The performned experiments on 3 specimens in order to investigate the flexural behavior of fiber reinforced polymer (FRP)-concrete-steel double-skin tubular members. With regard to the results, it was observed that the tension zone of the specimen FRP tubes was in hoop compression, while the compression zone was in hoop tension [21].

2. FE Modelling

Although, experimental studies can lead to more information on the structure behavior in real-world application, sometimes the accomplishment of experiments on the CFDST columns is expensive and time-consuming. Fortunately, during the recent years the development of finite element methods has enable the scholars and engineers to simulate the laboratory tasks in the software. With regard to the advantages of the finite element method in solving the difficult and complex problems of the engineering discipline, the present research has utilized ANSYS software.

2.1. Numerical model comparison with experiment

For being assured about accuracy of the software modelling, a comparison was made between the results of the present study and that of experiment research conducted by Tao et al. [1].

The sample of the CFDST column adopted from reference [1], labeled CC2A which was used for modelling the finite elements, possesses a circular section within the inner and outer tubes. The dimensions of the column and materials properties used by Tao et al. for fabricating the sample all are presented in table 1 [1].

Table 1. Materials properties and dimensions of CC2A sample section [1]

Steel Properties			Concrete Properties		χ	L (mm)	$D_i \times T_{si}$ (mm)	$D_o \times T_{so}$ (mm)	Sample
E_s (MPa)	F_{syi} (MPa)	F_{syo} (MPa)	E_c (MPa)	F'_c (MPa)					
200000	396.1	275.9	33300	47.4	0.47	540	48*3	180*3	CC2A

D_i and D_0 refer to the outside diameters of the inner and outer tubes, respectively. t_{so} denotes the thickness of skin of the outer steel tube and t_{si} denotes the thickness of inner steel tube skin. For improving the accuracy of the simulation of the columns actual behavior, important parameters including type of the fine element, gridding, contact surface of concrete-steel, boundary conditions and application of the required load during the simulation of the column were considered. For defining the concrete core, an eight-node solid element, called SOLID 65 with 3 degrees of transitional freedom in each node, was employed. The specified materials were concrete with cracking ability in three perpendicular direction due to the tensile and break under the impact of compressive stress and plastic deformations. The steel tube was defined using SOLID 45 element, and similar to the SOLID 65 it has eight nodes with 3 degrees of freedom in each node and it tallies good with other elements used during the modelling of CFDST columns.

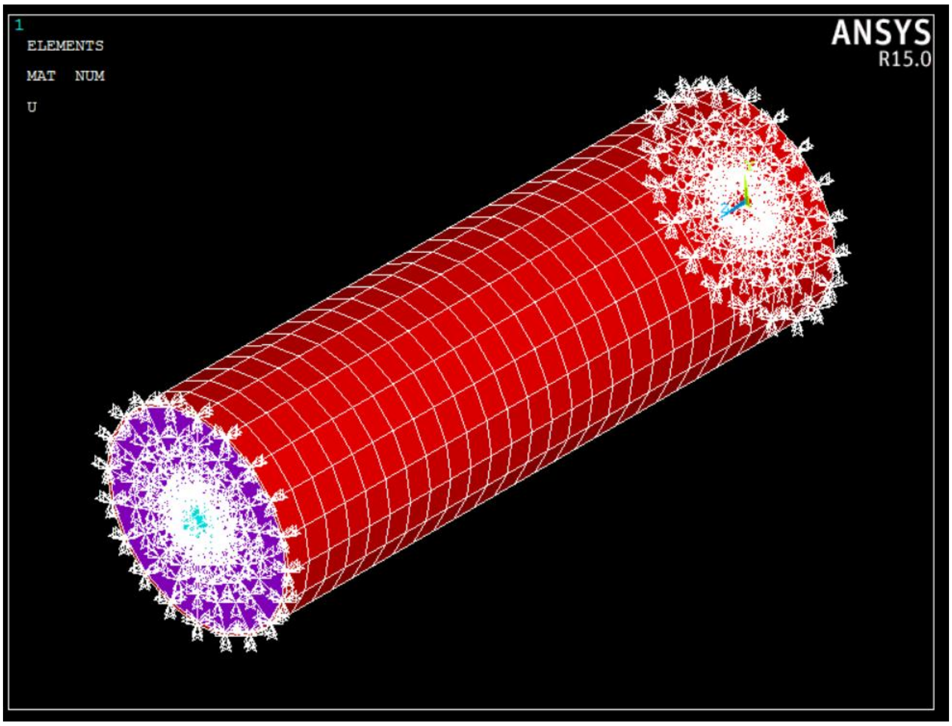

Figure 1: Modelled Column and boundary condition

The slipping and friction between the steel and concrete core was modelled by surface-to-surface contact element, named CONTACT 174. This element is able to transfer the compression along the normal direction and cut in tangent direction of the surfaces. Due to the existence contact area between the filler concrete and steel tubes, as well as, the non-linear properties of the concrete, the analysis of these columns should be accomplished in a non-linear manner. For this purpose, the non-linear geometrical behavior was taken into account during all analyses. For defining the nonlinear behavior of the materials, the strain-stress curves were considered for the concrete and steel.

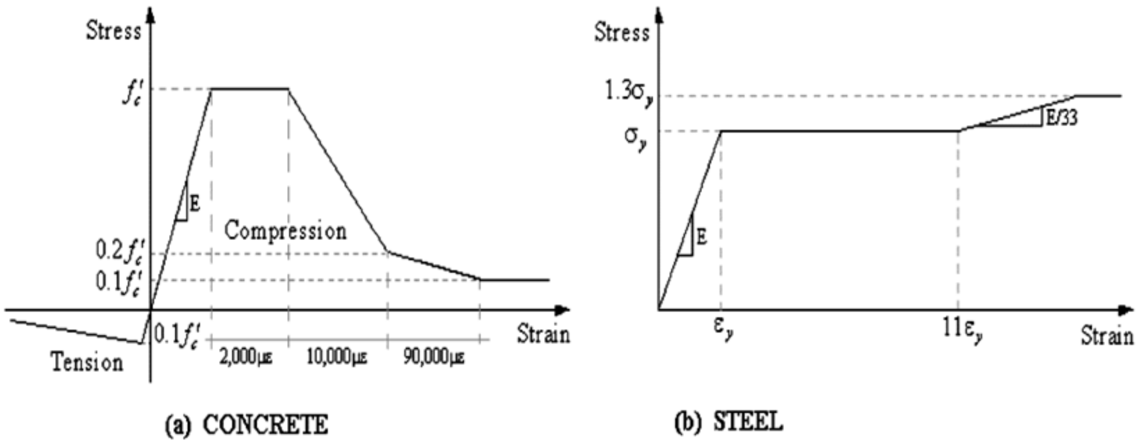

Figure 2: Behavior of the materials used in the columns modelling

(a) Confined (surrounded) concrete
(b) Steel [1]

Other items that must be considered during analysis is the mode of hardening or the variation of the yield level, as increase in the plastic strain takes place. As the main objective of the present article is investigation of buckling of the CFDST columns, the kinematic hardening rule was utilized. For defining the yielding level, the von Mises failure metric was used. In the present research, the Newton-Raphson iterative solving algorithm was employed for solving the non-linear problems (geometric nonlinearity and materials).

After modelling the sample and configuring the analysis parameters in ANSYS software regarding the experiments done by Tao et al [1], the accuracy of the results must be verified. For this purpose, the comparison between the results of numerical analysis of the CFDST column and laboratory sample (presented in table 1) will be elaborated. Figure 2 shows the load-displacement diagram for the sample along with the laboratory results.

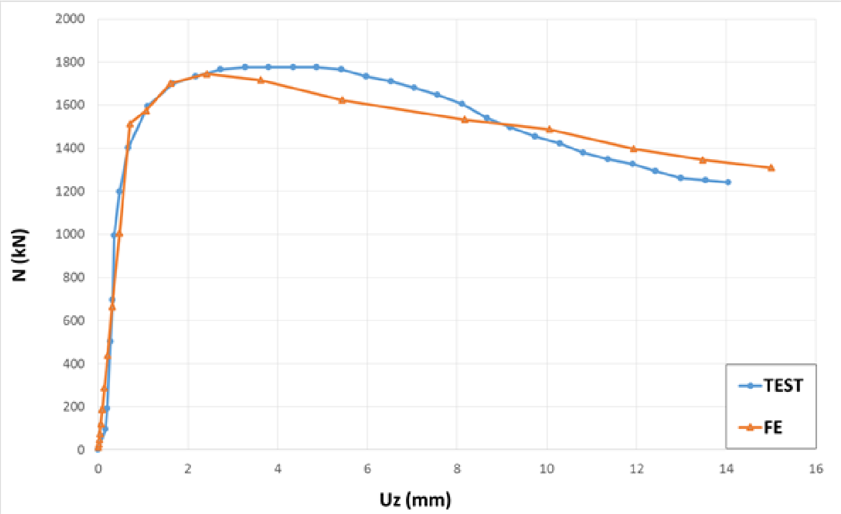

Figure 3: Comparison of load-displacement diagram for CC2A sample

Table 2 present the values associated with ultimate load capacity obtained from laboratory and numerical results. With regard to the 2.51% difference between the results associated with finite element (U_{FEM}) and ultimate load capacity experiment (U_{EXP}) for CC2A sample and comparison between the behavior associated with numerical and experimental sample (figure 2), it can be noted that the numerical model exhibits a proper accuracy. As a result, the suggested 3D finite element model can be used for predicting the behavior of the concrete-filled double skin steel tubular (CFDST).

Table 2. Comparison between the critical loads of CC2A sample obtained from numerical and experimental method

	U_{EXP} (kN)	U_{FEM} (kN)	Difference (%)
CC 2A	1790	1745	% 51.2

2.2. Proposed cross-section shape

As all the experiment applied on the CFDST columns are confined to the samples with simple geometrical specifications, we have attempted to study the buckling of the CFDST columns with new sections, such as hexagon sections, octagonal sections and hybrid square and circular sections and by making comparison between the buckling behaviors of these sections and that of circular section, it was sought to obtain the optimal section (Figure 3). For the correct comparison of the various shapes of the columns, the cross section of steel and concrete in all samples is considered equal to sample CC2A. In table 3, the properties associated with proposed sections are presented. The length of all specimens was equal to 540 mm. Moreover, due to the comparison with CC2A sample, the concrete and steel properties for new sections are considered same as the table 1.

Table 3: Materials properties and sections' dimensions

	CC2A	OHS	HHS	CHS	SHS
$D_i \times T_{si}$ (mm)	48*×3 *Circle diameter	54*×3 *Circumscribed circle diameter	198*×3 *Circumscribed circle diameter	178*×3 *Circle diameter	160*×3 *Length of square side
$D_o \times T_{so}$ (mm)	180*×3 *Circle diameter	190*×3 *Circumscribed circle diameter	58*×3 *Circumscribed circle diameter	38*×3 *Length of square side	48*×3 *Circle diameter

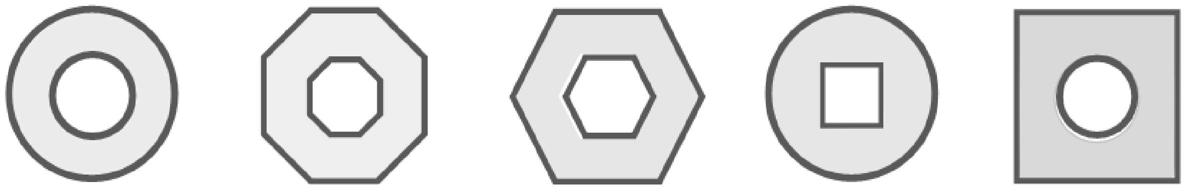

Figure 4: Shapes of studied CFDST

It should be noted that the study specimens of the present research, are short column which follow the allowable stress during buckling (See figure 7)

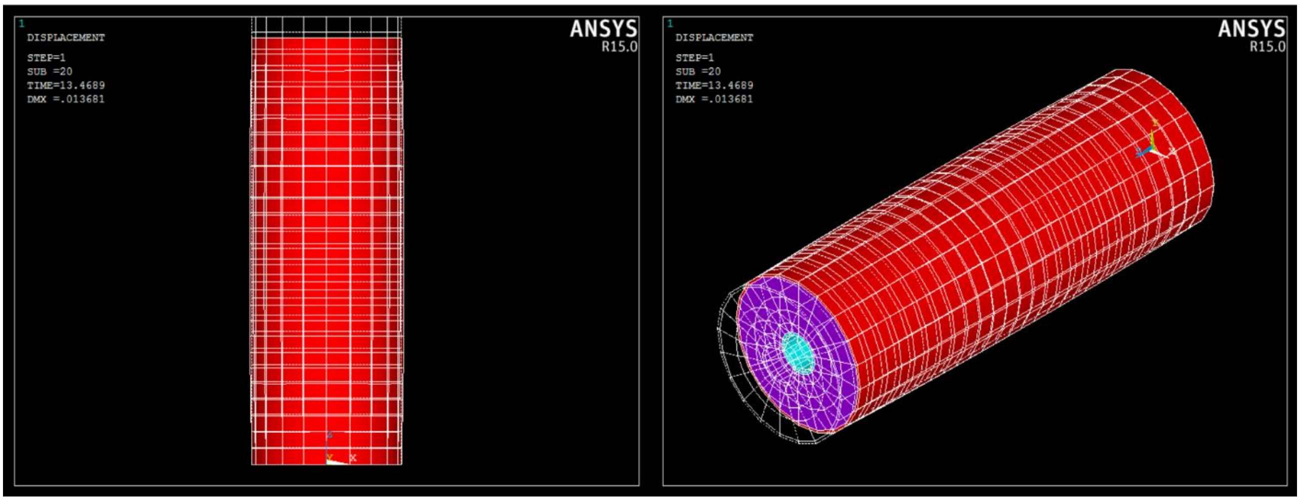

Figure 5: CC2A deformation

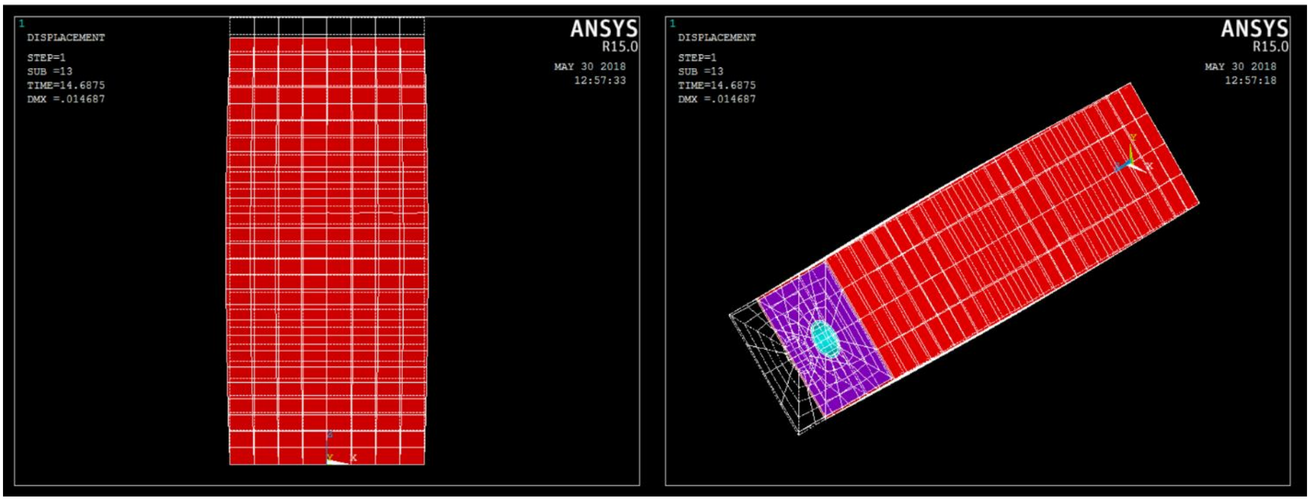

Figure 6: SHS deformation

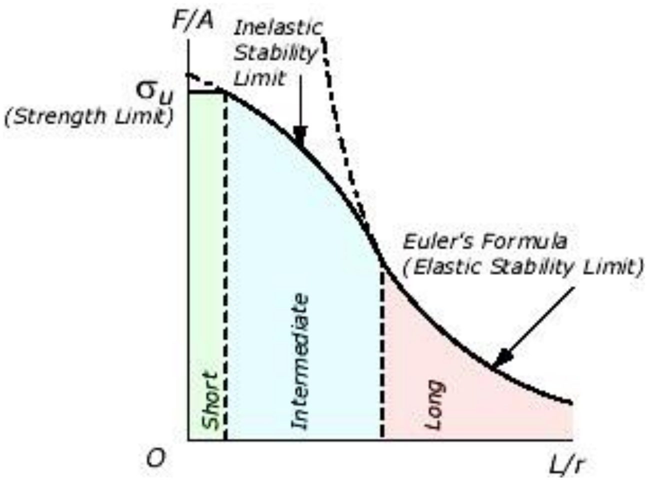

Figure 7: Compression strength of column as a function of length over radius of gyration [16]

The deformation in the sections lead to emergence of load-displacement curved of the CCFDST columns, as it is illustrated by figure 8.

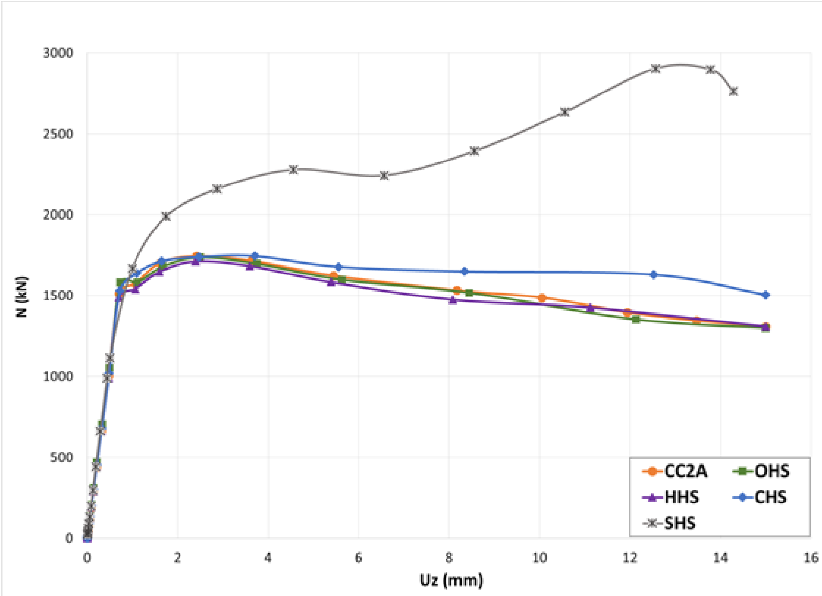

Figure 8: Comparison of load-displacement diagram of CFDST samples

For more precise observation, the critical load of each CFDST column was captured by table 4. As it is depicted by figure 5 and presented in table 4, it is obvious that the composite sections with SHS mode possessing the highest bearing capacity of compressive loading, exhibited the best performance in terms of buckling.

Table 4: Comparison of critical load of CFDST samples

Sample	Critical Load (kN)
CC2A	1745
OHS	1737
HHS	1711
CHS	1744
SHS	2905

2.3. Support condition effect

In the previous samples, the buckling critical load of the CFDST columns when their two ends were rigid was studied. Now, for observing the impact of support conditions on the buckling behavior of the CFDST columns, CC2A sample of reference [1] will be discussed and compared, assuming that one end is rigid, one end is hinged and two ends are hinged.

For investigating the impact of various support conditions on CFDST columns, the load displacement diagram resulted from columns analysis is plotted in figure 6. With regard to the figure, variation of support condition doesn't lead to any significant change in the buckling of the modelled CFDST columns.

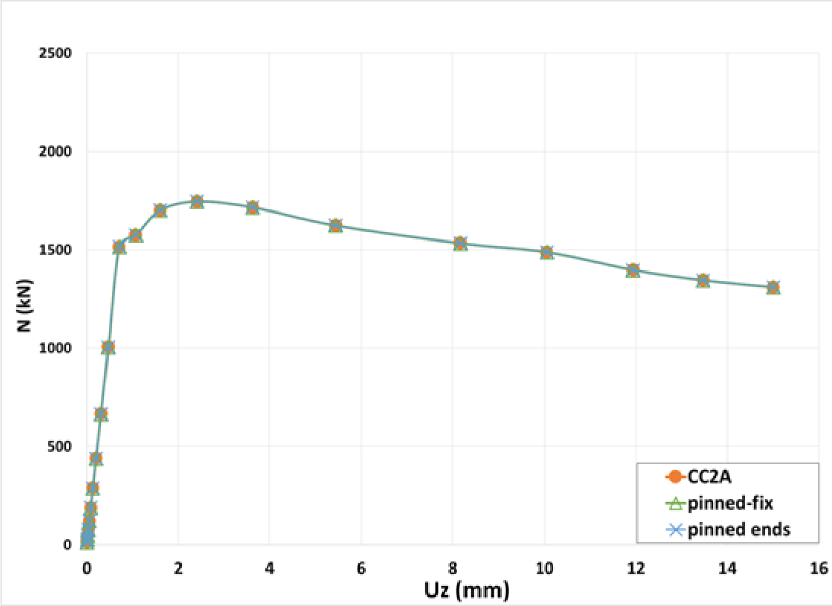

Figure 6: Comparison of load-displacement diagram of CFDST samples

Since the short columns follow the allowed stress of the material, they can be loaded till reaching to the yielding point of the materials and re-hardening zone, no significant variation is observed in the load-displacement diagram of the modelled samples.

2.4. Impact of variation in the backfill concrete

As it is obvious, density plays an important role during the use of the concrete in the CFDST columns is hardly possible or even impossible, the self-compacting concrete will be a proper alternative as the backfill concrete for the columns. Hence, the behavior of the CFDST columns filled with self-compacting concrete will be studied through numerical modelling methods. For this investigation, same dimensions of the column and properties of the steel tubes are considered to be same as the CC2A sample. But, due to the use of self-compacting concrete, we need to know the properties of this concrete. In a research conducted by Gholizadeh, the fabrication and experiment linked to this type of concrete are explained [17].
In the Gholizadeh research, totally 16 mixture designs of the self-compacting concrete with two target compressive strengths of 50 MPa and 60 MPa and two diameter ranges (55 to 60 cm and 65 t0 70 cm) of slump flow of the concrete were designed and produced with four modes of using limestone powder, Aeolian sand and sharing them with viscosity-modifying agent (VMA). In all of the designs, the super-lubricants were used and w/c ratios of the designs was varying in the range of 0.37 to 0.45. By studying the results obtained from Gholizadeh research, the properties of the self-compacting concrete required for modelling finite elements of the present research are presented in table 5.

Table 5: Results of compressive strength and elastic modulus of the SCC designs [17]

Elastic Modulus MPa		Compressive Strength		Number of mixture design
$E=\frac{(S_2-S_1)}{(\varepsilon_2-0.00005)}$		cm cubic 15 28 days old		
Average	Single	Average	Single	
89068	111372	4.55	9.54	65-H1SCC
	66764		8.55	
65636.5	68477	7.76	3.74	65-H2SCC
	62796		0.79	
37723.5	26140	1.52	7.51	65-H3SCC
	49307		5.52	
33330	23130	3.66	4.59	65-H4SCC
	43530		3.66	
49441.5	26020	1.65	5.62	55-H5SCC
	72863		7.67	
20365.5	19751	3.69	9.57	55-H6SCC
	20980		3.69	
51832	21567	2.68	5.60	55-H7SCC
	82097		2.68	
27252	32156	9.63	3.63	55-H8SCC
	22348		5.64	
22215.5	17843	5.56	7.47	65-L9SCC
	26588		5.56	
30480.5	35167	8.56	0.52	65-L10SCC
	25794		8.56	
19927	23078	1.43	2.44	65-L11SCC
	16776		0.42	
60939	49562	3.51	2.51	65-L12SCC

	72316		4.51	
19776.5	25511	4.67	2.47	55-L13SCC
	14042		4.67	
23435.5	15936	5.55	2.53	55-L14SCC
	30935		7.57	
43695.5	61363	3.70	1.62	55-L15SCC
	26028		3.70	
22631	27090	0.61	9.59	55-L16SCC
	18172		1.62	

For labelling the concrete mixtures, the first letter of SCC, refers to the self-compacting concrete and the number after SCC, refers to the design number. Moreover, H letter in the designs, specifies the cylindrical characteristic strength of 45 MPa and target strength of 55 MPa (High), and letter L represents the cylindrical characteristic strength of 35 MPa and target strength of 45 MPa (Low). Moreover, the last number refers to the minimum slump flow diameter or target slump of the self-compacting concrete (unit: cm).

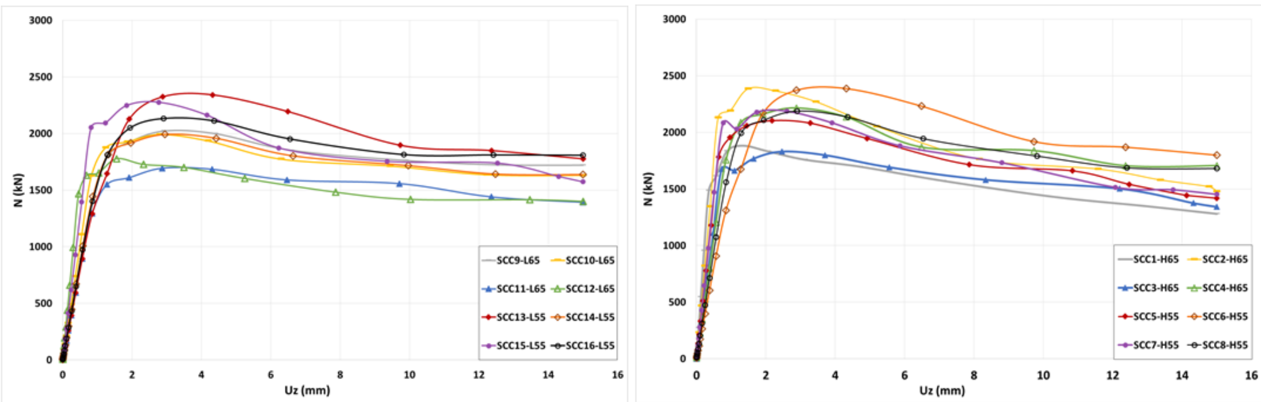

Figure 7: Comparison of load-displacement diagram of CFDST samples filled with concrete

After software analysis, the impact of properties of each concrete sample on the critical load was studied. Figure 7 shows the load-displacement diagram associated with these samples. Moreover, table 6 presents the critical load of the columns on the basis of the type of the backfill concrete for making a comparison

Table 6: Comparison of the critical load of CFDST samples filled with self-compacting concrete

Sample	E_c (MPa)	F'_c (MPa)	Critical load (kN)
66-H1SCC	89068	4.55	859.1881
66-H2SCC	5.65636	7.76	623.2385
66-H3SCC	5.37723	1.52	107.1830
66-H4SCC	33330	3.66	823.2215
55-H5SCC	5.49441	1.65	536.2103
55-H6SCC	5.20365	3.69	352.2386
55-H7SCC	51832	2.68	97.2186
55-H8SCC	27252	9.63	535.2187
65-L9SCC	5.22215	5.56	18.2022
65-L10SCC	5.30480	8.56	836.1990
65-L11SCC	19927	1.43	606.1693
65-L12SCC	60939	3.51	689.1777
55-L13SCC	5.19776	4.67	2341.833
55-L14SCC	5.23435	5.55	1992.051
55-L15SCC	5.43695	3.70	2276.576
55-L16SCC	22631	0.61	2132.975

With regard to table 6, two samples, named SCC2-H65 and SCC6-H55 exhibit almost same and highest critical loads. By comparing the samples of the same elastic modulus, it can be inferred that increase in the compressive strength of the concrete leads to increase in the amount of critical load. Moreover, comparing the samples of the same compressive strength revealed that there is a reverse relation between the amount of critical load and elastic modulus of the self-compacting concrete, similar to the SCC6-H65 sample in which the corresponding compressive strength of the concrete is lower than that of SCC2-H65 samples, while the strength is almost identic to that of SCC2-H65.

3. Conclusion

In the short double skinned composite columns with same cross-sections, the geometric deformation of the sections doesn't lead to a significant variation in the load-bearing capacity of the columns. But in the most ideal mode, the double skinned composite column with square section outer tube and circular section inner tube exhibits the highest ultimate load-bearing capacity. Similar to other short columns, any variation of the support conditions do not lead to a significant change in the buckling of the modelled CFDST columns. The use of self-compacting concrete as the backfill concrete is suggested, due to the hard conditions during concrete pouring of the CFDST. In the case of using the self-compacting concrete, any increase in the compressive strength of the concrete will lead to increase in the critical load of the columns. In the samples with almost equal compressive strength, any reduction in the elastic modulus of the self-compacting concrete will lead to increase in the critical load of the column.

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