Structural design of steel fibre reinforced concrete in-filled steel circular columns

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Abstract. This paper presents the behavior and design of axially loaded normal and steel fiber reinforced concrete in-filled steel tube (SFRCFT) columns, to examine the contribution of steel fibers on the compressive strength of the composite columns. Non-linear finite element analysis model (FEA) using ANSYS software has been developed and used in the analysis. The confinement effect provided by the steel tube is considered in the analysis. Comparisons of the analytical model results, along with other available experimental outputs from literature have been done to verify the structural model. The compressive strength and stiffness of SFRC composite columns were discussed, and the interpretation of the FEA model results has indicated that, the use of SFRC as infill material has a considerable effect on the strength and stiffness of the composite column. The analytical model results were compared with the existing design methods of composite columns – (EC4, AISC/LRFD and the Egyptian code of Practice for Steel Construction, ECPSC/LRFD). The comparison indicated that, the results of the FEA model were evaluated to an acceptable limit of accuracy. The code design equations were modified to introduce the steel fiber effect and compared with the results of the FEA model for verification.

Keywords: Composite structures; finite element; steel fibers; reinforced concrete; tubular columns; confined concrete

1. Introduction

Concrete filled steel tube columns have recently been extensively used in modern structures as typical steel concrete composite elements. The interaction between steel tube and concrete infill provides adequate strength; ductility and stiffness to concrete filled steel tubular columns, (Sakino *et al.* 2004, Han *et al.* 2008, Elchalakani and Zhao 2008, Yang and Han 2009, 2011). Moreover, the steel tubes provide a permanent framework to save material and speedup construction time. Furthermore, the concrete filled steel tubular columns (CFST) show superior mechanical behaviour to that of the conventional reinforced concrete columns due to the confining pressure provided by the steel tube and the prevention of overall buckling provided by the concrete core. However, many researchers cast doubt on the use of plain concrete as in-fill material in steel tubes, due to the extremely disastrous effects of the 1995 Kobe earthquake in Japan on steel and concrete composite structures.

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This prompted a change of seismic design perspectives from the previous emphasis on structural strength to emphasis on structural ductility and energy absorption (Kitad 1998). Accordingly, the in-fill concrete inside steel tubes is required to be of a quality that increases the ductility of composite columns. Among the various in-fill materials, steel fiber is recommended due to high flexural and tensile strength, lower shrinkage, and better fire resistance (Yiyan *et al*. 2011). The main objective of this research is to investigate the behavior and properties of steel fiber reinforced concrete-filled steel tube columns (SFRCFSC). The finite element program, ANSYS software is used in the analysis, because it has been successfully used in many researches such as Jaime *et al* (2009). The material nonlinearities of concrete and steel tube as well as concrete confinement were considered in the analysis. The results obtained from the finite element model for normal concrete filled steel columns were compared with those obtained from a recent experimental work made by (Sakino *et al.* 2004) as well as the results obtained using EC4 (2004), AISC/LRFD (2005) and Egyptian code of practice for steel construction ECPSC/LRFD (2007). While the finite element model for SFRCFC were compared with a recent experimental work made by Gajalakshim and Heleana (2012).

Modified design equations have been implemented to (EC4, AISC/LRFD and ECPSC/LRFD) to consider the effect of steel fiber reinforced concrete in the design of composite columns.

The effect of volume fraction of fiber on the behavior of SFRCFT column has not been studied thoroughly. This paper presents the effect of volume fraction of steel fiber to concrete (V_f%=0.0, 0.5, 1, 1.5, 2%) on the behavior of concentrically loaded SFRCFT column with different slenderness ratio (L/D=10, 20) and with different diameter to tube thickness ratio (D/t=25, 40). A comparative study between the FEA model output and the modified design equations' results has been performed to check the applicability of the expressions recommended by the various codes of practice. Of all the codes compared, EC4 showed the least variation and is found to be more viable to predict the strength of normal and SFRC in filled steel tubes.

2. Finite element model

2.1 General

Concrete filled steel tube (CFST) has been widely used due to its excellent structural performance in terms of strength, ductility and fire resistance. Compared with normal strength concrete or SFRC filled steel tube, SFRC filled steel tube can provide much higher strength and thus smaller column dimensions which is recommended for the development and planning of high-rise buildings. However, concrete material is prone to become very brittle with the increase of concrete strength, representing a serious drawback and limitation of its application in construction. When SFRC is filled into a steel tube to form composite columns, the confining pressure provided by the steel tube can improve the ductility of the SFRC and sudden failure induced by the brittleness of SFRC can be overcome. Therefore, it's very important to adopt a reasonable approach to consider the confinement effect in the analytical modeling of normal and SFRC filled steel tube.

The confining pressure provided by steel tube for SFRC is passive confinement meaning that the pressure is changed during the loading procedure. In this paper, the proposed concrete compressive stress-strain curve was adopted to build up the finite element analysis (FEA) models of normal and SFRC filled composite circular columns subjected to compressive load. Finally, the

FEA model has been verified against the latest experimental data of normal and SFRC filled composite circular columns.

2.2 Material Properties of Confined Concrete

The stress–strain curves for both unconfined and confined concrete are shown in Fig. 1, where f_c is the unconfined concrete cylinder compressive strength, which is equal to $0.8(f_{cu})$, and f_{cu} is the unconfined concrete cube compressive strength. The corresponding unconfined strain (ε_c) is taken as 0.003. The confined concrete compressive strength (f_{cc}) and the corresponding confined stain (ε_{cc}) can be determined in terms of f_c, ε_c and the lateral confining pressure imposed by the steel tube from Eqs. (1), (2), respectively, proposed by (Mander *et al.* 1988).

$$f_{cc} = f_c + K_1 f_1 \tag{1}$$

$$\varepsilon_{cc} = \varepsilon_c [1 + K_2 (f_1 / f_c)] \tag{2}$$

The lateral confining pressure (f_1) depends on the (D/t) ratio and the steel tube yield stress (f_y), and can be obtained from empirical equations given by Hu *et al.* (2003). The factors (K_1) and (K_2) are taken as 4.1 and 20.5, respectively, as given by Richard *et al.* (1928).

$$f_1 / f_y = 0.055048 - 0.001885(D/t) \qquad (17 \le D/t \le 29.2)$$

$$f_1 / f_y = 0.0 \qquad (29.2 \le D/t \le 150)$$

To define the full equivalent uniaxial stress–strain curve for confined concrete as shown in Fig. 1, three stages of the curve have to be identified.

The first stage is the initially assumed elastic range to the proportional limit stress. The value of the proportional limit stress is taken as 0.5 (f_{cc}) as given by Hu *et al.* (2003). The initial Young's modulus of confined concrete (E_{cc}) is reasonably calculated using the empirical Eq. (3), given by ACI code (1999).

$$E_{cc} = 4700 \sqrt{f_{cc}} \text{ MPa} \tag{3}$$

The second stage of the curve is the nonlinear portion starting from the proportional limit stress 0.5 (f_{cc}) to the confined concrete strength (f_{cc}). This part of the curve can be determined from Eq. (4), which is proposed by Saenz (1964). The unknowns of the equation are the uniaxial stress (f) and strain (ε) values defining this part of the curve. The strain values (ε) are taken between the proportional strain, which is equal to ($0.5f_{cc}$ / E_{cc}), and the confined strain (ε_{cc}), that corresponds to the confined concrete strength.

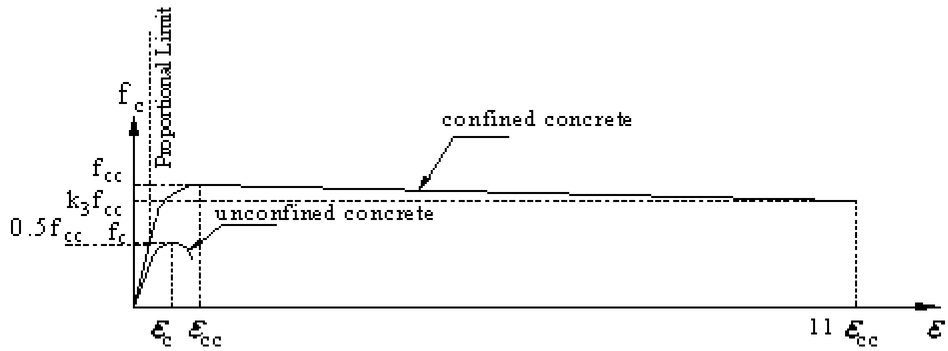


Fig.1 Equivalent uniaxial stress–strain curves for confined and unconfined concrete

The stress values (f) can be determined from Eq. (4) by assuming the strain values (ε)

$$f = E_{cc}\,\varepsilon / \{1 + (R + R_E - 2)(\varepsilon/\varepsilon_{cc}) - (2R - 1)(\varepsilon/\varepsilon_{cc})^2 + R(\varepsilon/\varepsilon_{cc})^3\} \quad (4)$$

$$R_E = E_{cc}\,\varepsilon_{cc} / f_{cc} \quad (5)$$

$$R = [R_E (R_\sigma - 1) / (R_E - 1)^2] - [1 / R_\varepsilon] \quad (6)$$

The constants R_σ and R_ε are equal to 4 as recommended by Hu and Schnobrich (1989)

The third stage of the confined concrete stress–strain curve is the descending part used to model the softening behavior of concrete from the confined concrete strength (f_{cc}) to a value lower than or equal to k3 f_{cc} with the corresponding strain of 11 ε_{cc}. The reduction factor (k3) depends on the D/t ratio of the steel tube. The approximate value of (k3) can be calculated from empirical equations given by Hu *et al.* (2003).

$$k3 = 0.000178(D/t)^2 - 0.02492\,(D/t) + 1.2722 \qquad (17 \le D/t \le 70)$$

$$k3 = 0.4 \qquad (70 \le D/t \le 150)$$

2.3 General Description of the Finite Element Model

FEA model is developed to simulate the behavior of normal and SFRC in-filled composite circular columns subjected to an axial compressive load by adopting ANSYS software as shown in Fig. 2. The stress-strain relation of confined concrete is adopted in ANSYS model as proposed in Section 2.2. For the steel circular tube, a typical elastic plastic stress–strain relation is simulated by an elastic-perfectly plastic model.

The steel tube is modeled using a 4-node shell element, with six degrees of freedom at each node (element; SHELL 63 in ANSYS12.0). Inelastic material and geometric nonlinear behavior are used for this element. A 50 mm thick steel plate, modeled using (element; SOLID 45 in ANSYS12.0), is added at the support locations in order to avoid stress concentration problems and to prevent localized crushing of concrete elements near the supporting points and load application locations.

The concrete core of SFRC in-filled steel tube columns is modeled using 8-node brick elements, with three translation degrees of freedom at each node (element; SOLID 65 in

ANSYS12.0) as shown in Fig. 3. Steel fibers is modeled in concrete using the rebar option included in SOLID 65 real constant by defining the steel fiber material properties, volumetric ratio and orientation angle in x, y and z directions.

The gap element is used for the interface between the concrete and the steel components. The gap element has two faces; when the faces are in contact; compressive forces are developed between the two materials resulting in frictional forces. The friction coefficient used in the analysis is 0.25. On the other hand, if the gap element is in tension, the two faces separated from each other, resulting in no contact between the concrete and steel, and consequently no bond is developed. TARGE170 element is used to represent various 3-D “target” surfaces for the associated contact elements (CONTA173).

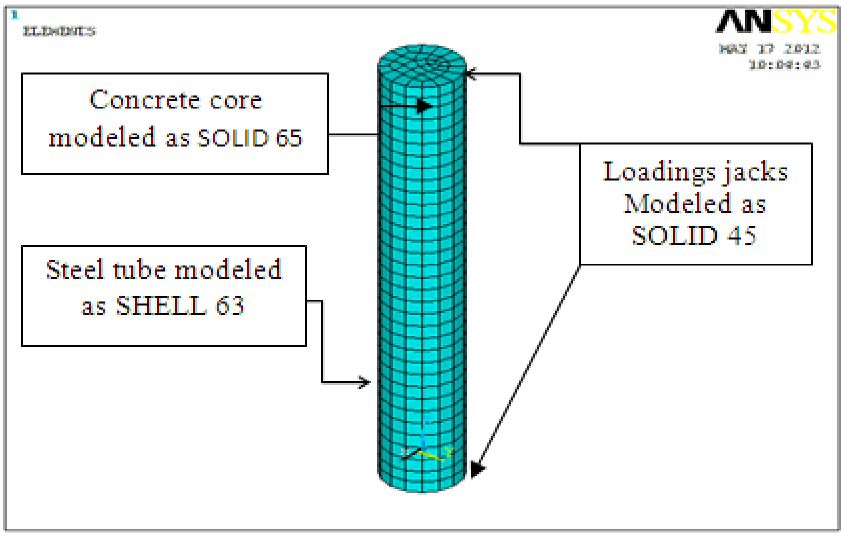


Fig. 2 Finite element meshes for concrete filled steel circular columns

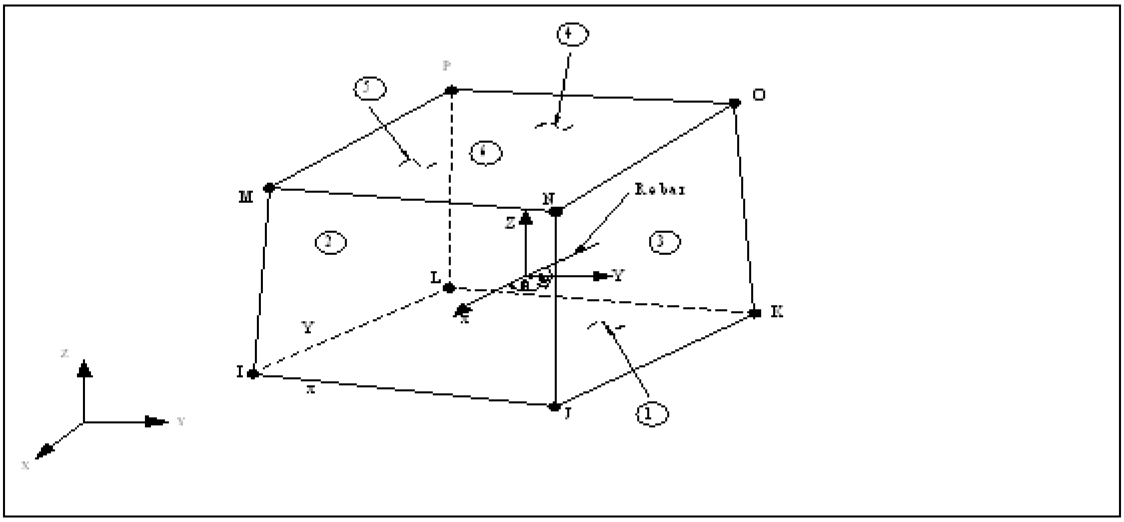


Fig. 3 Modeling of SFRC core using shell element (SOLID65)

The top surface of the column is prevented from displacement in the X and Y directions but allows displacement to take place in the Z direction. The bottom surface of the column is prevented from displacement in the X and Y directions and prevented from displacement in Z direction at the point opposite to the point of load application at the top of column. The compressive load is applied to the top surface in the Z direction through the rigid steel cap to distribute the load uniformly over the cross section.

3. Verification of the finite element analysis (FEA) model

The FEA model is adopted to simulate the behaviors of normal and SFRC filled composite circular columns subjected to axial compressive loads.

3.1 Verification of FEA model regarding simulating normal concrete in-field steel tube column

The experimental data of five concrete filled steel circular columns from (Sakino *et al.* 2004) are used to verify the proposed finite element model for normal concrete filled steel circular columns. Table1 lists the dimensions, D/t ratios, and material properties of the analyzed concrete filled steel circular columns.

Table 1 Geometry and material properties of normal concrete filled steel circular columns

Column Name	D (mm)	t (mm)	Length "L" (mm)	*D/t*	f_y (MPa)	f_c (MPa)	Reference
CC4-A-2	149	2.96	900	50.4	308	25.4	Sakino *et al.* (2004)
CC4-A-4-1	149			50.4	308	40.5	
CC4-C-2	301			101.5	279	25.4	
CC4-C-4-1	300			101.4	279	41.1	
CC4-D-4-1	450			152	279	41.1	

Table 2 Comparison between the FEA model outputs and corresponding results obtained from experimental studies, nominal EC4, AISC/ LRFD and ECPSC/LRFD Specifications.

Column Name	Results					Comparison			
	N_{exp} (kN)	N_{EC4} (kN)	N_{AISC} (kN)	N_{ECPSC} (kN)	N_{FEA} (kN)	N_{FEA} / N_{EC4}	N_{FEA} / N_{AISC}	N_{FEA} / N_{ECPSC}	N_{FEA} / N_{exp}
CC4-A-2	941	819	787	751	830	1.01	1.05	1.11	0.88
CC4-A-4-1	1064	1052	1008	949	1052	1.00	1.04	1.11	0.99
CC4-C-2	2382	2510	2408	2239	2252	0.90	0.94	1.01	0.95
CC4-C-4-1	3277	3562	3396	3122	3024	0.85	0.89	0.97	0.92
CC4-D-4-1	6985	7299	7179	6550	6730	0.92	0.94	1.03	0.96
Mean						0.94	0.97	1.04	0.94
Standard Deviation						0.07	0.07	0.06	0.04

The capacities' results of the concrete filled steel circular columns using the suggested finite element model, N_{FEA}, are compared with the experimental results given by Sakino *et al.* (2004), N_{exp}. The analytical results are also compared with the design equations of the AISC/LRFD (2005), N_{AISC}, the Egyptian code of practice for steel construction, N_{ECPSC}, and EC4 (2004), N_{EC4}, that are listed in Table 2.

It can be concluded that:

- The results of the FEA model are in compliance with the experimental results.
- The comparison shows that, the proposed FEA model provides results with very close estimates to determine the axial capacities of concrete filled steel tube columns compared to the three design codes.

3.2 Verification of FEA model regarding simulating SFRC in-field steel tube column

In order to verify the FEA model for simulating SFRC in-filled steel tube columns, a comparative study is conducted using the experimental results of 6- specimens tested by Gajalakshim and Heleana (2012). 114 mm diameter hot finished circular hollow section with 2 mm and 3 mm wall thickness were used for tests. The column dimensions were 1m long, with fixed conditions at the bottom. The concrete mix had a cube compressive strength of 20 MPa. The SFRC in-filled steel composite columns were prepared with different volume fraction of steel fibers that were chosen viz., 0.75 %, and 1.00%. Crimped steel fibers having an aspect ratio of 70 (length of the fiber (l_f) = 30.8 mm and diameter of fiber (d_f) =0.44 mm were used. Data of the test specimens and the comparison of the experimental results with the FEA model output are shown in Table 3.

Table 3 Comparison between the FEA model outputs and corresponding results obtained from experimental studies for SRFC in-filled steel tube columns

Column Name	Column dimensions and properties			Ultimate load(KN)		Comparison
	D/t	f_y N/mm^2	V_f %	N_{exp} (kN)	N_{FEA} (kN)	N_{FEA}/N_{exp}
CFT57	57	270	0	350	340	0.97
S1CFT57			0.75%	400	385	0.96
S2CFT57			1.00%	490	475	0.97
CFT38	38	293	0	430	436	1.01
S1CFT38			0.75%	480	468	0.98
S2CFT38			1.00%	560	566	1.01
Mean						0.98
Standard Deviation						0.02

- It can be concluded that the accuracy of the FEA model for simulating SFCR in-filled steel tube columns is acceptable.

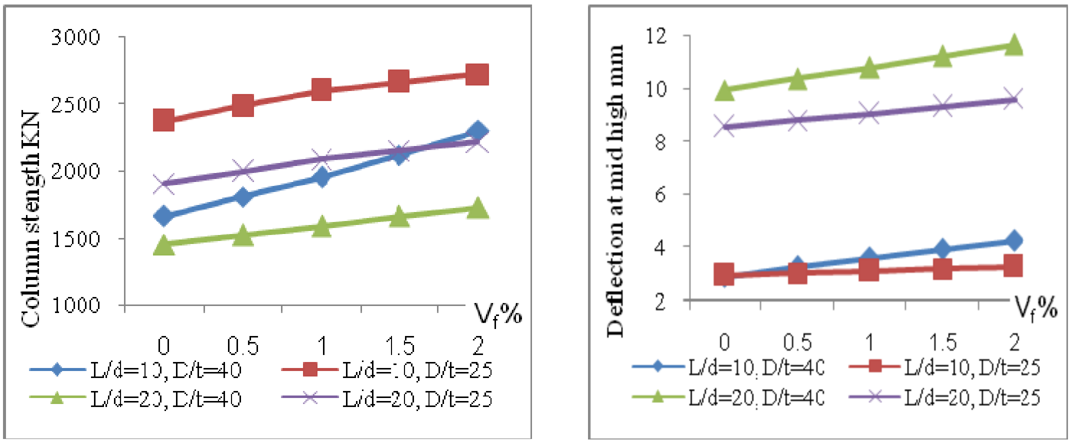
4. Parametric study and discussion

A total of 20 columns have been analyzed in the parametric study and the dimensions along with column strengths are listed in Table 4. The effect of volume fraction of steel fiber to concrete (V_f% =0.0, 0.5, 1.0, 1.5, 2.0%) on the behavior of concentrically loaded SFRCFT column was investigated. The columns are chosen with different slenderness ratio (L/D =10, 20) and different diameter to tube thickness ratio (*D/t* = 25, 40). The steel tube yield strength is 360 MP and the concrete cubic strength is 30 MP. The diameter of steel tubes is 200mm with thicknesses 5 and 8mm. The column length is 2000 and 4000 mm with hinged end conditions. The steel fiber aspect ratio L_f/d_f=120, in which the fiber length L_f=60mm and diameter d_f=0.5mm.

The measured strength of each column, together with the corresponding deflection of the column at mid-height, is presented in Table 4.

Fig. 4a shows that, the slenderness ratio has a marked detrimental effect on column strength, and the compressive strength increases with the increase of fiber percentage. It is observed that the slenderness ratio and the percentage of fibers influenced the load capacity. In comparison with the plain concrete in-filled column, the ultimate strength of the SFRC in-filled composite column is approximately 15%–38% higher.

The stiffness is defined as the ability to resist lateral deformation, and can be determined as the ratio of the compressive strength to the corresponding displacement at the columns' mid height. The lateral deflection of the columns at mid- height together with the fiber percentage of different column slenderness ratio, and tube thickness is presented in Fig. 4b. It is concluded that the use of fiber reinforced concrete in the steel tube has slight effect in column's stiffness, where the ratio of the compressive strength to the corresponding columns' mid-height displacement is slightly increased less than 4% for columns C06 to C20, while decreased by about 6% for columns C01 to C05.



(a) (b)

Fig. 4 (a) Effect of column slenderness and V_f% on column strength, (b) Effect of column slenderness and V_f% on mid high lateral deflection

The typical structural behavior of the analyzed columns is presented in Fig. 5 by the relationship between the load and the lateral deflection at mid-height. It is clearly shown from the figure that the deflection was small during the initial stage of loading and increased rapidly near the ultimate load. The figure also shows that the use of steel fiber reinforced concrete reduces the mid height displacement at any given level of load. It can be concluded that the flexibility of SFRC in-filled columns is reduced with the increase of volume fraction of steel fiber to concrete "V_f %" throughout the entire load-deflection range. The reason is attributed to the fact that the strength of SFRC composite columns increases with the increase of volume fraction of steel fiber to concrete "V_f%".

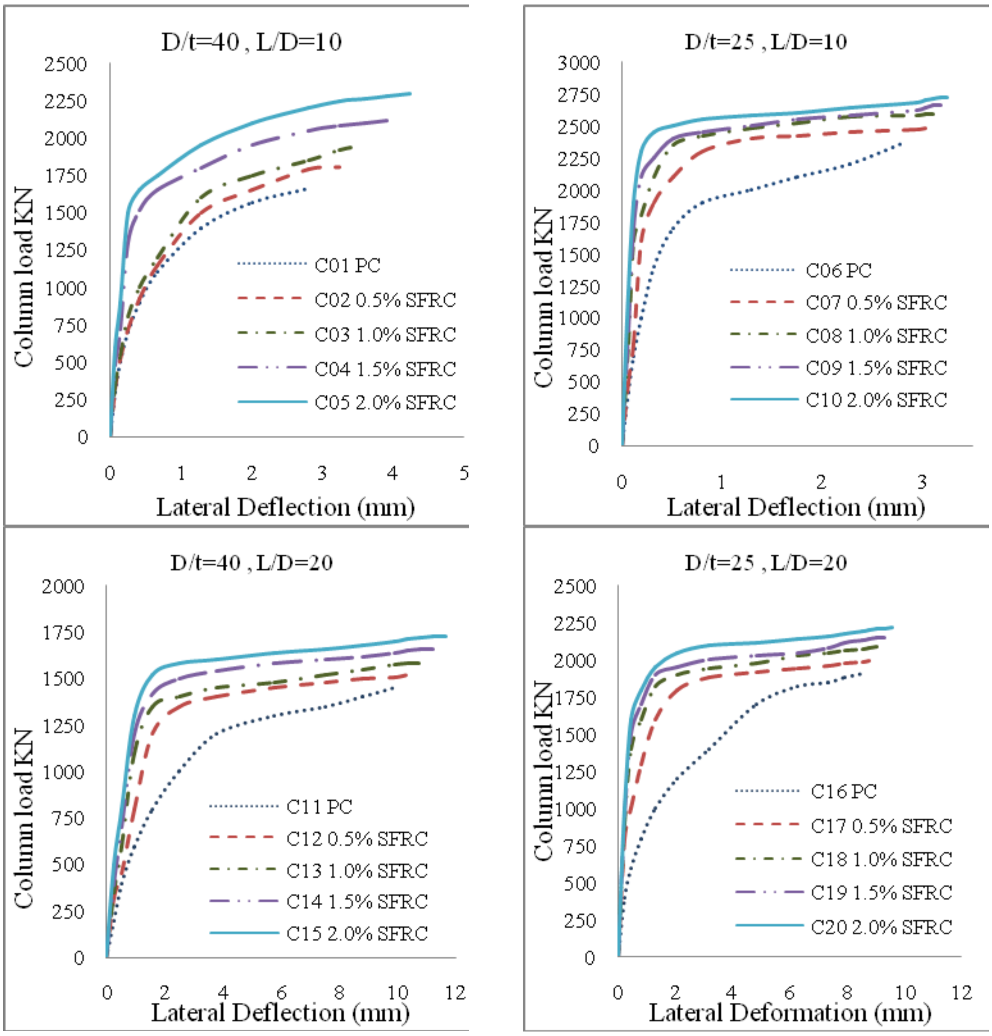


Fig. 5 Load deflection relationship of columns

Table 4 Geometry, material properties and FEA results of SFRC in-filled steel tube columns

Column name	Steel tube thickness t (mm)	Length L (mm)	V_f%	D/t	Slenderness ratio L/D	Column strength N_{FEA}(KN)	Deflection at mid high (mm)
C01	5	200	0	40	10	1661	2.89
C02			0.5			1805	3.25
C03			1.0			1952	3.60
C04			1.5			2120	3.92
C05			2.0			2294	4.24
C06	8		0	25		2370	2.94
C07			0.5			2480	3.03
C08			1.0			2597	3.11
C09			1.5			2660	3.18
C10			2.0			2720	3.25
C11	5	4000	0	40	20	1453	9.92
C12			0.5			1520	10.35
C13			1.0			1584	10.78
C14			1.5			1660	11.20
C15			2.0			1727	11.64
C16	8		0	25		1905	8.54
C17			0.5			1996	8.78
C18			1.0			2086	9.02
C19			1.5			2150	9.30
C20			2.0			2215	9.56

5. Modification of the design equations (EC4 2004, AISC/LRFD 2005, and the ECPSC/LRFD 2007) to design SFRC in-filled steel tube columns

The concrete compressive stress, f_c, and the modulus of elasticity E_c, are modified to consider the effect of steel fiber reinforcement. The modifications for the cylinder compressive stress f_{cf}, the cubic compressive stress, f_{cuf} and the modulus of elasticity, E_{cf} of SFRC shall be implemented to the EC4 (2004), AISC/LRFD 2005, and the ECPSC/LRFD (2007) to design SFRC in-filled steel circular columns. The modification will be performed as follows:

The cylinder and cubic compressive strength of SFRC, f_{cf} and f_{cuf} can be performed as per Nataraja *et al.* (1999) formula;

$$f_{cf} = f_c + 2.1604\,[W_f\,(l_f / d_f)] \tag{7a}$$

$$f_{cuf} = f_{cu} + 2.7\,[W_f\,(l_f / d_f)] \tag{7b}$$

where f_c and f_{cu} are the cylinder and cubic compressive strength of normal concrete in MPa, W_f is the weight percentage of fibers that is equal to $3.14V_f$, l_f and d_f are the length and diameter of fibers, respectively.

The modulus of elasticity E_{cf} of SFRC can be calculated according to Bentur and Mindess (1990) formula;

$$E_{cf} = \gamma\, V_f\, E_f + (1 - V_f)\, E_c \tag{8}$$

where E_f and E_c are the modulus of elasticity for fibers and concrete, respectively, while the correlation factor γ is given by

$$\gamma = \eta\ \{1 - [\tanh (n_r\, l_f / d_f) / (n_r\, l_f / d_f)]\} \tag{9}$$

The factor η depends on fiber distribution and is equal to 1/6, 1/3 for random distribution in 3D and 2D space, respectively.

While, the dimensionless coefficient n_r is equal to

$$n_r = [2\, E_c / E_f\, (1 + v_c)\, \log_e (1/V_f)]^{½} \tag{10}$$

where v_c is the Poisson's ratio of normal concrete that is equal to 0.2.

5.1 Modification of the design equations of EC4 (2004)

The maximum compressive force of a short composite column $N_{pl,\, rd}$ with a slenderness parameter $\lambda \leq 0.2$ can be computed by the sum of the resistances of its components as follows

$$N_{pl,\, rd} = [A_s\, f_y / \gamma_s] + [A_c\, f_{cf} / \gamma_c] \tag{11}$$

where γ_s and γ_c are the partial safety factors for steel and concrete and are equal to 1.1, 1.5, respectively.

The maximum compressive force of a slender composite column $N_{pl,\, rd}$ with a slenderness parameter $\lambda > 0.2$ shall be multiplied by a reduction factor χ

Therefore, the design load is equal to

$$N_d = \chi * N_{pl,\, rd} \tag{12}$$

$$\chi = 1 / [\varphi + \sqrt{(\varphi^2 - \lambda^2)}] \tag{13}$$

$$\varphi = 0.5\, [1 + 0.21\, (\lambda - 0.2) + \lambda^2] \tag{14}$$

The slenderness parameter λ is calculated as follows

$$\lambda = \sqrt{(N_{plr} / N_{cr})} \tag{15}$$

In which the elastic critical normal force N_{cr} is given as

$$N_{cr} = \pi^2\, (EI)_e / (KL)^2 \tag{16}$$

The effective rigidity $(EI)_e$ is given as

$$(EI)_e = E_s\, I_s + 0.6\, E_{cf}\, I_c \tag{17}$$

The plastic resistance force N_{plr} is given as

$$N_{plr} = A_s f_y + A_c f_{cf} \tag{18}$$

5.2 Modification of the design equations (AISC/LRFD 2005) to design SFRC in-filled steel tube columns.

The design compressive strength of an axial loaded column is given as

$$\varphi P_n \geq P_u \tag{19}$$

where φ is the resistance factor which is equal to 0.75

The nominal compressive strength P_n is given by

a) When $P_e \geq 0.44\, P_o$

$$P_n = P_o \quad [0.658^{(Po/Pe)}] \tag{20}$$

b) When $P_e < 0.44\, P_o$

$$P_n = 0.877\, P_e \tag{21}$$

$$P_o = A_s f_y + C_2 A_c f_{cf} \tag{22}$$

$$P_e = \pi^2\, (EI)_{eff} / (KL)^2 \tag{23}$$

$$(EI)_{eff} = E_s I_s + C_3 E_{cf} I_c \tag{24}$$

$$C_3 = 0.6 + [A_s / (A_c + A_s)] \leq 0.9 \tag{25}$$

where;
C_2 = 0.95 for circular sections.
$(EI)_{eff}$ = effective moment of inertia rigidity of composite column, Mpa.
I_c, I_s are the moment of inertia of the concrete and steel tube, respectively, in mm4
K = effective length factor
L = laterally un-braced length of the member, mm.

5.3 Modification of the design equations of Egyptian code of practice for steel construction (ECPSC/LRFD 2007)

The design strength of the symmetric axially loaded composite columns, P_u, shall be computed on the steel section area utilizing a modified radius of gyration, yield stress, Young's modulus, r_m, f_{ym} and E_{mf}, respectively.

$$P_u = \varphi\, A_s f_{crf} \tag{26}$$

φ is the resistance factor for compression member and equal to 0.8

For short columns
$\lambda_{mf} \leq 1.1$

$$f_{crf} = (1 - 0.348\,\lambda_{mf}^{2})\,f_{ymf} \tag{27}$$

For slender columns
$\lambda_{mf} \leq 1.1$

$$f_{crf} = 0.648\,f_{ymf} / \lambda_{mf}^{2} \tag{28}$$

The Euler buckling stress of SFRC composite column λ_{mf} can be given by;

$$\lambda_{mf} = KL\,[f_{ymf} / E_{mf}]^{1/2} / \pi\, r_m \tag{29}$$

$$E_{mf} = E_s + 0.4\,E_{cf}\,(A_c / A_s) \tag{30}$$

$$f_{ymf} = f_y + 0.68\,f_{cuf}\,(A_c / A_s) \tag{31}$$

where, r_m = radius of gyration of the steel tube only.

Table 5 Comparison between the FEA model outputs and corresponding results obtained from modified design equations of EC4, AISC/ LRFD and ECPSC/LRFD

Column Name	Results				Comparison		
	N_{EC4} (kN)	N_{AISC} (kN)	N_{ECPSC} (kN)	N_{FEA} (kN)	N_{FEA} / N_{EC4}	N_{FEA} / N_{AISC}	N_{FEA} / N_{ECPSC}
C01	1845	1780	1718	1661	0.90	0.93	0.97
C02	1956	1877	1803	1805	0.92	0.96	1.00
C03	2065	1974	1889	1952	0.95	0.99	1.03
C04	2176	2070	1974	2120	0.97	1.02	1.07
C05	2286	2166	2059	2294	1.00	1.06	1.11
C06	2400	2329	2274	2370	0.99	1.02	1.04
C07	2503	2421	2356	2480	0.99	1.02	1.05
C08	2607	2513	2436	2597	1.00	1.03	1.07
C09	2710	2604	2517	2660	0.98	0.95	1.06
C10	2813	2695	2596	2720	0.97	1.01	1.05
C11	1484	1437	1394	1453	0.98	1.01	1.04
C12	1577	1505	1445	1520	0.97	1.01	1.05
C13	1670	1571	1493	1584	0.95	1.01	1.06
C14	1764	1636	1539	1660	0.94	1.01	1.08
C15	1858	1699	1582	1727	0.93	1.02	1.09
C16	1949	1896	1853	1905	0.98	1.00	1.03
C17	2037	1961	1901	1996	0.98	1.02	1.05
C18	2125	2024	1948	2086	0.98	1.03	1.07
C19	2212	2087	1994	2150	0.97	1.03	1.08
C20	2300	2148	2038	2215	0.96	1.03	1.09
Mean					0.97	0.99	1.06
Standard Deviation					0.03	0.04	0.08

6. Comparative study between the results of FEA model and the design code equations

In this section, a comparative study between the FEA model output and the modified design equations' results is performed to check out the applicability of the expressions recommended by the various codes of practice. The ultimate axial strengths of SFRC in-filled steel tube circular columns obtained from the parametric study, N_{FEA} are compared with the design strengths predicted by the EC4, N_{EC4}, American Specifications AISC/LRFD (2005), N_{AISC}, and the Egyptian code of practice, ECPSC/LRFD, N_{ECPSC}. In calculating the design strengths, the unity material partial safety factors have been used.

Table 5 shows comparison of the column strengths obtained from the parametric study with the design strengths calculated from Eq. (11), (12) for EC4, Eq. (20), (21) for AISC/LRFD (2005), and Eq. (26) for ECPSC/LRFD, respectively.

It can be observed that the modified equations of the design codes calculate successfully the capacity of SFRC in-filled steel circular columns. The mean value of N_{FEA}/ N_{AISC} ratio is 0.99 with standard deviation of 0.04; the mean value of N_{FEA}/ N_{ECPSC} ratio is 1.06 with standard deviation of 0.08; the mean value of N_{FEA}/ N_{EC4}, ratio is 0.97 with standard deviation of 0.03. EC4 showed the least variation and is found to be more viable to predict the strength of normal and SFRC in-filled steel tubes.

7. Conclusions

A nonlinear finite element model for the analysis of normal and SFRC in-filled steel tube columns has been presented. The confined concrete model was accurately introduced. The stress–strain curve for steel tubes is assumed elastic-perfectly plastic in simulating the material of the steel tubes. The comparison between the finite element results, and the experimental results for the columns with different volume fraction of steel fiber to concrete and different geometric dimensions showed good accuracy in predicting the columns' behavior. The column strengths have been predicted using the finite element model and compared with the experimental results. A parametric study of 20 plain and SFRC in-filled steel tube circular columns with different slenderness ratio (L/D=10, 20) and of the steel tube diameter to plate thickness (D/t=25, 40) and concrete cube strength 30MPa is performed using the finite element analysis.

The results obtained from the proposed model exhibit good correlation with the available experimental results in the literature as well as the predicted EC4 (2004), AISC/LRFD (2005) and the ECPSC/LRFD (2007).

The use of SFRC has resulted in considerable improvement in the structural behavior of composite columns.

The slenderness ratio has a very remarkable effect on the strength and behavior of SFRC in-filled steel tube columns.

SFRC filled steel tubular columns have relatively higher strength compared with plain concrete filled columns.

The use of SFRC as a filling material increases the load bearing capacity to a much greater extent compared with that of plane concrete in-filled steel tube columns.

The design equations of (EC4 2004, AISC/LRFD 2005, and the ECPSC/LRFD 2007) have been modified to introduce the steel fiber effect in the design of composite columns.

A comparative study between the FEA model output and the modified design equations' results was performed and compatibility in results has been proved.

EC4 showed the least variation and is found to be more viable to predict the strength of plain and SFRC in-filled steel tubes.

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