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Behavior and Design of Steel Box Columns In-Filled with Plain and Steel Fiber Reinforced Concrete under Centric and Eccentric Loads

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Abstract

The present study investigates the behavior of steel tubular columns in-filled with plain and steel fiber (SF) reinforced concrete. A nonlinear finite element model (FEM) using ANSYS program has been developed and the results obtained from the FEM are compared with the recent experimental works. The comparison indicated that the results of the model are evaluated to an acceptable limit of accuracy. The main parameters considered in the analysis were the slenderness, steel box wall thickness, cross section, percentage of (SF) and load eccentricity. The results indicated that the addition of SF in core concrete has considerable effect on the behavior of concrete-filled steel tube columns. A modified design equations have been implemented to (Euro code 4 2004) and (AISC/LRFD 2009) to consider the effect of SF reinforced concrete in the design of composite columns. A comparison study between the FEM results and those of the modified design equations is performed and good agreement is proved.

Keywords: composite columns, finite element, steel fiber, non linear analysis, steel box

1. Introduction

Traditional concrete filled steel columns (CFSC) employ the use of hollow steel sections filled with concrete. These columns have been used extensively as they speed up construction by eliminating formwork and the need for tying of longitudinal reinforcement. The steel box of these composite columns acts as longitudinal and lateral reinforcement therefore, it is not required any additional reinforcement to the columns. Local buckling becomes a critical issue for design of steel tube columns (Liang el al. 2006, 2007; Mursi, Uy 2003, 2004; Petrus et al. 2010; Uy et al. 2011). For this reason steel tubes are filled with concrete to overcome this weakness. Furthermore, the concrete is enhanced in its strength, durability and performance as it suffers less creep and shrinkage and the quality is improved thus allowing a larger compressive stresses to be resisted by the column (Chitawadagi et al. 2010; Liu 2004, 2006; Tao et al. 2008, 2011). Moreover SF reinforcement concrete is used as an in-fill material due to its greater flexural and tensile strength than normal concrete (Premalatha, Sundara 2009; Ardeshana, Desai 2012; Yaragal et al. 2011).

The main objective of this research is to investigate the behavior and properties of SF reinforced concrete in-filled steel tube columns. A finite element program using ANSYS software is used in the analysis. The material nonlinearities of concrete and steel tubes as well as concrete confinement were considered in the analysis. A parametric study is carried out to investigate the effect of wall thickness, slenderness ratio of column and percentage of SF in concrete on the ultimate strength of composite columns. A modified design equations have been implemented to Euro Code 4 2004, (EC4) specification, (AISC/LRFD 2009) specification to consider the effect of fiber reinforced concrete in the design of composite steel beam columns.

2. Finite element model

2.1 General

The actual behavior of normal and SF reinforced concrete in-filled steel box columns is simulated. The main four components of these columns are modeled. These components are the confined concrete containing SF, the steel box, the steel plates as a loading jacks and the interface between the concrete and the steel box. In addition to these parameters, the choice of the element type and mesh size that provide reliable results with reasonable computational time is also important in simulating structures with interface elements (Abdallah 2012).

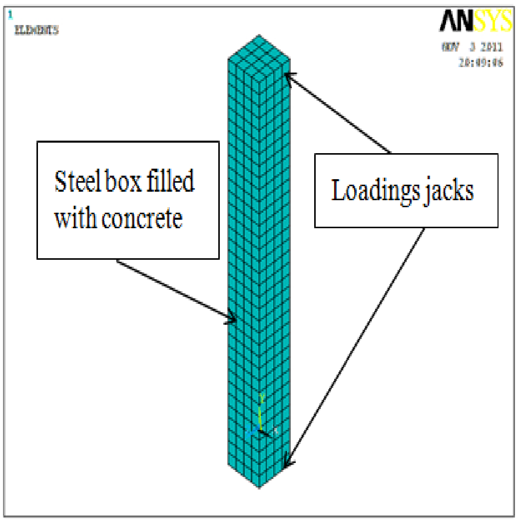
2.2 Finite Element Type and Mesh

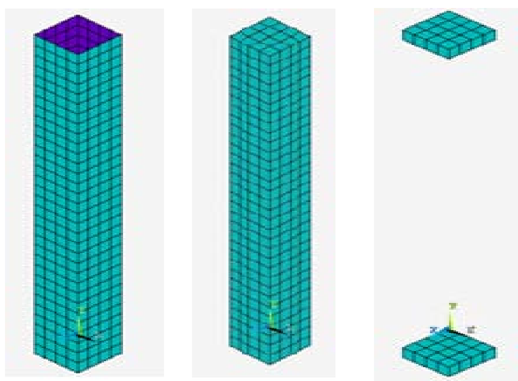
The concrete core of fiber reinforced concrete filled steel box columns is modelled using 8-node brick elements, with three translation degrees of freedom at each node (element; SOLID 65 in ANSYS12.0). SF is modelled in concrete using the rebar option included in SOLID 65 real constant by defining the SF material properties, volumetric ratio and orientation angle in x, y and z directions. The steel box is modelled 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 behaviour are used for this element. Von Mises yield criteria is used to define the yield surface. No strain-hardening is assumed for the steel box. Thus, if strain-hardening characteristics are observed in concrete filled steel box column behaviour, it is primarily due to the interaction between the steel and concrete components. A 50 mm thick steel plate, modelled using (element; SOLID 45 in ANSYS12.0), was 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 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 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 developed.TARGE170 is used to represent various 3-D “target” surfaces for the associated contact elements (CONTA173). Figure 1 shows the finite element mesh of the concrete-filled steel box column.

2.3 Boundary condition and load application

The top surface of the column is prevented from displacement in the X and Z directions but allows displacement to take place in the Y direction. On the other hand, the bottom surface of the column is prevented from displacement in the X and Z directions and prevented from displacement in Y direction at the point that is opposite to the point of load application at the top of column, as shown in Figure 2. The corners of the steel tube are assumed to be exactly 90^{o} and corner radii are not considered. The compressive load is applied to the top surface in the Y direction through a rigid steel cap to distribute the load uniformly over the cross section.

Figure 1.Typical model of concrete in-filled steel box columns’ components



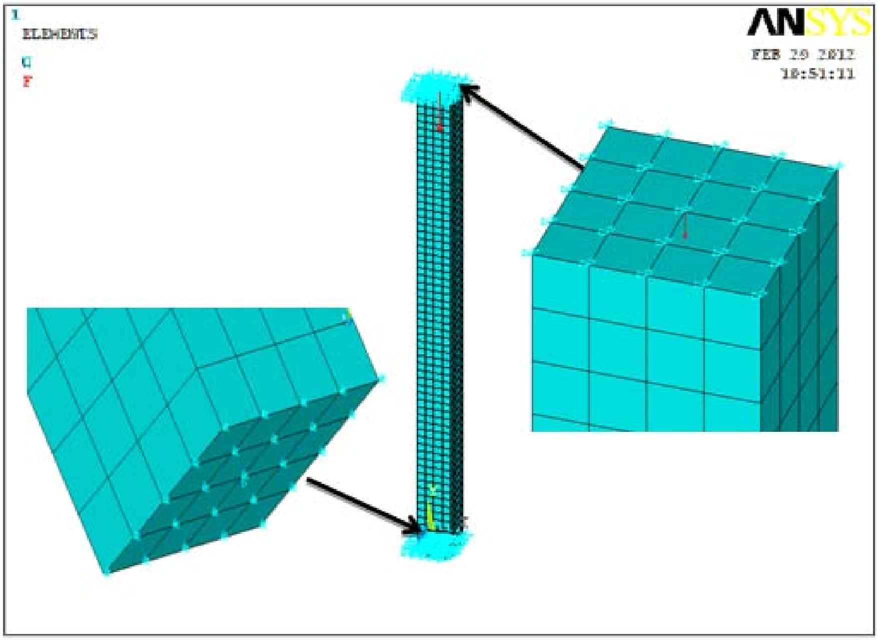


Shell 63 Steel box plates

Solid 65 Infill concrete

Solid 45 Loading jacks’ plates

Figure2. Load application and column' restraints

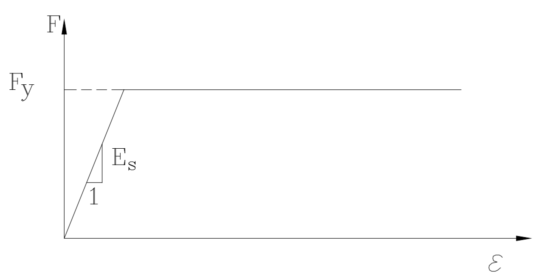


2.4 Material modeling of steel box

The uniaxial behaviour of the steel box material can be simulated by an elastic-perfectly plastic model as shown in Fig. 3. When the stress points fall inside the yield surface, the behaviour of the steel box is linearly elastic. If the stresses of the steel box reach the yield surface, the behaviour of the steel box becomes perfectly plastic. Consequently, the steel tube is assumed to fail and sustain no further loading.

In the analysis, the Poisson's ratio ν_s of the steel tube is assumed to be $\nu_s = 0.3$, the modulus of elasticity E_s = 210000 MPa, yield stress f_y =360MPa.

Figure 3.Stress-strain curve of steel material



2.5 Material modeling of concrete core

The Equivalent uniaxial stress–strain curves for both unconfined and confined concrete are shown in Fig. 4, 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 from Eqs. (1) and (2), respectively, proposed by (Mander *et al*., 1988).

$$f_{cc} = f_c + 4.1 f_l \tag{1}$$

$$\varepsilon_{cc} = (1+20.5(f_l / f_c)) \tag{2}$$

where: f_l is the lateral confining pressure imposed by the steel tube which depends on the B/t ratio and the steel tube yield stress.

The approximate value of (f_l) can be obtained from empirical equations given by (Hu *et al* 2003), where a wide range of B/t ratios ranging from 17 to 150 are investigated. The value of (f_l) is equal to f_y [0.055048 − 0.001885(B/t)] for steel tubes with a small B/t ratio. On the other hand, the value of (f_l) is equal to zero for steel tubes with B/t ratios greater than or equal to 29.2.

To define the full equivalent uniaxial stress–strain curve for confined concrete as shown in Figure 4, three parts of the curve have to be identified.

The first part 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 Equation (3) given by (ACI 1999). The Poisson's ratio (υ_{cc}) of confined concrete is taken as 0.2.

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

The second part 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 a common equation proposed by (Saenz, 1964).

$$f = \frac{E_{cc}\,\varepsilon}{1 + (R + R_E - 2)\left(\frac{\varepsilon}{\varepsilon_{cc}}\right) - (2R - 1)\left(\frac{\varepsilon}{\varepsilon_{cc}}\right)^2 + R\left(\frac{\varepsilon}{\varepsilon_{cc}}\right)^3} \tag{4}$$

where: R_E and R values are calculated from Eq. (5)

$$R_E = \frac{E_{cc}\,\varepsilon_{cc}}{f_{cc}} \quad and\ R = \frac{R_E(R_\sigma - 1)}{(R_E - 1)^2} - \frac{1}{R_\varepsilon} \tag{5}$$

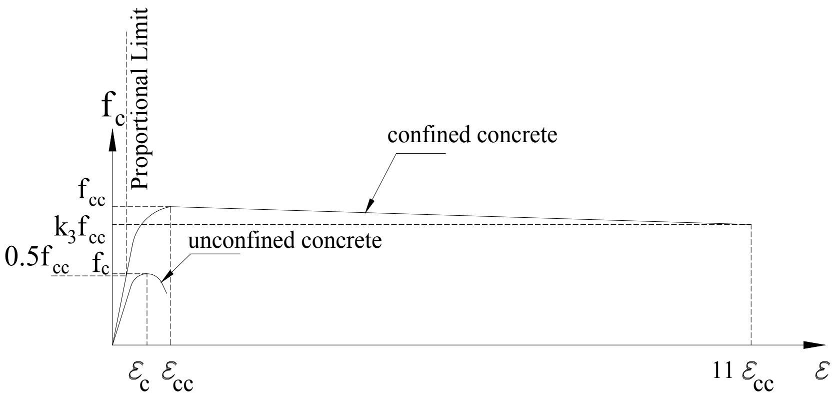
while the constants R_σ and R_ε are taken equal to 4.0, as recommended by (Hu, Schnobrich 1989).

The third part of the confined concrete stress–strain curve is the descending part used to model the softening behaviour 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 $11\varepsilon_{cc}$. The reduction factor ($k3$) depends on the B/t ratio and the steel tube yield stress (f_y), that can be calculated from empirical equations given by (Hu *et al*, 2003).

$k3$=0.000178$(B/t)^2$−0.02492(B/t)+1.2722 for($17 \le B/t \le 70$) (6)

$k3$=0.4 for($70 \le B/t \le 150$)

Figure 4.Equivalent uniaxial stress–strain curves for confined and unconfined concrete



3. Verification of the finite element model

In this part, the experimental data of eight SF reinforced concrete filled steel box columns (SFRCFSC) tested by (Tokgoz, Dundar 2010) are used to verify the proposed FEM. The load is applied at the corner of square tube columns with height L=1250 mm, yield stress f_y =290 MPa, width B, wall thickness, t. SF length L_f =35 mm, diameter d_f =0.55 mm and fibre percentage V_f % = 0.75%. Table 1 lists the dimensions and material properties of the analyzed columns. The results of eccentric capacities of the concrete filled steel box columns using the suggested finite element model, N_{model}, are compared with the experimental results N_{exp} as shown in Table1.

Table 1.Comparison between the FEM outputs and experimental studies

Column Name	B mm	t mm	f_c (MPa)	N_{exp} (kN)	N_{model} (kN)	$\frac{N_{model}}{N_{exp}}$
FSTC-I-SF	60	5	54.13	124	120	0.97
	70	5	54.13	174	170	0.98
	80	4	54.13	175	178	1.02
	100	4	54.13	248	255	1.03
CFSTC-II-SF	60	5	58.67	104	108	1.04
	70	5	58.67	148	154	1.04
	80	4	58.67	156	160	1.04
	100	4	58.67	222	218	0.98
Mean						1.01
Standard Deviation						0.03

It can be concluded from the study that the proposed FEM provides very close estimates for determining the eccentric capacities of SFRCFSC compared to the experimental results given by (Tokgoz, Dundar 2010).

4. Parametric study

A parametric study is conducted using the proposed FEM on various SFRCFSC with width B=200mm, concrete strength f_c =30 MPa, steel yield strength f_y =360 MPa, SF length L_f =60mm, and diameter d_f=0.5mm, to investigate the effect of four main parameters on the ultimate capacity of columns. The first parameter B/t represents the effect of the tube thickness (t=10 and 5mm) on the lateral support of the concrete core. B/t is considered to vary from strong lateral support where B/t= 20 (compact steel section) to relatively weak lateral support of B/t= 40 (non-compact steel section). While the second parameter L/B shows the effect of the column slenderness ratio on the ultimate capacity of SFRCFSC. The study investigated three ratios for L/B (8, 15, and 30) for short, medium and long columns respectively. The third parameter to be studied is the percentage of SF in concrete, V_f %. The percentage of SF in concrete is taken equal to 0% up to 4%. The last parameter discusses the eccentricity effect, (e_x/B and e_y/B), that is considered to be equal to 0.5. The Load capacities for concentric and eccentric loading of the analyzed SFRCFSC are illustrated in Tables 2 and 3.

Table 2.Column Capacity for concentric load

Column	B/t	L (m)	Column capacity for concentric load (kN) SF percentage V_f%				
			0	1	2	3	4
C1		1.6	2730	2930	3196	3263	3310
C2	20	3.0	2182	2250	2550	2700	2900
C3		6.0	805	942	993	1062	1188
C4		1.6	1583	1708	1978	2240	2366
C5	40	3.0	1312	1350	1500	1863	2009
C6		6.0	581	885	935	950	1065

Table 3.Column Capacity for eccentric load

Columns	B/t	L (m)	Column capacity for eccentric load (kN) SF percentage V_f%				
			0	1	2	3	4
C1		1.6	1660	1930	1945	2145	2361
C2	20	3.0	1125	1219	1484	1529	1665
C3		6.0	510	675	700	725	862
C4		1.6	826	920	993	1080	1143
C5	40	3.0	757	809	841	886	1010
C6		6.0	230	360	410	580	655

5. Results discussion

5.1 Effect of steel plate wall thickness (B/t)

Wall thickness of steel box has a substantial effect on column strength. Compact steel plate for column wall thickness provides more confinement to the concrete core that causes the increase in the overall column capacity. Non-compact steel plate of steel box column provides less confinement that will result in substantial decrease in the column capacity. The effect of column wall thickness has a significant effect on short columns' behaviour, while slender columns affected by the overall column buckling.

5.2 Effect of column slenderness

The increase in column height has a minor effect on short and medium columns, which fails due to the inelastic bucking, which means that the column fails by crushing of concrete and/or yielding of the steel plates then the column capacity decreases with percentage ranges from 3 % to 30 %, while for long columns, the column height has a great influence on the column capacity, which fails due to overall buckling before crushing of concrete and/or yielding of the column steel plates.

5.3 Effect of SF percentage

For short and medium columns increasing the percentage of fibres from 0% to 4%, will lead to an increase in column capacity by percentage varies from 3% to 28% for axial load and varies from 6% to 30% for eccentric load. The highest rate of increase lies for a percentage of fibres between 1% and 2%. Therefore it is recommended to use 1.5% of SF in case of short and medium columns. For long columns increasing the percentage of fibres from 0% to 4%, will lead to an increase in column capacity by percentage varies from 22% to 37% for axial load and varies from 16% to 50% for eccentric load. The highest rate of increase in the difference lies in the percentages between 0% and 1%. Therefore it is recommended to use 0.5% of SF in case of long column. Fig.5 and Fig.6 show the axial and eccentric strength of concrete column capacity versus V_f% for different B/t and L/B ratios.

Figure 5.Column capacity versus V_f% for different L/B ratios for B/t=20

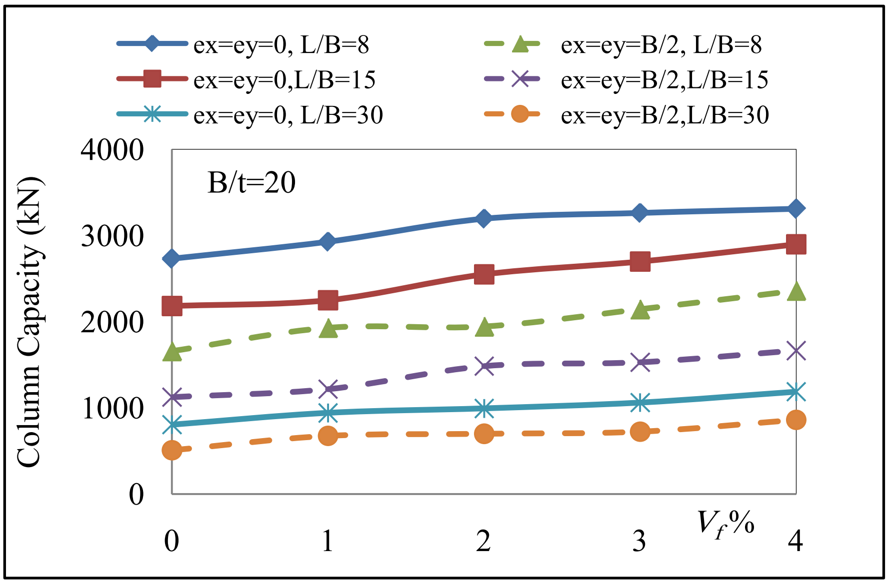
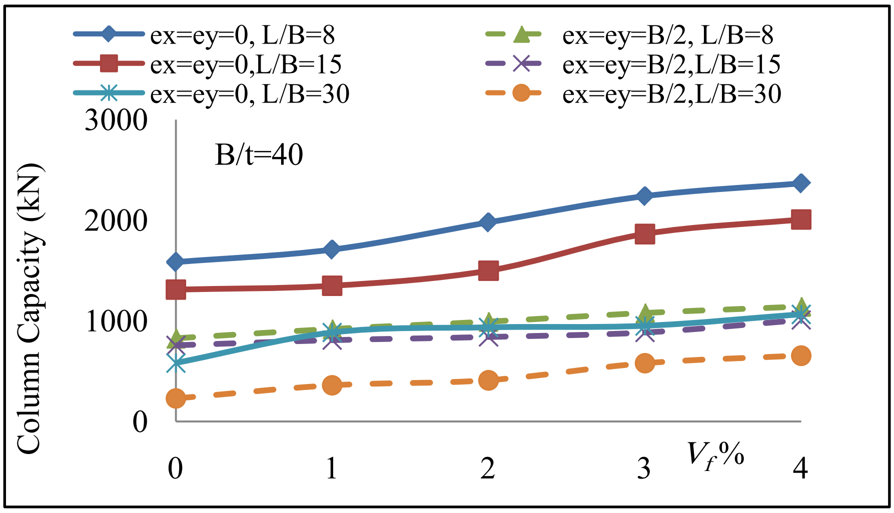


Fig. 6.Column capacity versus V_f% for different L/B ratios for B/t=40



6. Modifications for EC4 (2004) and AISC/LRFD (2009) to design SFRCFSC

The compressive strength of SFRC f_{cf} can be performed as per (Nataraja *et al* 1999) formula;

$$f_{cf} = f_c + 2.1604\left(w_f\ (l_f/d_f)\right) \tag{7}$$

Where: f_c is the cylinder compressive strength of plain concrete in MPa, w_f is the weight percentage of fibres that is equal to $3.14V_f$, l_f and d_f is the length and diameter of fibers, respectively.

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

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

The correlation factor γ is given by;

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

$$n_r = \sqrt{\frac{2E_c}{E_f(1+\nu_c)\ log_e\left(1/V_f\right)}} \tag{10}$$

where: E_f and E_c are the modulus of elasticity for fibers and concrete, respectively, and ν_c is the Poisson's ratio of plain concrete. The factor η depends on fiber distribution and is equal to 1/6, 1/3 for random distribution of fibres in 3D and 2D, respectively.

The modifications in EC4 2004 to design SFRCFSC shall be performed by replacing the cylindrical compressive strength f_c and the modulus of elasticity E_c of plain concrete by f_{cf} and E_{cf} of SFRC in

Equations 6.28, 6.30 and 6.40 of EN 1994-1-1. Furthermore, the modifications in AISC/LRFD 2009 shall be performed in a similar procedure in Equations I2-13 and I2-14.

7. Comparison between column capacities according to modified codes' equations and FEM

Twelve columns have been analyzed and the dimensions along with column strengths are listed in Table 4. The effect of volume fraction of SF to concrete on the behaviour of concentrically loaded SFRCFT column is investigated. The columns are chosen with different slenderness ratio (L/B = 8 , 15) and different width to tube thickness ratio (B/t = 20, 25, 40). The steel tube yield strength is 360 MPa and the concrete cubic strength is 30 MPa. The steel box width is 200mm with thicknesses 5, 8 and 10mm. The column length is 1600 and 3000 mm. The SF aspect ratio L_f/d_f =60, in which the fiber length L_f =30mm and diameter d_f =0.5mm.

Table 4.Geometry and material properties of CFSBC

Col. No.	t(mm)	L(mm)	V_f%	B/t	L/B
C01	10	1600	1.0	20	8
C02			2.0		
C03	8		1.0	25	
C04			2.0		
C05	5		1.0	40	
C06			2.0		
C07	10	3000	1.0	20	15
C08			2.0		
C09	8		1.0	25	
C10			2.0		
C11	5		1.0	40	
C12			2.0		

The analytical results of the modified design equations by the (AISC/LRFD, 2009) Specification, NAISC, and the results by EC4, NEC4 are compared to the results obtained from the verified FEM, N_{FEM} that are listed in Table 5. The comparative study shows that the modified equations calculate successfully the capacity of SFRCFSC. The results of design equations are a good agreement compared to the results of the models

Table 5.Comparison between the FEM outputs and corresponding results obtained from modified design equations of nominal EC4 and AISC/ LRFD Specifications

Col. No.	Results			Comparison	
	N_{EC4} (kN)	N_{AISC} (kN)	N_{model} (kN)	$\frac{N_{model}}{N_{EC4}}$	$\frac{N_{model}}{N_{AISC}}$
C01	3223	2903	2930	0.91	1.01
C02	3311	3011	3196	0.97	1.06
C03	2779	2563	2280	0.82	0.89
C04	2871	2675	2489	0.87	0.93
C05	2096	2035	1708	0.81	0.84
C06	2194	2154	1978	0.90	0.92
C07	2740	2714	2250	0.82	0.83
C08	2814	2810	2550	0.91	0.91
C09	2362	2395	2025	0.86	0.85
C10	2440	2495	2197	0.90	0.88
C11	1782	1893	1350	0.76	0.71
C12	1865	1997	1500	0.80	0.75
Mean				0.86	0.88
Standard Deviation				0.06	0.10

8. Conclusions

A non linear finite element analysis model has been developed for investigating the behaviour of normal and SF reinforced concrete in-filled steel box columns under axial and biaxial loading. The effect of column slenderness, steel box plate width-to-thickness ratio, and the percentage of SF in concrete on composite column strength were investigated using the FEM presented in this paper. The developed FEM has been verified by the available excremental results, as well as the design codes' equations, EC4 and ASD/LRFD. From the performed analysis on different sets of fibre reinforced concrete filled steel box columns, the following conclusions are found:

1) The results obtained from the developed model exhibits good correlation with the available experimental results as well as with the calculated results applying the (Euro code 4, 2004) and (AISC/LRFD, 2009).
2) The ratio of B/t significantly affects the behaviour of concrete filled steel box columns. In general as the ratio of B/t is increased, both the axial and eccentric load capacity will be decreased.
3) Wall thickness of steel box has a great effect on short to medium columns. Increasing the steel plate thickness results in substantial increase in overall column capacity, while long columns fails due to the overall column buckling then increasing the wall thickness has a limited effect.
4) The slenderness ratio L/B has a very remarkable effect on the strength and behaviour of concrete filled steel box columns under axial and eccentric loading.
5) Increasing the column height has a minor effect on short and medium columns, which fails due to inelastic bucking, which means that the column fails by crushing of concrete and/or yielding of steel plates, while for long columns, the column fails due to overall buckling before crushing of concrete and/or yielding of steel plates which cause a big decreasing in the column capacity.
6) The use of SFRC has resulted in considerable improvement in the structural behaviour of concrete filled steel box columns subjected to axial and eccentric loading.
7) For short and medium columns increasing percentage of fibres from 0% to 4%, led to the increase in column capacity. The highest rate of increase is between 1 % and 2 %. Therefore it is recommended to use 1.5% of SF in case of short and medium columns.
8) For long columns increasing percentage of fibres from 0% to 4%, led to an increase in column capacity. The biggest rate of increase is between 0% and 1%. Therefore it is recommended to use 0.5% of SF.
9) A modified design equations have been implemented to (EC4, 2004) specification and (AISC/LRFD, 2009) specification to consider the effect of fibre reinforced concrete in the design of composite columns. A comparison study between the analytical model output and the modified design equations results is performed and good agreement is proved.

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