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Durability of Steel Fiber Reinforced Concrete Filled Steel Tubes under Eccentric Loads

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ABSTRACT

A non-linear finite element model (FEM) is developed to study the flexural behavior of steel fiber reinforced concrete filled steel tube column (SFRCFSC). A FE program using ANSYS software is applied in the analysis. A parametric study is performed to investigate the effect of steel fiber (SF) percentage in concrete on the ultimate strength of composite columns. Confinement of the concrete core provided by the steel case is also investigated. Modified design equations were implemented to Euro Code 4 and AISC /LRFD specification to consider the effect of fiber reinforced concrete in the design of composite beam columns. A comparison study between the analytical model output and the modified design equations' results is performed and compliance is verified. It can be concluded that the increase of the SF from 0% to 4% enhances durability aspects and increases short and long columns' flexural strength up to 30% and 50%, respectively.

Keywords; Composite columns, finite element, steel fibers, ultimate strength, confinement.

INTRODUCTION

Traditional concrete filled steel columns employ the use of hollow steel sections filled with concrete. These columns have been used extensively to speed up construction by eliminating formwork and the need for tying of longitudinal reinforcement. Furthermore, the concrete is enhanced in its durability and performance to experience less creep and shrinkage and the quality is improved consequently allowing larger compressive stresses to be resisted by the column (Premalatha, J., Sundara, R., 2009, Ardeshana, A. L., Yaragal, S.C., et al., 2011 and Desai, A. K., 2012). The use of SF will result in further enhancement to the column properties due to the fact that under an applied load, distributed micro-cracks will be induced and the SF will bridge the cracks and minimize interconnecting voids. This will be resulted in dense concrete with enhanced properties.

This research investigates the behavior and properties of SFRCFSC which will directly results in enhanced durability properties for these elements. As aforementioned, a FE program using ANSYS software is applied in the analysis. The material nonlinearities of concrete and steel tubes as well as concrete confinement are considered in the analysis. A parametric study is carried out to investigate the effect of wall thickness, column's slenderness ratio and SF percentage of in concrete on the ultimate strength of composite columns. A modified design equations have been implemented to Euro Code 4, 2004, (EC4) and (AISC /LRFD, 2009) specifications to consider the effect of fiber reinforced concrete on the design of composite beam columns.

FINITE ELEMENT MODEL

To simulate the physical behavior of SFRCSC, mainly four components of these columns have to be modeled properly. These components are; the confined concrete containing SF, the steel tube, the steel plates as loading jacks and the interface between the concrete and the steel tube. In addition to these parameters, the choice of the element's type and mesh size that provides reliable results at reasonable computational time is also important in simulating structures with interface elements, (Abdallah, S., 2012).

Finite element's type and mesh. The concrete core is modeled using 8-node brick elements, (element; SOLID 65 in ANSYS12.0). SF is modeled 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 tube is modeled using a 4-node shell element (element; SHELL 63). Inelastic material and geometric nonlinear behavior are used for this element. A 50 mm thick steel plate, modeled using (element; SOLID 45), was added at the support locations to avoid stress concentration problems and 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 develop between the two materials resulting in frictional forces. The friction coefficient used in the analysis is 0.25. When the gap element is in tension, the two faces become separated from each other resulting in no contact between the concrete and steel. TARGET 170 is used to represent various 3-D "target" surfaces for the associated contact elements (CONTA173). Figure 1 shows the FE mesh of the SFRCFSC.

Boundary condition and load application. The column's top surface 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 column's bottom surface is prevented from displacement in the X, Y and Z directions. 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.

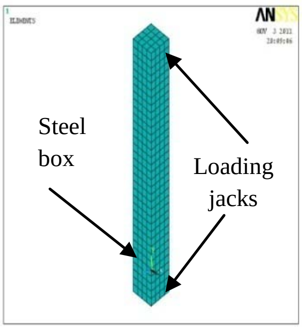


Figure 1. Typical model of SFRCFSC

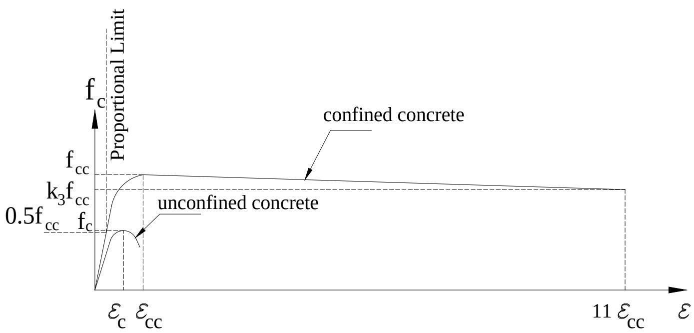


Figure 2. Equivalent uniaxial stress–strain curves for confined and unconfined concrete

Material modelling. The uniaxial behaviour of the steel box is simulated by an elastic-perfectly plastic model. The Equivalent uniaxial stress–strain curves for both unconfined and confined concrete are shown in Figure 2, 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 Eq. (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 steel tube yield stress and it's width to thickness ratio (B/t). 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 [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 uni-axial stress–strain curve for confined concrete as shown in Fig. 2, three parts of the curve have to be identified.

The first part is the initially assumed elastic range to the proportional limit stress. The proportional limit stress is taken $0.5(f_{cc})$ 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 (4), which is a common equation proposed by (Saenz, 1964).

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

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

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

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

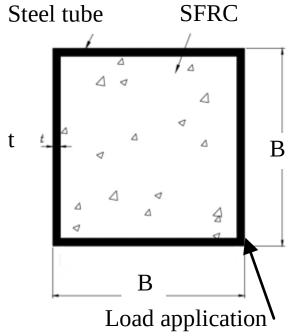
The third part of the confined concrete stress–strain curve is the descending part used to model the softening behavior of concrete from the confined concrete strength (f_{cc}) to a value lower than or equal to k3 f_{cc} with the corresponding strain of $11\varepsilon_{cc}$. The reduction factor (k3) 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 $(17\leq B/t\leq 70)$& $k3=0.4$ for $(70\leq B/t\leq 150)$ (6)

VERIFICATION OF THE FINITE ELEMENT MODEL

In this part, the experimental data of eight SFRCFSC tested by (Tokgoz, S. and Dundar, C., 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 SF percentage V_f%=0.75%. Table 1 lists the dimensions, B/t, L/B ratios, 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)	$\frac{N_{model}}{N_{exp}}$	Cross section
CFSTC -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, S and Dundar, C., 2010).

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. Three main parameters are studied to investigate their effect regarding the ultimate capacity of SFRCFSC. The first parameter is the column's width to steel plate wall thickness (B/t), which represents the effect of the tube thickness (t=10 and 5mm) on the lateral support of the concrete core. B/t varies from strong lateral support where B/t= 20 (compact steel section) to relatively weak lateral support of B/t= 40 (non-compact steel section). The second parameter is the height to width ratio (L/B), which 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 is the SF percentage, (V_f %) which is taken equal to 0% up to 4%. The columns are subjected to centric and eccentric loads in which the eccentricities (e_x/B and e_y/B), that are considered to be equal to 0.5. The geometry and columns' capacity of the analyzed SFRCFSC are illustrated in Table 2. Fig. 3 shows the axial and eccentric strength of concrete column capacity versus V_f % for different B/t and L/B ratios. Fig. 4 presents the variation of SFRC strength f_{cf} and modulus of elasticity E_{cf} versus V_f %

Table 2. Geometry, material properties and capacity of SFRCFSC

columns	B/t	L m	Column capacity for concentric load (kN)					Column capacity for eccentric load (kN)				
			SF percentage V_f %					SF percentage V_f %				
			0	1	2	3	4	0	1	2	3	4
C1	20	1.6	2730	2930	3196	3263	3310	1660	1930	1945	2145	2361
C2		3.0	2182	2250	2550	2700	2900	1125	1219	1484	1529	1665
C3		6.0	805	942	993	1062	1188	510	675	700	725	862
C4	40	1.6	1583	1708	1978	2240	2366	826	920	993	1080	1143
C5		3.0	1312	1350	1500	1863	2009	757	809	841	886	1010
C6		6.0	581	885	935	950	1065	230	360	410	580	655

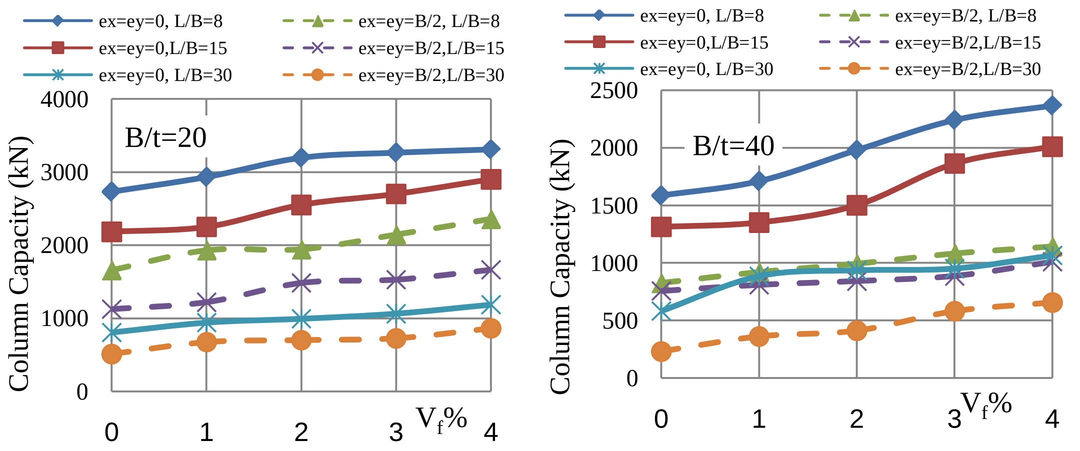


Figure 3. Column capacity for centric and eccentric loads versus V_f % for different L/B and B/t ratios

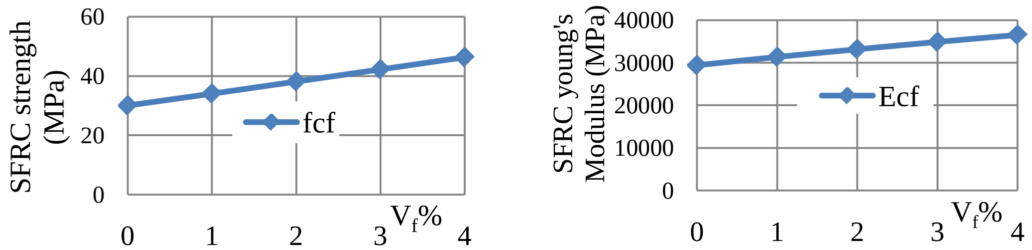


Figure 4. SFRC strength f_{cf} and modulus of elasticity E_{cf} versus V_f %

DISCUSSION OF RESULTS

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 an increase in column capacity. Non-compact steel plate for wall column thickness provides less confinement that will result in obvious decrease in the column capacity. The effect of column wall thickness for long columns has a less effect on the column behavior due to the overall column buckling.

Effect of column's slenderness ratio (L/B). The increase in column's height has a limited effect for short and medium height columns that fail due to the inelastic bucking, which means that the column fails by crushing of concrete and/or yielding of the steel plates followed by a decrease in column's capacity in percentage ranges from 3 % to 30 %, while for long columns, height has a great influence on the column's capacity, and it fails due to overall buckling before crushing of concrete and/or yielding of the column steel plates.

Effect of SF percentage (V_f %). The increase of the SF percentage from 0% to 4% for short and medium height columns leads to an increase in column's capacity by a variable percentage that may reach 30 %. The highest rate of increase lies in a percentage of fibers between 1% and 2%. Therefore it is recommended to use a SF percentage of 1.5%. For long columns, increasing the SF percentage from 0% to 4%, leads to an increase in column's capacity by percentage reaches to 40 % for axial load and reaches to 50% for eccentric load.

The highest rate of increase lies in the percentages between 0% and 1%. Therefore it is recommended to use 0.5% of SF in case of long column.

DISCUSSION OF THE DURABILITY PROPERTIES OF SFRCSC

A great deal of research has been addressing durability of SFRC elements in recent years. Also, the use of hollow steel sections will generally result in enhanced properties for the column and will improve the durability aspects as it will protect the concrete core from harmful substances causing disintegration and will slow up its degradation as a result of environmental effects. Then, for optimal performance, they should be used together, making use of the beneficial properties of both. Many experimental studies have proved that there is a direct relation between the increased concrete ultimate strength and the better durability properties. It is clear from figure 4 that increasing SF percentage from 0% to 4% increases the SFRC strength and modulus of elasticity by 60% and 20% respectively. In this regard, it is no doubt that, the improved column capacity discussed for the previous parameters will directly enhance the durability properties.

MODIFICATION FOR EC4 (2004) AND AISC/LRFD (2009) TO DESIGN SFRCFSC

Compressive strength of SFRC f_{cf} can be performed as per (Nataraja et al., 1999) formula;

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

Where; f_c is the cylinder compressive strength of plain concrete in MPa, w_f is the weight percentage of fibers that is equal to $3.14\,V_f$, 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 A., and Mindess, S., (1990) formula;

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

The correlation factor γ is given by;

$$\gamma = \eta\left[1 - \frac{\tanh(n_r l_f/d_f)}{n_r l_f/d_f}\right] \qquad n_r = \sqrt{\frac{2E_c}{E_f(1+\nu_c)\log_e(1/V_f)}} \tag{9}$$

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 fibers 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 given by Equations (7) and (8) in to 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 to Equations I2-13 and I2-14.

COMPARISON BETWEEN COLUMN CAPACITIES ACCORDING TO MODIFIED CODES' EQUATIONS AND FEM

A total of 12 columns have been analyzed and the dimensions along with column strengths are listed in Table 3. The effect of volume fraction of steel fiber to concrete on the behavior 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 MP and the concrete cubic strength is 30 MPa. The width of steel box is 200mm with thicknesses 5, 8 and 10mm. The column length is 1600 and 3000 mm with hinged end conditions. The steel fiber aspect ratio L_f/d_f =60, in which the fiber length L_f =30mm and diameter d_f =0.5mm.

Table 3. Comparison between the FEM outputs and corresponding results obtained from modified design equations of nominal EC4 and AISC/ LRFD Specifications

Col. No.	t mm	L mm	V_f%	B/t	L/B	Results			Comparison	
						N_{EC4} (kN)	N_{AISC} (kN)	N_{model} (kN)	$\frac{N_{model}}{N_{EC4}}$	$\frac{N_{model}}{N_{AISC}}$
C01	10	1600	1	20	8	3223	2903	2930	0.91	1.01
C02	10	1600	2	20	8	3311	3011	3196	0.97	1.06
C03	8	1600	1	25	8	2779	2563	2280	0.82	0.89
C04	8	1600	2	25	8	2871	2675	2489	0.87	0.93
C05	5	1600	1	40	8	2096	2035	1708	0.81	0.84
C06	5	1600	2	40	8	2194	2154	1978	0.90	0.92
C07	10	3000	1	20	15	2740	2714	2250	0.82	0.83
C08	10	3000	2	20	15	2814	2810	2550	0.91	0.91
C09	8	3000	1	25	15	2362	2395	2025	0.86	0.85
C10	8	3000	2	25	15	2440	2495	2197	0.90	0.88
C11	5	3000	1	40	15	1782	1893	1350	0.76	0.71
C12	5	3000	2	40	15	1865	1997	1500	0.80	0.75
Mean									0.86	0.88
Standard Deviation									0.06	0.10

The analytical results of the modified design equations by (AISC/LRFD, 2009) Specification, N_{AISC}, and the results by EC4, N_{EC4} are compared to the results obtained from the verified FEM, N_{FEM} that are listed in Table 3. The comparative study shows that the modified equations calculate successfully the capacity of SFRCFSC. The results of design equations are compliant with the results of the models.

CONCLUSIONS

It can be concluded from the previous study that:

1- The results obtained from the developed FEM exhibit good correlation with the available experimental data and the calculated results applying (EC4, 2004) and (AISC/LRFD, 2009).

2- The ratio of B/t significantly affects the behavior of SFRCFSC. 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 fail due to the overall column buckling, therefore increasing the wall thickness has a limited effect on long columns.

4- The slenderness ratio L/B has a very remarkable effect on the strength and behavior 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, that fail 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 that contribute to outstanding decrease in the column's capacity.

6- For short and medium columns increasing SF percentage from 0% to 4%, has led to increase in column capacity. The highest rate of increase is between 1% and 2%. Therefore it is recommended to use 1.5% of SF. For long columns increasing SF percentage from 0% to 4%, has led to an increase in column capacity. The highest rate of increase is between 0% and 1%. Therefore it is recommended to use 0.5% of SF.

7- The durability aspects will be enhanced considerably, as increasing the SF percentage from 0% to 4% increases the SFRC strength and modulus of elasticity by 60% and 20% respectively.

8- A modified design equations have been implemented to (EC4, 2004) and (AISC/LRFD, 2009) specifications to consider the effect of fiber reinforced concrete in the design of composite columns. A comparison study between the FEM outputs and the modified design equations results is performed and compliance is verified.

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