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Analysis of Reinforced Concrete and Composite Columns With and Without Steel Fibers

Serkan Tokgoz[1], Cengiz Dundar[2]

[1]*Department of Civil Engineering, Mersin University, Turkey*
[2]*Department of Civil Engineering, Cukurova University, Adana, Turkey*

ABSTRACT

Analysis of eccentrically loaded plain and steel fiber high strength reinforced concrete and concrete-encased composite columns is presented. In the analysis procedure, the experimental nonlinear stress–strain relations are used for plain and steel fiber concrete material. The concrete compression zone of the section is divided into segmental subdivisions parallel to the neutral axis. The compression stress resultants of the concrete material and structural steel have been calculated in the centre of each segment. In the presented study, a computer program has been developed based on the proposed procedure for the prediction of ultimate strength analysis of eccentrically loaded steel fiber high strength reinforced concrete and composite columns. The main parameters of this study are the concrete compressive strength, load eccentricity, steel yield stress, slenderness effect and steel fiber content. The results show that adding steel fibers into high strength concrete significantly improves the ductility and deformability of reinforced concrete and composite columns under biaxial bending and axial load.

INTRODUCTION

High strength concrete is commonly used in the construction of tall buildings, bridges, piles etc. High strength concrete provides economy and performance advantages in structural design. On the other hand, high strength concrete shows brittle behaviour under compression ([1]). Therefore, confinement and ductility features of high strength reinforced concrete and composite columns are very significant especially in the seismically active regions. The addition of steel fibers into high strength concrete definitely improves ductility and deformability properties of column members.

A number of researches were conducted to determine the behaviour of high strength steel fiber reinforced concrete columns. Hsu *et al.* [2] reported test results of 14 square section slender high strength reinforced concrete columns with and without steel fibers. Foster and Attard [3] tested high strength steel fiber reinforced concrete columns under concentric or eccentric compression to investigate the effects of steel fibers. Foster [4] examined the effects of steel fibers on the cover spalling and ductility of concrete columns. Tokgoz [5] investigated the effects of steel fiber addition on the behaviour of biaxially loaded high strength reinforced concrete columns.

In addition to reinforced concrete columns some experimental and theoretical studies were carried out to describe the behaviour of composite columns (Roik and Bergmann [6], Munoz and Hsu [7], Uy [8], Shanmugam and Lakshmi [9], Mirza and Lacroix [10], Dundar et. al. [11], Tokgoz and Dundar [12], Hsu *et al.* [13], Liang [14], Ellobody et. al. [15]).

The primary purpose of this investigation is to examine the behaviour of eccentrically loaded pin-ended plain and steel fiber high strength reinforced concrete and concrete-encased composite columns. Thus, the columns were analysed based on a theoretical method using experimental stress-strain relations of plain and steel fiber concrete to predict the ultimate strength capacities. A good degree of accuracy has been obtained between the test and the theoretical results in the study.

ANALYSIS METHOD

A theoretical method is suggested for the analysis of plain and steel fiber high strength reinforced concrete and composite columns. The method has been previously reported by Tokgoz [5] for steel fiber reinforced concrete columns. In the proposed procedure, the nonlinear stress–strain relation can be used for the materials and slenderness effect is taken into account. The concrete compression zone of the section is divided into segments parallel to the neutral axis. The compression stress resultants of the concrete material and the structural steel stresses have been calculated in the centre of each segment. In the presented study, a computer program was developed based on the proposed procedure for the ultimate strength analysis of eccentrically loaded both short and slender plain and steel fiber high strength reinforced concrete and composite columns.

Basic Assumptions

1. Plane sections remain plane during and after bending.
2. Experimental stress–strain relations were used for the concrete compression zone of plain and steel fiber high strength concrete columns. The typical experimental stress-strain relations are shown in Figure 1.

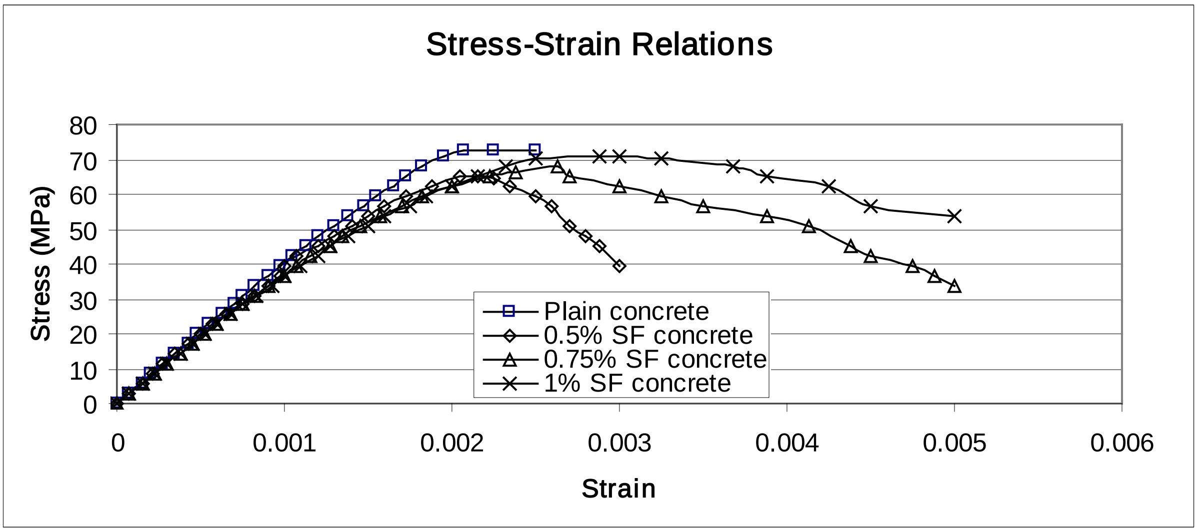

Figure 1 The typical stress-strain relations for plain and steel fiber (SF) concrete

3. The reinforcing steel bars are assumed to be elastic–perfectly plastic.
4. There is perfect bond between steel and concrete.
5. Effect of creep, shrinkage and the tensile strength of concrete are ignored.
6. Axial and shear deformation effects are neglected.

Formulation of the Analysis Method

A composite column cross section subjected to eccentrically applied compressive axial load N is shown in Figure 2.

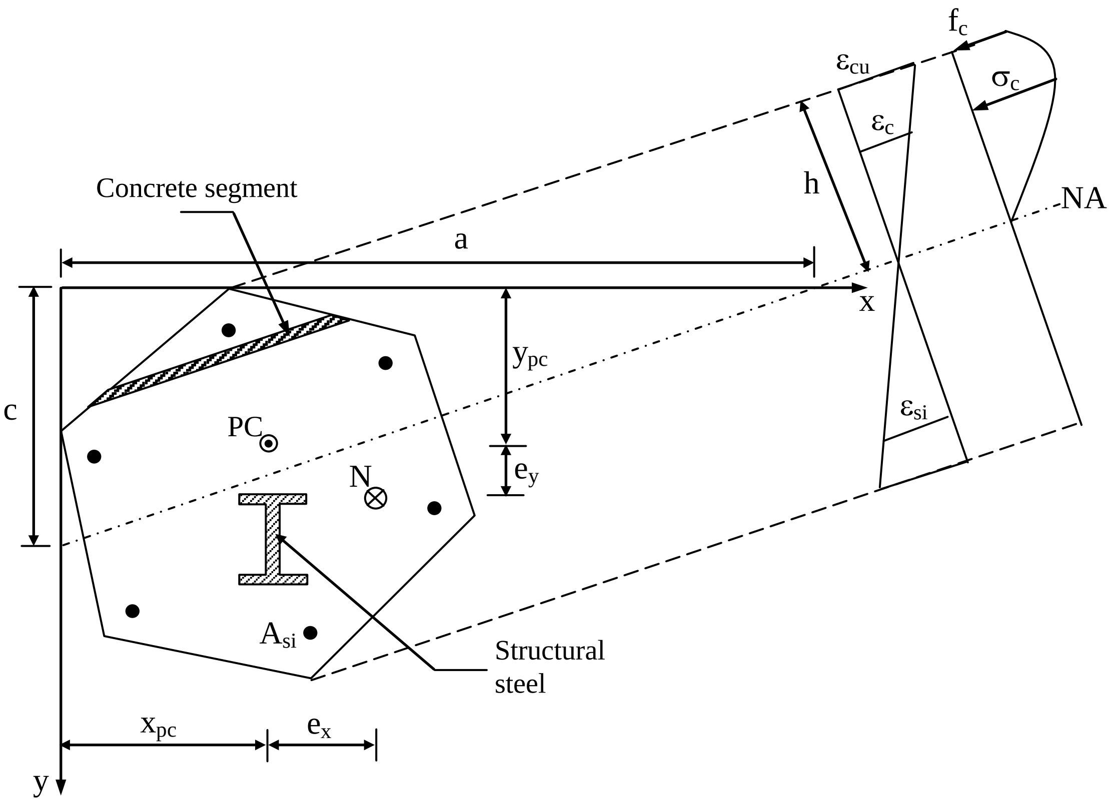

Figure 2 Composite column cross section

According to the assumption that plane sections remain plain, the strain at any point in the cross section (x_i,y_i) is given as follows:

$$\varepsilon_i = \varepsilon_{cu}\left[\left(\frac{y_i}{c}+\frac{x_i}{a}\right)-1\right] \tag{1}$$

where a and c are the horizontal and the vertical distances between the origin of the x-y axis system and the neutral axis and ε_{cu} is the maximum compressive fiber strain in the concrete.

The curvature (φ) of the member can be determined using the strain distribution as follows (Figure 2):

$$\varphi = \frac{\varepsilon_c}{h} \tag{2}$$

where ε_c is the concrete strain; h is the distance from the maximum compressive fiber to the neutral axis.

Equilibrium Equations

The external axial force N and the bending moments M_x and M_y should be equated to the internal axial force and corresponding moments in order to satisfy the force equilibrium condition for a column member subjected to biaxial bending and axial load. Therefore, the equilibrium equations can be written as follows:

$$\sum_{k}^{t} \overline{A}_{ck}\, \sigma_{ck} - \sum_{i}^{m} A_{si} \sigma_{si} - \sum_{j}^{n} A_{tj} \sigma_{tj} - N = 0 \qquad (3)$$

$$\sum_{i}^{m} A_{si}\, \sigma_{si} (y_i - y_{pc}) + \sum_{j}^{n} A_{tj} \sigma_{tj} (y_{tj} - y_{pc}) - \sum_{k}^{t} \overline{A}_{ck}\, \sigma_{ck} (\overline{y}_{ck} - y_{pc}) - M_x = 0 \qquad (4)$$

$$\sum_{i}^{m} A_{si}\, \sigma_{si} (x_i - x_{pc}) + \sum_{j}^{n} A_{tj} \sigma_{tj} (x_{tj} - x_{pc}) - \sum_{k}^{t} \overline{A}_{ck}\, \sigma_{ck} (\overline{x}_{ck} - x_{pc}) - M_y = 0 \qquad (5)$$

where, σ_{ck} is the concrete compressive stress at the centre of the *k*th segment; $\overline{A}_{ck}$ and ($\overline{x}_{ck}$, $\overline{y}_{ck}$) indicate the area and the centre coordinates of *k*th concrete segment, respectively; t is the number of segment of the concrete in compression zone; σ_{si} is the stress of *i*th reinforcing bar; m is the total number of reinforcing bars; n is the total number of segment of the structural steel; A_{tj} and (x_{tj}, y_{tj}) are the area and the centre coordinates of the *j*th structural steel segment, respectively; σ_{tj} is the structural steel stress at the centre of the *j*th segment; x_i and y_i are the coordinates of the *i*th reinforcing bar; x_{pc} and y_{pc} are the plastic centre coordinates of the composite column section ([11,12]).

The equations (4,5) are solved for the neutral axis parameters (a, c). When substituting these parameters in Eq. (3), the biaxially eccentric ultimate load N_u can be obtained as follows:

$$N_u = \sum_{k}^{t} \overline{A}_{ck}\, \sigma_{ck} - \sum_{i}^{m} A_{si}\, \sigma_{si} - \sum_{j}^{n} A_{tj}\, \sigma_{tj} \qquad (6)$$

The abovementioned procedure is also valid for the analysis and design of reinforced concrete columns by neglecting the structural steel contributions from the equilibrium equations.

Slenderness Effect

The slenderness effect is taken into account by using The Moment Magnification Method recommended by ACI 318–05 [16] Building Code. The primary moments are magnified with the moment magnification factor (δ). The magnified column moment can be defined as follows:

$$M_c = \delta M_2 \qquad (7)$$

where

$$\delta = \frac{C_m}{1 - \dfrac{N_u}{0.75 N_{cr}}} \geq 1.0 \qquad (8)$$

in which C_m is equivalent moment correction factor. This factor is taken as follows:

$$C_m = 0.6 + 0.4 \frac{M_1}{M_2} \geq 0.4 \quad , \qquad M_1 \leq M_2 \qquad (9)$$

where M_1 and M_2 are the end moments of the column. C_m=1.0 for the pin ended column; N_{cr} is the elastic buckling load of a column;

$$N_{cr} = \frac{\pi^2 E I}{(L_{ef})^2} \qquad (10)$$

where L_{ef} is the effective length and equals kL; k is the effective length factor; EI is the flexural rigidity of the column section. ACI 318-05 Building Code recommends the following two expressions for flexural rigidity of reinforced concrete columns:

$$EI=\frac{0.2 E_c I_g}{1+\beta_d}+E_s I_s \tag{11}$$

or

$$EI=\frac{0.4 E_c I_g}{1+\beta_d} \tag{12}$$

The flexural rigidity EI_m incorporated both ACI [16] and AISC [17] Specifications was suggested for prediction of slender composite columns by Munoz and Hsu [7]. The proposed flexural rigidity is given by the following equation:

$$EI_m=\frac{0.4E_c I_g}{1+\beta_d}+E_s I_s+E_{sr} I_{sr} \tag{13}$$

in which E_c, E_s and E_{sr} are the modulus of elasticity of concrete, reinforcing steel and structural steel materials, respectively; I_g, I_s and I_{sr} are the moment of inertia of gross concrete section, reinforcement and structural steel, calculated with respect to the plastic centre of the composite column section, respectively; β_d is the sustained load factor (β_d=0 for short-term axial load).

The modulus of elasticity for steel fiber and plain high strength concrete is assumed as follows (ACI 363 [18]):

$$E_c=4730\sqrt{f_c} \tag{14}$$

where f_c is expressed in MPa.

For biaxial bending, ACI 318–05 Code recommends that the moment magnification factors are computed for each axis separately and multiplied by the corresponding moments as follows:

$$M_{ux}=\delta_x N_u e_y , \quad M_{uy}=\delta_y N_u e_x \tag{15}$$

ANALYSIS OF COLUMN SPECIMENS

The plain and steel fiber high strength reinforced concrete and composite column specimens ([19]) analysed based on the proposed theoretical method for the prediction of ultimate strength capacities. The experimental stress-strain relations were used for plain and steel fiber concrete and slenderness effect wase considered in the analysis. The column specimen details are shown in Figure 3. The features of the column specimens are shown in Table 1.

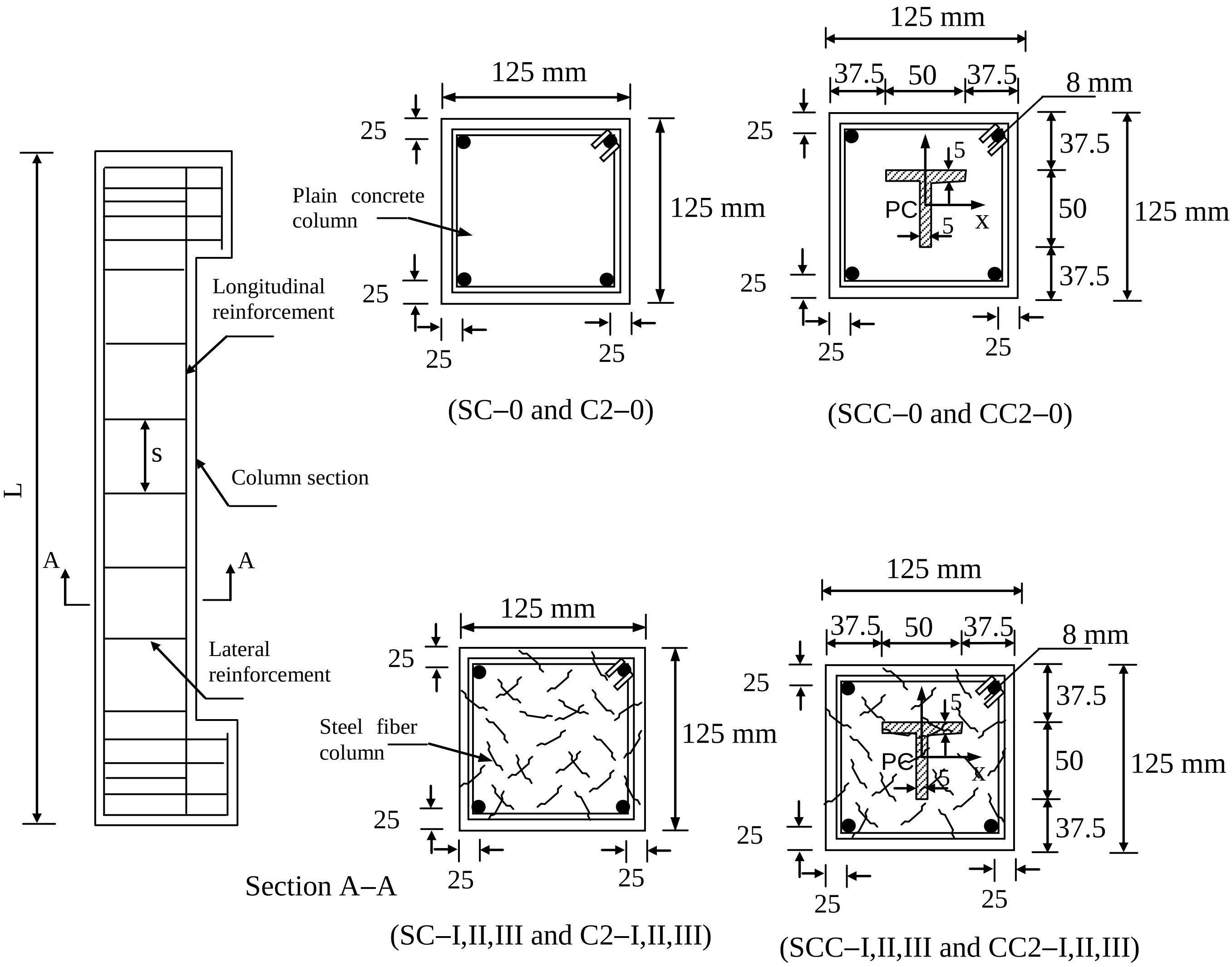

Figure 3 Details of column specimens

The column specimens have been analysed by using the developed computer program. The experimental results, computed theoretical strength capacities and comparative results of the predicted load to test load are shown in Table 2.

A good degree of accuracy has been achieved between the test and the analysis results for most of the column specimens (Table 2). The average value of predicted load to test load has been obtained 0.923. It is concluded from the results that the addition of steel fibers into concrete has no significant effect on ultimate strength capacity of column specimens.

The results indicate that the proposed method has given reasonable accuracy to predict the ultimate strength capacity of plain and steel fiber reinforced concrete and composite columns.

Table 1 The Features of the Column Specimens

Specimen no.	L (mm)	f_c (MPa)	e_x (mm)	e_y (mm)	N_{test} (kN)
SC–0	850	73.42	45	45	249
SC–I	850	76.87	45	45	256
SC–II	850	72.53	45	45	274
SC–III	850	69.71	45	45	243
SCC–0	850	65.94	45	44.25	236
SCC–I	850	74.72	45	44.25	262
SCC–II	850	76.52	45	44.25	253
SCC–III	850	73.75	45	44.25	265
C2–0	1300	58.46	45	45	194
C2–I	1300	59.03	45	45	192
C2–II	1300	61.20	45	45	205
C2–III	1300	58.81	45	45	201
CC2–0	1300	58.19	45	44.25	183
CC2–I	1300	61.13	45	44.25	213
CC2–II	1300	60.64	45	44.25	19
CC2–III	1300	59.04	45	44.25	214

Table 2 Ultimate Strength Results of the Column Specimens

Specimen no.	N_{test} (kN)	N_u (kN)	M_{ux} (kN.cm)	M_{uy} (kN.cm)	N_u/N_{test}
SC–0	249	218.29	983.22	983.22	0.877
SC–I	256	229.38	1024.09	1024.09	0.896
SC–II	264	224.57	997.85	997.85	0.851
SC–III	243	221.64	993.81	993.81	0.912
SCC–0	236	219.28	971.23	986.66	0.929
SCC–I	262	251.56	1114.65	1132.36	0.960
SCC–II	253	243.89	1080.66	1097.83	0.964
SCC–III	265	237.29	1033.62	1050.06	0.895
C2–0	194	171.44	814.23	814.23	0.884
C2–I	192	174.03	850.25	850.25	0.906
C2–II	205	178.25	862.25	862.25	0.870
C2–III	201	176.94	859.46	859.46	0.880
CC2–0	183	184.08	854.68	869.31	1.006
CC2–I	213	199.51	934.71	950.76	0.937
CC2–II	194	204.07	957.61	974.08	1.052
CC2–III	214	202.18	948.84	965.19	0.945
Mean ratio					0.923

CONCLUSION

Analysis of the eccentrically loaded plain and steel fiber high strength reinforced concrete and concrete-encased composite columns is presented in this study. In the method, the nonlinear stress–strain relation is used for the materials. The concrete compression zone of the section and entire section of the structural steel are divided into segments parallel to the neutral axis. The compression stress resultants of the concrete material and structural steel have been calculated in the centre of each segment. In the presented study, a computer program has been developed based on the suggested procedure to obtain the ultimate strength capacity of eccentrically loaded plain and steel fiber high strength reinforced concrete and composite columns. The main parameters of this study are the concrete compressive strength, load eccentricity, steel yield stress, slenderness effect and steel fiber content. The ultimate strength capacity of column specimens has been obtained in the study. The results show that adding steel fibers into high strength concrete significantly improves the ductility and deformability of reinforced concrete and composite columns. The analysis has revealed that the flexural rigidity is the most effective parameter to predict the ultimate strength capacity of slender reinforced concrete and composite columns under biaxial bending and axial load.

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REFERENCES

[1] Hsu, L.S.M. and Hsu, C.T.T. (1994) Stress-strain behavior of steel-fiber high–strength concrete under compression. *ACI Struct. J.*, **91**(4), 448–457.

[2] Hsu, C.T.T., Hsu, L.S.M. and Tsao, W.H. (1995) Biaxially loaded slender high–strength reinforced concrete columns with and without steel fibres. *Mag. Concrete Res.*, **47**(173), 299–310.

[3] Foster, S.J. and Attard, M.M. (2001) Strength and ductility of fiber–reinforced high–strength concrete columns. *J. Struct. Eng.*, **127**(1), 28–34.

[4] Foster, S.J. (2001) On behavior of high–strength concrete columns:cover spalling, steel fibers, and ductility. *ACI Struct. J.*, **98**(4), 583–589.

[5] Tokgoz, S. (2009) Effects of steel fiber addition on the behaviour of biaxially loaded high strength concrete columns. *Mater. Struct.*, **42**(8), 1125–1138.

[6] Roik, K. and Bergmann, R. (1990) Design method for composite columns with unsymmetrical cross-sections. *J. Const. Steel Res.*, **15**, 153–168.

[7] Munoz, P.R. and Hsu, C.T. (1997) Behavior of biaxially loaded concrete-encased composite columns. *J. Struct. Eng.*, **123**(9), 1163–1171.

[8] Uy, B. (2001) Local and post local buckling of fabricated steel and composite cross sections. *J. Struct. Eng.*, 127(6), 666–677.

[9] Shanmugam, N.E. and Lakshmi, B. (2001) State of the art report on steel–concrete composite columns. *J. Const. Steel Res.*, **57**(10), 1041–1080.

[10] Mirza, S.A. and Lacroix, E.A. (2004) Comparative strength analyses of concrete-encased steel composite columns. *J. Struct. Eng.*, **13**0(12), 1941–1953.

[11] Dundar, C., Tokgoz, S., Tanrikulu, A.K. and Baran, T. (2008) Behaviour of reinforced and concrete-encased composite columns subjected to biaxial bending and axial load. Build. Environ., **43**(6), 1109–1120.
[12] Tokgoz, S. and Dundar, C. (2008) Experimental tests on biaxially loaded concrete-encased composite columns. *Steel Compos. Struct*., **8**(5), 423–438.
[13] Hsu, H.L., Jan, F.J. and Juang, J.L. (2009) Performance of composite members subjected to axial load and bi-axial bending. *J. Const. Steel Res.*, **65**(4), 869–878.
[14] Liang, Q.Q. (2009) Strength and ductility of high strength concrete-filled steel tubular beam–columns. *J. Const. Steel Res.*, **65** (3), 687–698.
[15] Ellobody, E., Young, B. and Lam, D. (2011) Eccentrically loaded concrete encased steel composite columns. Thin-Walled Struct., **49**(1), 53–65.
[16] Building code requirements for structural concrete (2005). American Concrete Institute, Farmington Hills, Mich (ACI 318–05).
[17] Load and resistance factor design specification for structural steel buildings (1993). 2nd ed. Chicago IL, American Institute of Steel Construction (AISC).
[18] ACI Committee 363 (1984). State of art report on high strength concrete. *ACI J.*, **81**(4), 364–411.
[19] Tokgoz, S., Dundar, C. and Tanrikulu, A.K. (2011) Experimental behaviour of steel fiber high strength reinforced concrete and composite columns. *J. Const. Steel Res.* (Under review).