Structural Behavior of Fiber Reinforced Concrete Filled Steel Box Columns

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Abstract: **Concrete filled steel box columns have been extensively used in modern structures and tall buildings due to the enhanced performance of these columns specially the strength and ductility enhancements. The present study will take a further step in that direction through adding additional enhancements and investigating the steel fiber reinforced concrete filled steel box columns. The study will prove that the behavior of these columns will result in enhanced performance comparable to the conventionally concrete filled steel box columns which may cause a reduction in the column size and can consequently contribute to significant economic benefits. A nonlinear finite element model using ANSYS program has been developed in order to investigate the structural behavior of the inspected columns. The results obtained from that model have been compared with those calculated using Euro code (EC4), AISC/LRFD (2005) and the Egyptian Code of Practice for Steel Construction (ECPSC/LRFD 2007). The comparison indicated that the results of the model have been evaluated to an acceptable limit of accuracy. A parametric study was carried out to investigate the effect of wall thickness, length of column and percentage of steel fiber in concrete on the ultimate strength of composite columns. Confinement of the concrete core provided by the steel case was also involved. Width-to-column wall thickness ratios between 20≤B/t≤40, the length-to-column width ratios of 8≤L/B≤30, and the internal concrete of nominal unconfined cylinder strength of 30 MPa with steel fiber percentage up to 4% were investigated. It can be concluded from the results that an increase in compressive strength and flexural strength up to 10 % may be gained. It can moreover, be easily demonstrated that the proposed method is the most effective in enhancing the ductility capacity and reducing the construction cost.**

Keywords - Composite columns; finite element; steel fibers

I. 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. Furthermore, the concrete is enhanced in its 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. The fiber reinforced concrete (FRC) is defined as concrete containing dispersed randomly oriented fibers. There are different types of fibers among them are steel fibers, glass fibers, carbon fibers and natural fibers. The characteristics of fiber reinforced concrete change with varying fiber materials, geometries, distribution, orientation and densities. The main objective of this research is to investigate the behavior and properties of steel fiber reinforced concrete-filled steel box columns (SFRCFSC). A new finite element program using ANSYS software is used in the analysis. The material nonlinearities of concrete and high strength steel tubes as well as concrete confinement were considered in the analysis. Parametric study is conducted to investigate the effects of cross-section geometry and concrete strength on the behavior and strength of the steel fiber reinforced concrete filled steel box columns. The results obtained from the finite element model are compared with those obtained from a recent experimental work made by "Schneider (1998)" as well as the results obtained using Euro-code (EC4), AISC/LRFD (2005) and Egyptian code of practice for steel construction ECPSC/LRFD (2007).

II. Finite Element Model

A. General

In order to simulate the physical behavior of steel fiber reinforced concrete-filled steel box columns, mainly four components of these columns have to be modeled properly. These components are the confined concrete containing steel fibers, 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, " Abdullah, S. (2012)".

B. Finite Element Type and Mesh

The concrete core of fiber reinforced concrete filled steel box columns is modeled using 8-node brick elements, with three translation degrees of freedom at each node (element; SOLID 65 in ANSYS12.0). 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 steel box is modeled using a 4-node shell element, with six degrees of

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freedom at each node (element; SHELL 63 in ANSYS12.0). Inelastic material and geometric nonlinear behavior 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 behavior, it is primarily due to the interaction between the steel and concrete components. A 50 mm thick steel plate, modeled 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 develop 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 become separated from each other, resulting in no contact between the concrete and steel, and consequently no bond is developed. TARGE170 is used to represent various 3-D "target" surfaces for the associated contact elements (CONTA173). Fig. 1 shows the finite element mesh of the concrete-filled steel box column.

C. 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 opposite to the point of load application at the top of column. 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.

D. Material modeling of steel box

The uniaxial behavior of the steel box can be simulated by an elastic-perfectly plastic model as shown in Fig. 2. When the stress points fall inside the yield surface, the behavior of the steel box is linearly elastic. If the stresses of the steel box reach the yield surface, the behavior of the steel box becomes perfectly plastic. Consequently, the steel tube is assumed to fail and not able to resist any 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 Es = 210000 MPa, yield stress fy =360MPa.

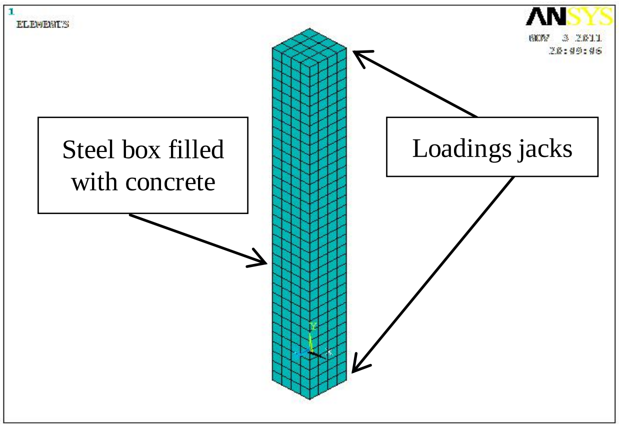

Figure 1. Typical model of concrete filled steel box columns.

E. Material modeling of concrete core

Equivalent uni-axial stress–strain curves for both unconfined and confined concrete are shown in Fig. 3, 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 (1) and (2), respectively, proposed by "Mander et al. (1988)".

$$f_{cc} = f_c + k_1 f_l \quad (1)$$

$$\varepsilon_{cc} = \varepsilon_c \left(1 + k_2 \frac{f_l}{f_c}\right) \quad (2)$$

Where f_l, is the lateral confining pressure imposed by the steel box. The lateral confining pressure (f_l) 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) has a significant effect 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.

$$f_l/f_y = 0.055048 - 0.001885(B/t) \qquad (17 \le B/t \le 29.2)$$

$$f_l/f_y = 0 \qquad (29.2 \le B/t \le 150)$$

The factors (k_1) and (k_2) are taken as 4.1 and 20.5, respectively, as given by "Richart et al. (1928)".

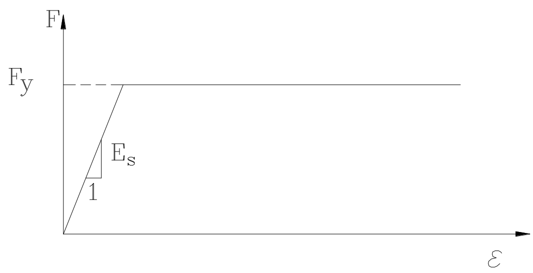

Figure 2. Elastic perfectly plastic model for steel box.

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To define the full equivalent uni-axial stress–strain curve for confined concrete as shown in Fig. 3, 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 (4), which is a common equation proposed by "Saenz (1964)". This equation is used to represent the multi-dimensional stress and strain values for the equivalent uniaxial stress and strain values. The unknowns of the equation are the uni-axial 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 $(0.5\,fcc/Ecc)$, and the confined strain (ε_{cc}), which corresponds to the confined concrete strength. The stress values (f) can be determined easily from (4) by assuming the strain values(ε).

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

Where R_E and R values are calculated from (5) and (6) respectively:

$$R_E = \frac{E_{cc}\varepsilon_{cc}}{f_{cc}} \tag{5}$$

$$R = \frac{R_E(R_\sigma-1)}{(R_E-1)^2} - \frac{1}{R_\varepsilon} \tag{6}$$

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 (fcc) to a value lower than or equal to $K_3\ f_{cc}$ 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). The approximate value of k_3 can be calculated from empirical equations given by "Hu et al. (2003)".

$k_3=0.000178(B/t)^2-0.02492\,(B/t)+1.2722 \quad (17\leq B/t\leq 70)$

$k_3 = 0.4 \qquad (70 \leq B/t \leq 150)$

III. Verification of The Finite Element Model

In this part, the experimental data of three concrete filled steel box columns from "Mursi, M. and Uy, B. (2003)", four concrete filled steel box columns from "Mursi, M. and Uy, B. (2004)" and three concrete filled steel box columns from "Schnieder, S.P. (1998)" are used to verify the proposed finite element model for concrete filled steel box columns.

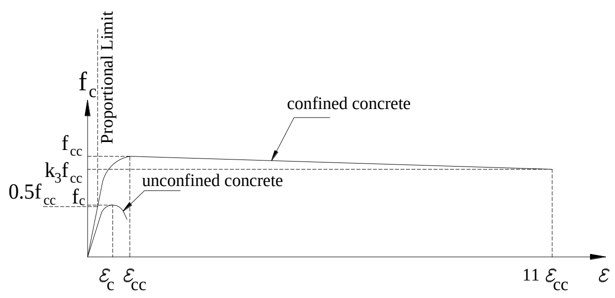

Figure 3. Equivalent uniaxial stress–strain curves for confined and unconfined concrete.

Table I lists the dimensions, B/t, L/B ratios, and material properties of the analyzed concrete filled steel box columns.

The results of concentric and eccentric capacities of the concrete filled steel box columns using the suggested finite element model, N_{model}, are compared with the experimental results given by "Mursi, M. and Uy, B. (2003)", "Mursi, M. and Uy, B. (2004)" and "Schnieder, S.P. (1998)", N_{exp}.

The analytical results are compared with the design equations of the "AISC/LRFD (2005)" Specification, N_{AISC}, and the ones by "the Egyptian code of practice for steel construction", N_{ECPSC}, and the results by "Euro code 4", N_{EC4} are listed in table II.

From table II, it can be noticed that:

- The behavior of the model is of a good agreement compared to the experimental results.
- The comparison shows that the proposed finite element model provides very close estimates for determining the axial capacities of concrete filled steel box columns compared to the three design codes.

IV. Parametric Study

A parametric study is conducted using the proposed model on various steel fiber reinforced concrete filled steel box columns to investigate the effect of four main parameters on the ultimate capacities of SFRCFSC.

These parameters are: width–to-column wall thickness ratio, B/t; the length-to-column width ratio, L/B; the percentage of steel fibers in concrete, Vf%; and the eccentricity effect. The first parameter, B/t, represents how much does the tube thickness provide lateral support to the concrete core, it has been considered to vary from strong lateral support of B/t equals 20 (compact steel section) to relatively weak lateral support of B/t equals 40 (non-compact steel section). While the second parameter, L/B, shows the effect of the column slenderness ratios to the ultimate capacities of steel fiber reinforced concrete filled steel box columns. In this case, three ratios equal to 8, 15, and 30 are considered for short, medium and long respectively for different B/t ratios. The third parameter concerns with the effect of percentage of steel fiber in concrete, Vf %. The percentage of steel fibers in concrete is taken equal to 0% up to 4%.

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TABLE I: GEOMETRY AND MATERIAL PROPERTIES OF CONCRETE FILLED STEEL BOX COLUMNS

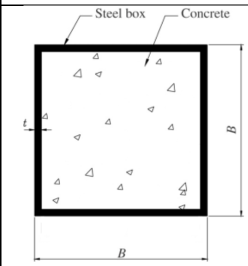
Column Name	B (mm)	t (mm)	Length "L" (mm)	B/t	L/B	f_y (MPa)	f_c (MPa)	Reference	Cross section
C-X-S-40	104	3	2800	34.7	26.92	269	65	"Mursi,M. and Uy,B. (2003)"	
C-X-S-50	134	3	2800	44.7	20.89	269	65		
C-X-S-60	164	3	2800	54.7	17.07	269	65		
SH-C210S	210	5	730	42	3.48	761	20	"Mursi,M. and Uy,B. (2004)"	
SH-C260S	260	5	880	52	3.38	761	20		
SH-C210L	210	5	3020	42	14.38	761	20		
SH-C260L	260	5	3020	52	11.62	761	20		
S1	127	3.15	610	40.4	4.8	356	30.454	"Schnieder, S.P. (1998)"	
S2	127	4.34	610	29.2	4.8	357	26.044		
S3	127	4.55	610	22.3	4.8	322	23.805		

TABLE II: COMPARISON BETWEEN THE FINITE ELEMENT MODEL OUTPUTS AND CORRESPONDING RESULTS OBTAINED FROM EXPERIMENTAL STUDIES, NOMINAL EC4, AISC/ LRFD AND ECPSC/LRFD SPECIFICATIONS.

Column Name	e (mm)	e/L	Results					Comparison			
			N_{exp} (kN)	N_{EC4} (kN)	N_{AISC} (kN)	N_{ECPSC} (kN)	N_{model} (kN)	$\frac{N_{model}}{N_{EC4}}$	$\frac{N_{model}}{N_{AISC}}$	$\frac{N_{model}}{N_{ECPSC}}$	$\frac{N_{model}}{N_{exp}}$
C-X-S-40	10	0.096	736	633	573	-*	739	1.167	1.289	-*	1.004
C-X-S-50	15	0.112	1090	1036	1023	-*	1068	1.03	1.044	-*	0.979
C-X-S-60	20	0.128	1444	1357	1579	-*	1421	1.047	1.047	-*	0.984
SH-C210S	0	0	3609	3503	3762	3769	3584	1.023	0.953	0.951	0.993
SH-C260S	0	0	3950	5024	4897	4798	3972	0.791	0.811	0.828	1.006
SH-C210L	20	0.95	2939	2960	3200	3267	3000	1.014	0.938	0.918	1.023
SH-C260L	25	0.96	3062	3883	4431	4376	3080	0.793	0.695	0.704	1.006
S1	0	0	917	992	852	916	904	0.911	1.061	0.987	0.986
S2	0	0	1095	1064	1058	1058	1158	1.088	1.095	1.095	1.058
S3	0	0	1113	993	988	990	1040	1.047	1.053	1.051	0.934
Mean								0.991	0.998	0.933	0.997
Standard Deviation								0.123	0.163	0.134	0.032

* Note: The ECPSC recommends that fc should not be taken more than 50 MPa.

The last parameter discusses the eccentricity effect, (e_x/B and e_y/B), that is considered to be equal to 0.5.

The geometry and material properties of the analyzed steel fiber reinforced concrete filled steel box columns are illustrated in table III.

TABLE III: GEOMETRY AND MATERIAL PROPERTIES OF CONCRETE FILLED STEEL BOX COLUMNS..

columns	Dimensions (mm)			L/B ratio	B/t ratio	concrete strength	Steel yield strength
	B	*t*	*L*			f_c	f_y
	(mm)	*(mm)*	*(mm)*			*(MPa)*	*(MPa)*
C01	200	10	1600	8	20	30	360
C02			3000	15			
C03			6000	30			
C04	200	8	1600	8	25	30	360
C05			3000	15			
C06			6000	30			
C07	200	5	1600	8	40	30	360
C08			3000	15			
C09			6000	30			

V. DISCUSSION OF THE RESULTS

A. Effect of steel plate wall thickness

Wall thickness of steel box has a great effect on short to medium height columns. Compact steel plate for column wall thickness provides more confinement to the concrete core that causes increasing in overall column capacity. Non-compact steel plate for wall column thickness provides less confinement that will result in substantial decrease in the column capacity. The effect of column wall thickness on long columns has a less effect on the column behavior due to the overall column buckling. Fig. 4 shows the axial and eccentric column capacity versus B/t ratio for different L/B ratios.

B. Effect of column height

The increase in column height has a minor effect on short and medium columns, the fail is attributed to the inelastic bucking, meaning 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. Fig. 5 shows the axial and eccentric

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column capacity versus L/B ratio for different B/t ratios and Fig. 6 shows axial column capacity versus L/B ratio for different value of Vf%.

C. Effect of percentage of steel fiber

For short and medium columns increasing the percentage of fibers 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 fibers between 1% and 2%. Therefore it is recommended to use 1.5% of steel fibers in case of short and medium columns.

For long columns increasing the percentage of fibers 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 difference in increase lies in the percentages between 0% and 1%. Therefore it is recommended to use 0.5% of steel fibers in case of long column.

Fig. 7 shows the axial and eccentric column capacity versus Vf % for different B/t and L/B ratios.

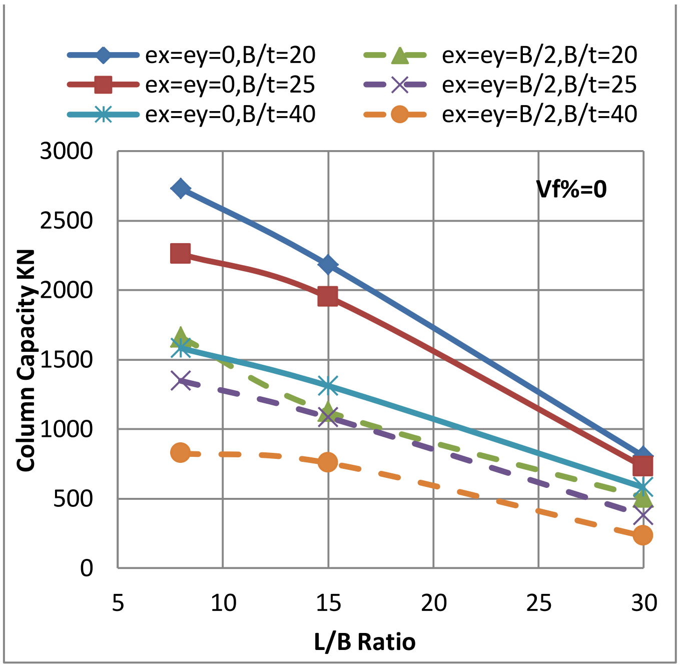

Figure 5. Column capacity versus L/B ratio for different B/t ratios.

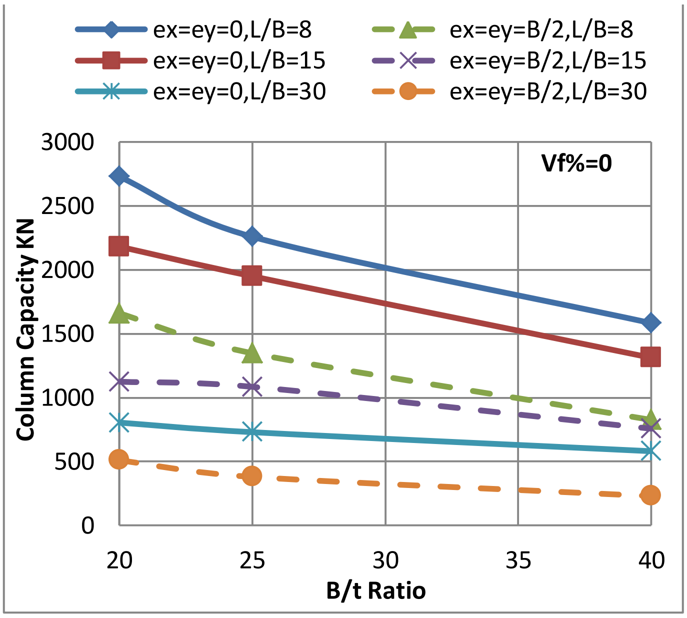

Figure 4. Column capacity versus B/t ratio for different L/B ratios.

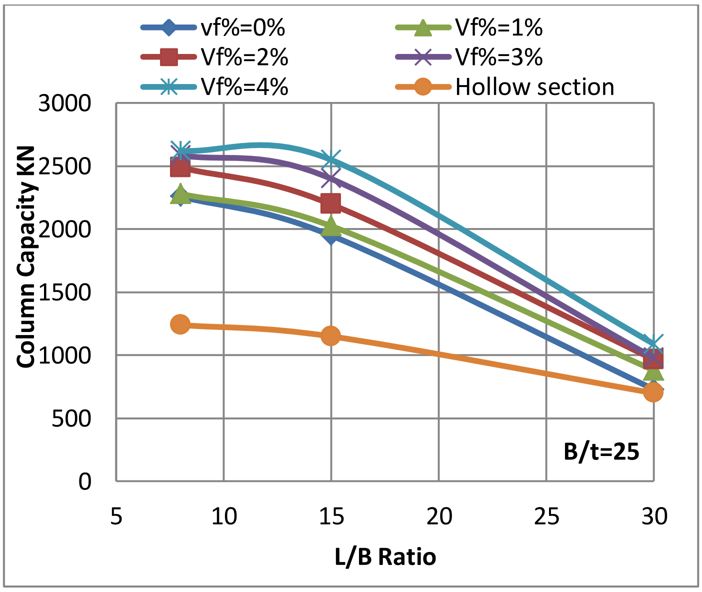

Figure 6. Column capacity versus L/B ratio for different Vf%.

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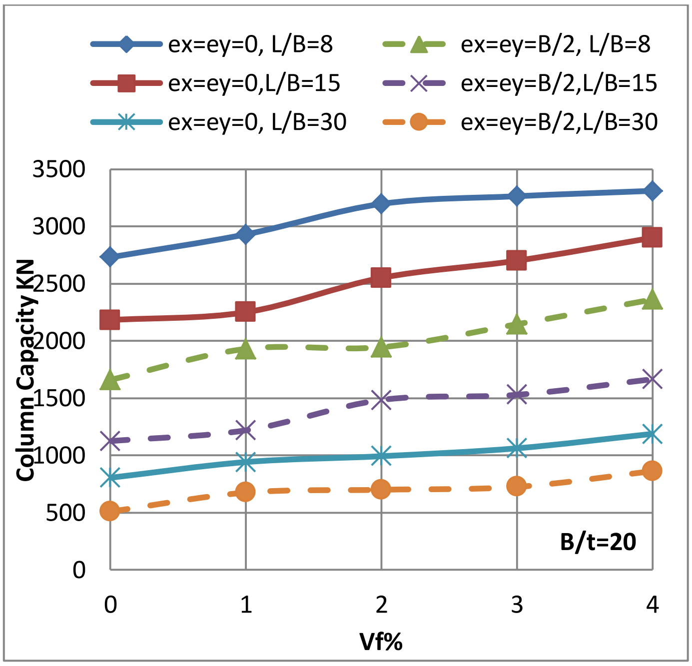

Figure 7. Column capacity versus Vf% for different L/B ratios.

VI. SUMMARY AND CONCLUSION

The developed finite element model is used to predict the behavior of fiber reinforced concrete filled steel box columns. From the analysis performed on different sets of Fiber 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 the calculated results applying the Eurocode (EC4), AISC/LRFD (2005) and the Egyptian code of practice for steel construction ECPSC/LRFD (2007).

2) The ratio of B/t significantly affects the behavior 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 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, the fail is attributed to inelastic bucking, meaning 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 results show that the axial and eccentric capacities for concrete filled steel box columns are increased as the concrete strength is increased.

7) Under eccentric loading B/t ratios and/or L/B ratios are increased, the maximum eccentric load of the column is decreased.

8) The use of SFRC has resulted in considerable improvement in the structural behavior of concrete filled steel box columns subjected to axial and eccentric loading.

9) For short and medium columns increasing percentage of fibers from 0% to 4%, has 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 steel fibers in case of short and medium columns.

10) For long columns increasing the percentage of fibers from 0% to 4%, has 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 steel fibers.

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