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Experimental tests on biaxially loaded concrete-encased composite columns

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Abstract. This paper reports an experimental investigation of the behaviour of concrete-encased composite columns subjected to short-term axial load and biaxial bending. In the study, six square and four L-shaped cross section of both short and slender composite column specimens were constructed and tested to examine the load-deflection behaviour and to obtain load carrying capacities. The main variables in the tests were considered as eccentricity of applied axial load, concrete compressive strength, cross section, and slenderness effect. A theoretical procedure considering the nonlinear behaviour of the materials is proposed for determination of the behaviour of eccentrically loaded short and slender composite columns. Two approaches are taken into account to describe the flexural rigidity (EI) used in the analysis of slender composite columns. Observed failure mode and experimental and theoretical load-deflection behaviour of the specimens are presented in the paper. The composite column specimens and also some composite columns available in the literature have been analysed and found to be in good agreement with the test results.

Keywords: composite column; biaxial bending; slenderness effect; ultimate strength; flexural rigidity.

1. Introduction

The concrete-encased composite columns have been constructed as the combination of concrete, structural steel and reinforcing steel materials. They provide more rigidity and prevent local buckling failure and fire damages in the structures. It is important to note that composite columns resist to dynamic and wind loads effectively in the structures. Moreover, the use of composite columns in the structures enables to a reduction in column size when compared with reinforced concrete column design. Thus, composite columns can provide more usable floor areas especially in high rise buildings. Owing to those beneficial features, composite columns have become very popular and effective for structural design.

Some composite columns generally located at the corner of the buildings are commonly subjected to biaxial bending and axial load. These composite columns can be designed as not only square or rectangular shaped but also arbitrarily shaped, such as L-shaped cross section. Extensive experimental and theoretical studies were carried out on the eccentrically loaded composite columns. Furlong

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(1967,1979,1983) presented experimental and theoretical studies to investigate the behaviour of eccentrically loaded composite columns. Virdi and Dowling (1973), Bridge and Roderick (1978), Taylor *et al*. (1983) and Morino *et al*. (1984) conducted experimental studies on square cross section of both short and slender concrete-encased composite columns subjected to biaxial bending and axial load. Mirza (1989) investigated the effects of different variables on the variability of the ultimate strength of composite columns. Roik and Bergmann (1990) reported an experimental research and suggested a design method for unsymmetrical section of short and slender composite columns under eccentric loading. Mirza and Skrabek (1991,1992) examined the variability of the ultimate strength of short and slender composite beam-columns. Munoz (1994) and Munoz and Hsu (1997-a,1997-b) reported experimental and theoretical investigations of the behaviour of small scale square section of composite columns under biaxially eccentric load. They also suggested an analysis method for the determination of the behaviour of short and slender composite columns and vast amount of composite column data were verified to show the effectiveness of the proposed method in the studies. El-Tawil *et al*. (1995) developed a computer program based on the fiber element method for the analysis of both short and slender composite columns according to the ACI 318 Code (2002) and AISC-LRFD Specification (1993). Mirza and Tikka (1999-a,1999-b) and Tikka and Mirza (2006-a,2006-b) researched the influence of different variables on effective flexural rigidity (EI) of slender columns subjected to bending about both major and minor axis of the steel section in symmetrical single curvature under short-term loads. Wang (1999) performed two series of tests on slender composite columns under eccentric loading to compare the accuracy of the predictions using EC4 (1994) and BS 5400 (1987) and to assess the accuracy of the proposed method based on the steel column approach in BS 5950 (1990). Johansson and Gylltoft (2001) investigated experimental and theoretical behaviour of eccentrically loaded slender circular steel concrete composite columns. Three-dimensional nonlinear finite element methods were established and verified with the experimental results. Uy (2001-a) proposed a numerical method based on the finite strip method to determine the axial compressive strength of steel and composite cross sections. The method was compared with the test results and found to be useful for these sections. Uy (2001-b) studied experimental and theoretical investigation of both encased and concrete filled composite columns. Chicoine *et al*. (2002) examined the behaviour of axially loaded partially encased composite columns using finite element method. A design equation was proposed to determine the axial capacity of the composite columns. Weng and Yen (2002) researched the differences between ACI 318 Code and AISC-LRFD Specification used for the design of concrete-encased composite columns. Lachance (1982), Chen *et al*. (2001) and Sfakianakis (2002) presented a numerical analysis method for arbitrarily shaped short composite columns. Al-Shahari *et al*. (2003) conducted an experimental study to investigate the behaviour of uniaxially loaded pin ended light weight aggregate composite columns. They checked the adequacy of the AISC-LRFD and BS 5400 Specifications. Renaud *et al*. (2003) presented a numerical method based on the displacement finite element method to simulate the mechanical behaviour of composite steel and concrete columns. Mirza and Lacroix (2004) reported the comparisons of the strength of rectangular composite columns computed by using the ACI 318, AISC-LRFD Specification and Eurocode 4 (1994). Tikka and Mirza (2005) studied to investigate the effect of different variables on moment diagram factor of slender composite columns. Marques de Souza and Caldas (2005) presented a numerical formulation for the nonlinear analysis of slender steel-concrete composite columns of generic cross-sectional shape subjected to axial force and biaxial bending. Dundar *et al*. (2008) proposed an iterative method for analysis of arbitrarily shaped short and slender composite columns under biaxial bending and axial load. It is obvious that there is lack of experimental data especially for arbitrarily shaped slender concrete-encased composite columns available in the literature.

The primary purpose of this research is to investigate the load-deflection behaviour and ultimate strength capacity of square and L-shaped cross section of both short and slender composite columns. For this aim, six square and four L-shaped composite column specimens were constructed and tested under short-term axial load and biaxial bending in the Structural Laboratory of Cukurova University, Adana. In addition, an iterative theoretical method has been suggested for the prediction of the ultimate strength and load-deflection behaviour of arbitrarily shaped both short and slender eccentrically loaded composite columns. The analysis results of the composite columns have been compared with the test results and discussed in the paper.

2. Experimental program

An experimental investigation to determine the complete load-deflection behaviour and load carrying capacity of both short and slender composite columns is presented in the experimental study. The main variables considered in the test program were the concrete compressive strength, cross section, eccentricity of applied axial load and slenderness effect. The failure mode and experimental load-deflection behaviour of the specimens were examined in the tests. The complete experimental and theoretical load-deflection diagrams were obtained and illustrated in the study.

2.1 Test specimens

The experimental study was consisted of ten composite column specimens. Two specimens were square section short composite columns (CC1-CC2), four specimens were square section slender composite columns (CC3-CC6) and the other four specimens were L-shaped section slender composite columns (LCC1-LCC4). The cross section details and dimensions of the composite column specimens are shown in Fig. 1.

The composite column specimens were reinforced with longitudinal, lateral and structural steel materials. The longitudinal reinforcements were consisted of 6 mm and 8 mm deformed bars had the yield strength of 630 MPa and 500 MPa, respectively. The lateral reinforcements were designed by using 6 mm diameter deformed bars and were bent into 135 degree hooks at their ends. In the experimental study, T, I, and, L-shaped section had the yield strength of 235 MPa structural steel were encased by reinforced concrete to build the composite column specimens.

The heavily reinforced brackets were designed in both ends of the specimens in order to prevent local failures at the ends of the composite columns and to allow for a consistent biaxial bending condition. Normal Portland cement and maximum 20 mm diameter well drained local aggregate were used in the concrete mixture. The composite column specimens were cast horizontally inside a formwork and were compacted using hand-held mechanical vibrators. Three standard control cylinder specimens (150×300 mm) were cast from each batch of concrete mixture. The cylinder specimens were compacted on a vibrating table and were cured under the same condition as the column specimens in the Structural Laboratory.

The control cylinder specimens were axially tested on the day of the composite column specimen test to determine the average concrete compressive strength and to attain complete stress-strain relationship of each column specimen in order to use in the ultimate strength and load-deflection analysis. The average concrete compressive strengths of the composite column specimens were obtained between 22.69 and 52.30 MPa. The typical concrete stress-strain relationships obtained experimentally from the cylinder specimens are given in Fig. 2.

The overall length (L), the average concrete compressive strength (f_c), the eccentricities of applied

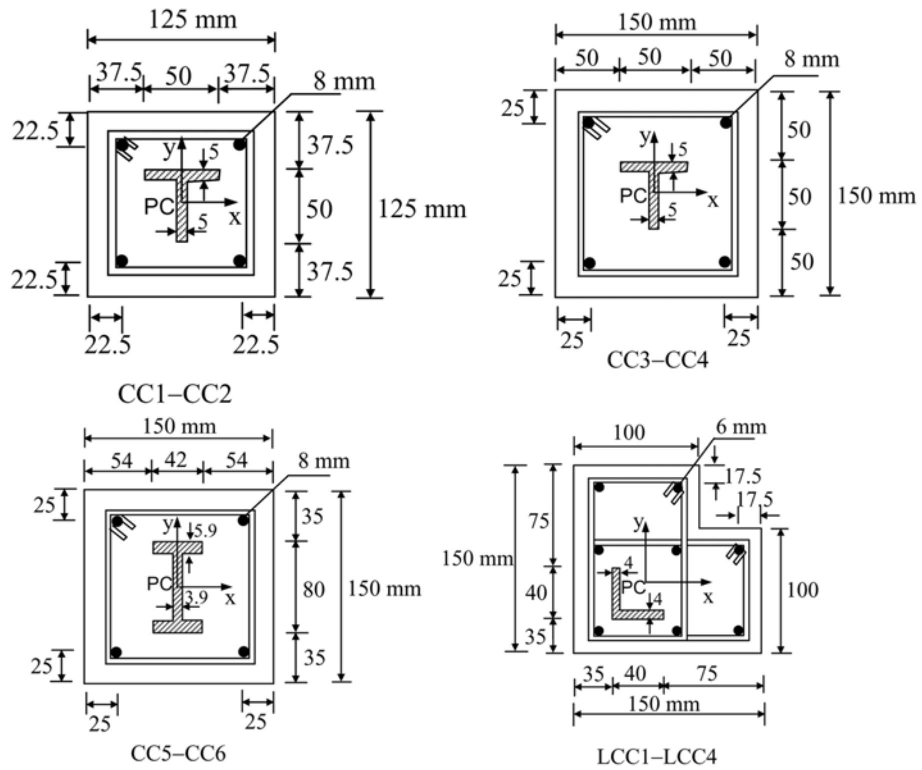

Fig. 1 Cross section details of the specimens CC1-CC6 and LCC1-LCC4

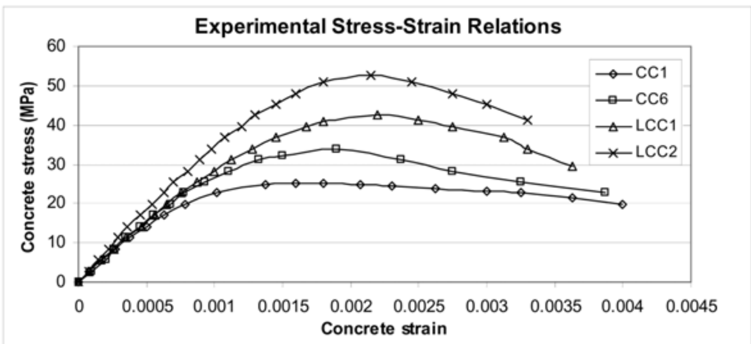

Fig. 2 The typical experimental concrete stress-strain relations

axial load (e_x, e_y) described with respect to the plastic centre PC of the composite column section (Dundar *et al*. 2008) and details of the lateral reinforcements of the specimens (diameter ϕ and spacing s) are presented in Table 1.

2.2 Test setup and test procedure

The composite column specimens (CC1-CC6, LCC1-LCC4) were tested with pin ended conditions.

Table 1 Details of the composite column specimens

Specimen no.	L (mm)	f_c (MPa)	e_x (mm)	e_y (mm)	ϕ/s (mm/cm)
CC1	850	25.78	47.5	45.7	6/8
CC2	850	30.18	57.5	55.9	6/10
CC3	1300	22.69	50	48.5	6/10
CC4	1300	45.40	40	39.2	6/12
CC5	1300	29.76	50	50	6/10
CC6	1300	33.99	55	55	6/10
LCC1	1300	41.40	42.7	42.7	6/10
LCC2	1300	52.30	47.4	47.4	6/11
LCC3	1300	32.81	53	53	6/13
LCC4	1300	34.34	58	58	6/12

Four linear variable displacement transducers were applied horizontally on each midheight of column face to measure the deflections of the specimen into two principal directions. The 50 tf capacity load cell was accommodated between the loading plate and the hydraulic jack at the top of the specimen to obtain the axial load values during the test. The transducers and the load cell were calibrated before they were used in the tests. The column specimens were tested in a vertical position with various values of eccentricities in the test study. The loading plates and pins were located to the desired biaxial eccentricity point at the top and the bottom of each specimen. The schematic arrangement of eccentrically loaded composite column test setup is presented in Fig 3.

Monotonically increasing axial load was applied to the composite column specimens at a rate of 1 kN/s. The digital readings of axial load and lateral displacements in each principal axis were collected by using an electronic data acquisition system during testing of each specimen. The test was continued beyond the peak load. When significant drop was recorded in load resistance, the test was terminated.

2.3 Behaviour of the composite column specimens

Most of the composite column specimens were behaved in a ductile manner under short-term axial load and biaxial bending. It was observed that the flexural minor cracks started to appear on tensile side at generally midheight or close to midheight locations of the composite column specimens at a load level of about 40 ~ 50% maximum load. Then, the existing cracks propagated and new flexural cracks occurred on the convex side of the column specimens due to the increment of load level. After that, axial load started to drop and the lateral displacements increased beyond the peak load. Finally, significant drop measured in load resistance, the major tensile cracks observed on the tensile side and the concrete crushed on the compression side at or close to midheight of the composite column specimens (Fig. 4). At the time of failure the concrete crushed and the longitudinal reinforcing bars buckled in the compression side of the column specimens and then test was terminated.

The complete experimental load-deflection curves were obtained for all the composite columns in the experimental study. The typical experimental and theoretical load-deflection behaviour for the specimens CC1, CC4, LCC2 and LCC3 are illustrated in Fig. 5(a)-(f) for x and y directions. The procedure for the determination of the theoretical load-deflection behaviour for the eccentrically loaded composite columns is given in Section 3.

It is shown in the diagrams that a good degree of accuracy was obtained between the complete experimental and the theoretical load-deflection behaviour for the composite column specimens (Fig. 5(a)-(f)). The

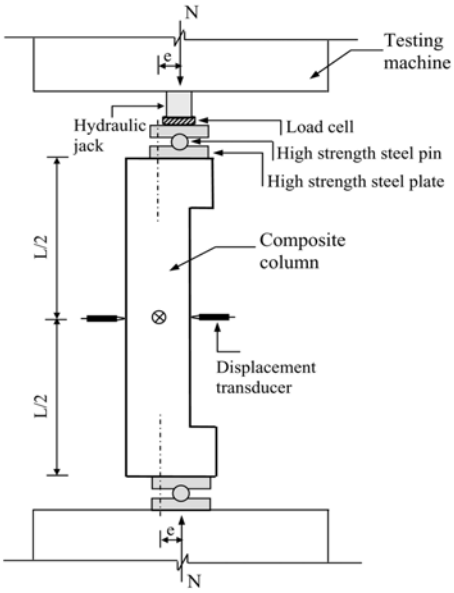

Fig. 3 Composite column test setup

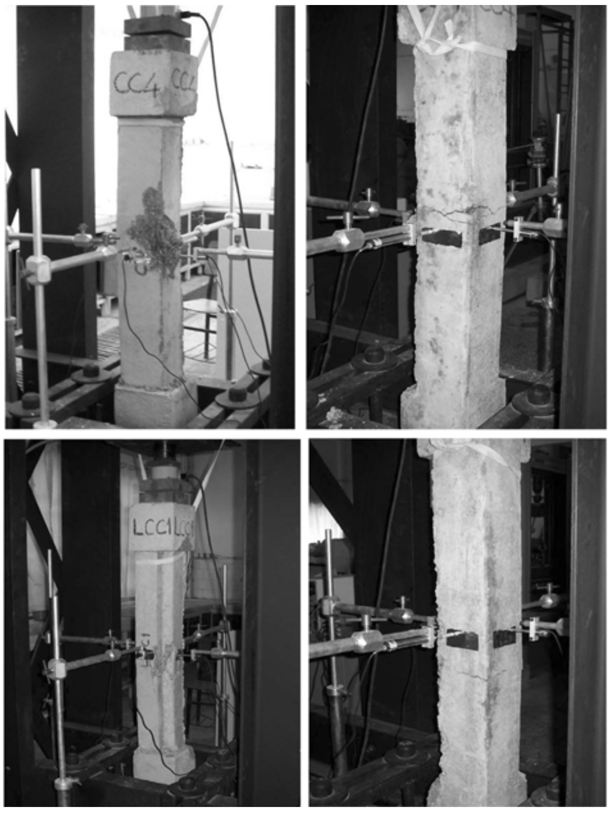

Fig. 4 Composite column specimens after testing

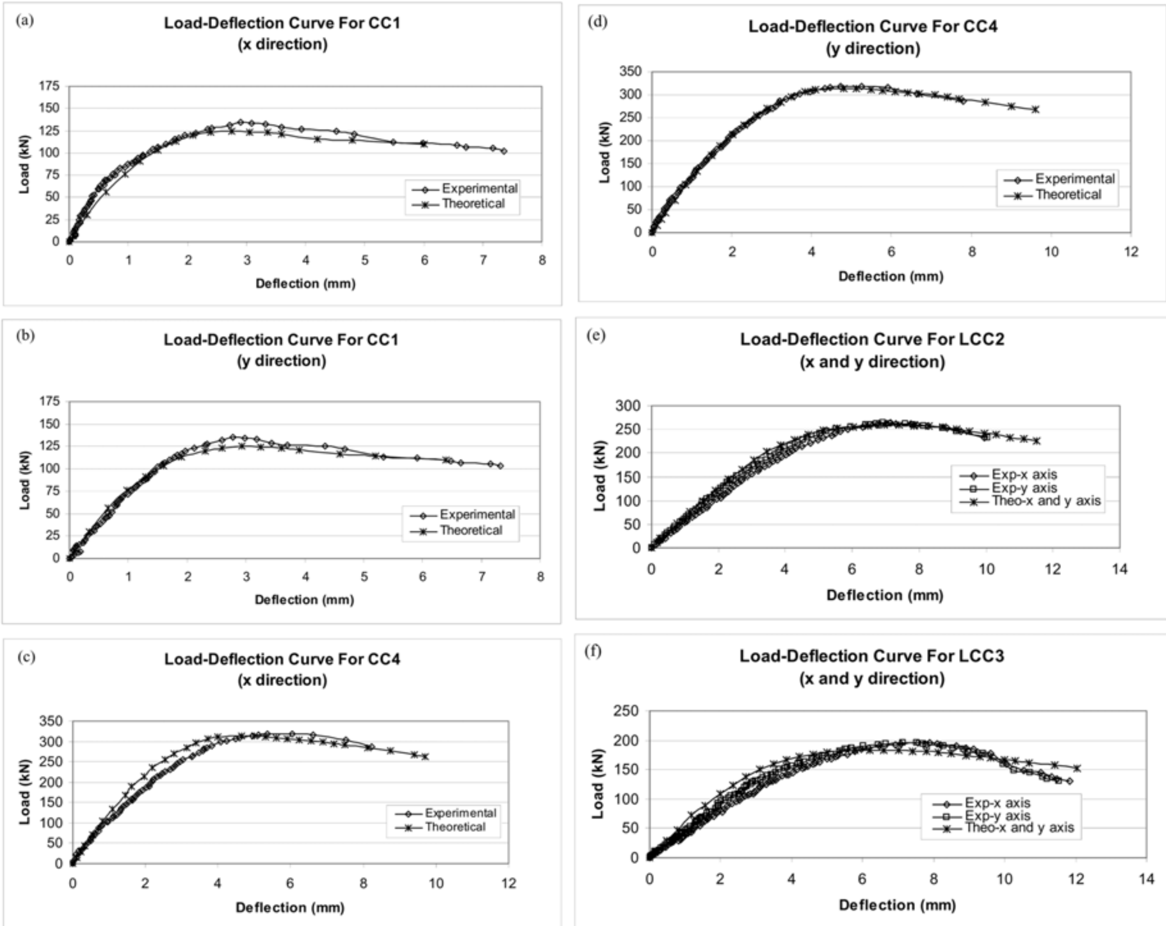

Fig. 5(a)-(f) Load-deflection diagrams of the specimens CC1, CC4, LCC2 and LCC3

descending branches of the experimental load-deflection curves were attained beyond the pick load and ductile behaviour was observed for the specimens had the concrete compressive strength less than 45 MPa. On the other hand, the specimens CC4 and LCC2 behaved more brittle than the other specimens due to the mechanical properties of their concrete compression strength level. It is widely believed that concrete compressive strength and ductility are inversely proportional (Saatcioglu and Razvi 1998). Therefore, concrete confinement provided by lateral ties and arrangement of longitudinal reinforcements becomes a critical issue to improve the ductility of higher strength concrete composite columns.

The presented experimental investigation has informed noticeable knowledge to describe the behaviour of the eccentrically loaded both short and slender composite columns. A photograph of all the composite column specimens after experimental test is shown in Fig. 6.

3. Review of the proposed analysis method

A theoretical procedure for analysis and design of arbitrarily shaped both short and slender composite

Fig. 6 Photograph of all the composite column specimens after experimental test

columns subjected to biaxial bending and axial load was reported previously by Dundar *et al*. (2008). The analysis method is modified and also a simplified stability analysis procedure is recommended here to obtain the complete load-deflection behaviour of composite columns theoretically. A computer program has been developed to perform the analysis method in the study.

3.1 Fundamental equations for the analysis

The arbitrarily shaped composite column cross section subjected to compressive axial load N is shown in Fig. 7. According to the Bernoulli's assumption that plane sections remain plain, the strain at any point in the cross section (x_i,y_i) can be written 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 column member can be described using the strain distribution as follows (Fig. 7):

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

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

In the analysis method, nonlinear stress-strain relations are considered for the materials. Therefore, the compression zone of the arbitrarily shaped cross section and entire section of the structural steel are divided into parallel segments to the neutral axis in order to determine the stress resultants of the materials (Dundar *et al*. 2008).

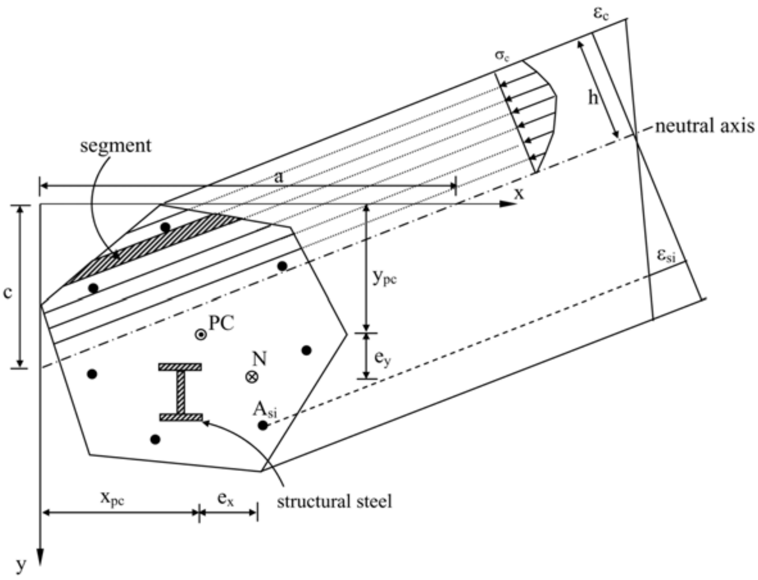

Fig. 7 Composite column cross section

3.2 The equilibrium equations

The plastic centre of the arbitrarily shaped composite column section is considered to express the basic equations of equilibrium (Dundar *et al*. 2008). The external axial load (N) and biaxial bending moments (M_x, M_y) should be equated to the internal axial load and bending moments to provide the static equilibrium condition. The internal load and moments can be calculated by the summation of the individual contributions of forces, stresses and strains of the concrete, reinforcing steel bars and the structural steel on the entire cross section. Therefore, the following equilibrium equations must be satisfied to compute the flexural strength of a composite column section:

$$f_1 = \sum_k^t \bar{A}_{ck}\sigma_{ck} - \frac{A_{st}}{m}\sum_i^m \sigma_{si} - \sum_j^n A_{tj}\sigma_{tj} - N = 0 \tag{3}$$

$$f_2 = \frac{A_{st}}{m}\sum_i^m (y_i - y_{pc})\sigma_{si} + \sum_j^n A_{tj}\sigma_{tj}(y_{tj} - y_{pc}) - \sum_k^t \bar{A}_{ck}\sigma_{ck}(\bar{y}_{ck} - y_{pc}) - M_X = 0 \tag{4}$$

$$f_3 = \frac{A_{st}}{m}\sum_i^m (x_i - x_{pc})\sigma_{si} + \sum_j^n A_{tj}\sigma_{tj}(x_{tj} - x_{pc}) - \sum_k^t \bar{A}_{ck}\sigma_{ck}(\bar{x}_{ck} - x_{pc}) - M_y = 0 \tag{5}$$

where, σ_{ck} is the concrete compressive stress at the centroid of the *k*th segment; $\bar{A}_{ck}$ and $(\bar{x}_{ck}, \bar{y}_{ck})$ indicate the area and the centroid coordinates of *k*th concrete segment, respectively; A_{st} is the total area of the reinforcing bars within the cross-section; *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 centroid coordinates of the jth structural steel segment, respectively; σ_{tj} is the structural steel stress at the centroid of the jth segment; x_i and y_i are the coordinates of the ith reinforcing bar; x_{pc} and y_{pc} are the plastic centroid coordinates of the composite column section.

The algebraic equations (Eqs. (3)-(5)) are solved by a numerical procedure (Dundar and Sahin 1993) based on the Newton-Raphson iterative method for the three unknowns (a,c,A_{st}) for design a composite column. For the ultimate strength analysis, the solution of the Eq. (4) and Eq. (5) provides the neutral axis position that satisfies the equilibrium equations. Then, the ultimate strength capacity of a composite column can be computed by substituting the parameters (a, c) in Eq. (3), resulting in

$$N_u = \sum_k^t \bar{A}_{ck}\sigma - \frac{A_{st}}{m}\sum_i^m \sigma_{si} - \sum_j^n A_{tj}\sigma_{tj} \tag{6}$$

3.3 Slenderness effect

The slenderness effect in columns occurs due to the additional bending moments produced by the large lateral displacement (Δ) at the midheight of the column. The deflected shape of a slender composite column under an eccentrically applied axial load is illustrated in Fig. 8. The slenderness effect of the composite columns is taken into account by using The Moment Magnification Method recommended by ACI 318 Building Code. The primary moments have been magnified with the moment magnification factor (δ). The magnified column moment can be expressed as follows:

$$M_c = \delta M_2 \tag{7}$$

where

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

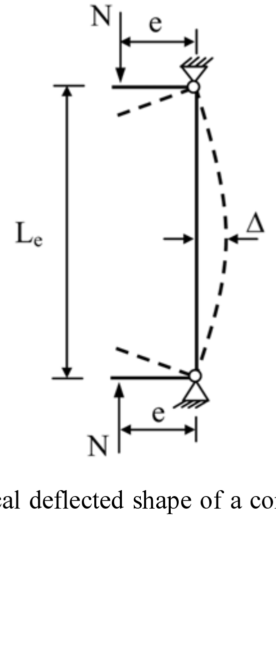

Fig. 8 The typical deflected shape of a composite column

in which C_m is the end effect factor taken as follows:

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

with 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;

$$N_{cr} = \frac{\pi^2 EI}{(L_e)^2} \tag{10}$$

where L_e is the effective length and EI is the flexural rigidity of the composite column section.

The flexural rigidity is the most effective parameter on the computation of the ultimate strength capacity of slender composite columns. Several researchers pointed out the importance of the flexural rigidity for the analysis of slender composite columns in their investigations, such as Furlong (1983), Roik and Bergmann (1990), Munoz (1994), Munoz and Hsu (1997-b), Mirza and Tikka (1999-a,1999-b) and Tikka and Mirza (2006-a,2006-b). This parameter reasonably approximates the variations in stiffness due to cracking, creep and also nonlinearity of stress-strain curve. In the presented study, two approaches have been used to describe the flexural rigidity for analysis of slender composite columns reported previously by Roik and Bergmann (1990) and Munoz and Hsu (1997-b) as follows:

Roik and Bergmann (1990) proposed an empirical equation based on the EC4 Code for the determination of the flexural rigidity $EI_{(I)}$ for unsymmetrical cross section of composite columns. The recommended equation to describe the flexural rigidity of the composite columns is expressed as follows:

$$EI_{(I)} = E_{ce}I_c + E_sI_s + E_{sr}I_{sr} \tag{11}$$

where E_{ce} was suggested as $600f_c$ for composite columns by Roik and Bergmann (1990); E_s and E_{sr} are the modulus of elasticity of reinforcing steel and structural steel materials, respectively; I_c, I_s and I_{sr} are the moments of inertia of the uncracked concrete, the reinforcement and the structural steel section, calculated with respect to the elastic centroidal axis of the section, respectively (Dundar *et al.* 2008).

A modified flexural rigidity $EI_{m(II)}$ incorporated both ACI and AISC Specifications was suggested for calculation of slender composite columns by Munoz and Hsu (1997-b). The proposed modified flexural rigidity is given by the following equation:

$$EI_{m(II)} = \frac{0.4E_cI_g}{1+\beta_d} + E_sI_s + E_{sr}I_{sr} \tag{12}$$

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 ($\beta_d = 0$ for short-term axial load).

In the proposed procedure, the modulus of elasticity of the concrete is assumed as follows (ACI 318 2002):

$$E_c = 4730\sqrt{f_c} \tag{13}$$

where f_c is expressed in MPa.

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

$$M_{ux} = \delta_x Nu\, e_y,\; M_{uy} = \delta_y N_u\, e_x \tag{14}$$

3.4 Load-deflection curve of composite columns

Rangan (1990) reported a simplified stability analysis method to describe the complete load-deflection behaviour of reinforced concrete columns. The suggested theoretical method is applied here to attain the complete load-deflection behaviour of eccentrically loaded composite columns. The procedure is discussed in the following expressions:

The deflected shape of a composite column (Fig. 8) may be assumed as a sinusoidal function and can be expressed as:

$$u(x) = \Delta \mathrm{Sin}\left\{\frac{\pi x}{L_e}\right\} \tag{15}$$

Then, differentiation of Eq. (15) gives the curvature at midheight of the composite column as follows:

$$\varphi = \frac{d^2u}{dx^2} = \frac{\pi^2}{L_e^2}\Delta \mathrm{Sin}\left\{\frac{\pi x}{L_e}\right\} \tag{16}$$

The curvature for each principal direction can also be written from the linear strain distribution as follows (Fig. 7):

$$\varphi_x = \frac{\varepsilon_c}{c}, \quad \varphi_y = \frac{\varepsilon_c}{a} \tag{17}$$

The deflection at midheight of the composite column for each principal direction can be expressed by substituting $x = y = \frac{L_e}{2}$ and resulting in,

$$\Delta_x = \varphi_x \frac{L_e^2}{\pi^2} \qquad \Delta_y = \varphi_y \frac{L_e^2}{\pi^2} \tag{18}$$

The axial load capacity of a composite column section and the corresponding midheight deflections in each principal axis are computed by using the aforementioned procedure for chosen any strain value. The complete load-deflection behaviour of the composite columns is performed by calculating the axial load and corresponding midheight deflections for each strain increments.

4. Computer analysis of test results

4.1 Analysis of composite columns tested by the authors

The specimens (CC1-CC6, LCC1-LCC4) were analysed for the prediction of the ultimate flexural strength capacities using the developed computer program. In the analysis, the experimental concrete stress-strain relationships obtained from the cylinder specimens of the composite columns were used for the concrete compression zone. The two abovementioned flexural rigidity approaches $EI_{(I)}$ and $EI_{m(II)}$ were assumed for the computation of corresponding ultimate axial load capacities $N_{u(I)}$ and $N_{u(II)}$ of the slender composite columns. The experimental results, the predicted ultimate axial loads, the moment capacities and the comparative ratios of the predicted load to the test load for the specimens are presented in Table 2.

The comparative results show that a good agreement between the theoretical and the experimental results of the composite column specimens has been obtained. The flexural rigidity parameter was played significant role on the computation of slender composite columns. Besides this, the concrete compressive fiber strain and the concrete strength had significantly effect on the prediction of the flexural strength capacity of the composite columns. By comparing the theoretical ultimate strength capacities with the test results (Table 2), both the proposed flexural rigidity approaches have been found to be suitable for analysis of eccentrically loaded slender composite columns.

Table 2 Ultimate strength capacities and comparative results of the specimens

Specimen no.	N_{test} (kN)	$N_{u(I)}$ (kN)	$N_{u(II)}$ (kN)	$M_{ux(I)}$ (kN-cm)	$M_{uy(I)}$ (kN-cm)	$N_{u(I)} / N_{test}$	$N_{u(II)} / N_{test}$
CC1	135	123.89	122.21	583.51	607.48	0.918	0.905
CC2	111	104.87	103.52	599.48	617.29	0.945	0.933
CC3	176	163.93	160.45	839.24	866.63	0.931	0.912
CC4	319	313.32	295.49	1300.92	1328.75	0.982	0.926
CC5	185	209.87	204.11	1102.81	1110.66	1.134	1.103
CC6	208	207.36	201.24	1192.11	1198.76	0.997	0.968
LCC1	278	261.13	250.44	1186.12	1186.12	0.939	0.901
LCC2	264	263.82	249.09	1316.65	1316.65	0.999	0.944
LCC3	196	182.73	176.85	1021.64	1021.64	0.932	0.902
LCC4	182	166.21	161.15	1010.49	1010.49	0.913	0.885
			Mean ratio			0.969	0.938

4.2 Analysis of composite columns tested by Virdi and Dowling (1973)

Virdi and Dowling (1973) reported pin ended slender composite columns (A-F) tested under biaxial bending and axial load. The cross section details and steel arrangements of the composite column specimens are shown in Fig. 9. The yield strength of the reinforcing bars and the structural steel are 413.7 and 227.5 MPa, respectively. The specimen details of the composite columns (A-F) are given in Table 3. The slender composite column specimens were analysed with the developed computer program using the concrete stress-strain model proposed by Hognestad *et al*. (1955). The both flexural rigidity approaches $EI_{(I)}$ and $EI_{m(II)}$ were used in the Moment Magnification Method for the analysis of slender composite columns. The experimental and the theoretical flexural strength capacities as well as the comparative results are presented in Table 4.

The computed results indicate that the predicted strength capacities agree well with the test results for most of the specimens tested by Virdi and Dowling (1973). Similarly, the flexural rigidity had also here effect on the computation of the ultimate strength capacity of slender composite columns. Good agreement has been accomplished between the test results and the ultimate strength capacities of the slender composite columns computed using both flexural rigidity approaches (Table 4).

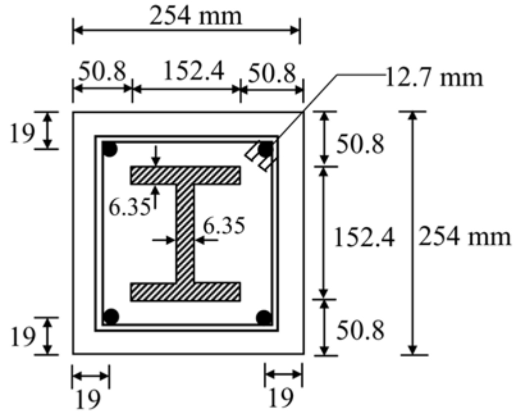

Fig. 9 Composite column cross section tested by Virdi and Dowling (1973)

Table 3 Details of the composite columns tested by Virdi and Dowling (1973)

Specimen no.	L (mm)	f_c (MPa)	e_x (mm)	e_y (mm)
A	1828	39.62	63.5	36.8
B	1828	37.93	127	73.7
C	1828	39.62	190.5	110.5
D	3657	41.97	63.5	36.8
E	3657	39.62	127	73.7
F	3657	41.97	190.5	110.5

Table 4 Comparative results of the composite column specimens A-F

Specimen no.	N_{test} (kN)	$N_{u(I)}$ (kN)	$N_{u(II)}$ (kN)	$M_{ux(II)}$ (kN-cm)	$M_{uy(II)}$ (kN-cm)	$N_{u(I)}/N_{test}$	$N_{u(II)}/N_{test}$
A	1256.02	1323.57	1280.93	5101.94	8990.56	1.054	1.020
B	647.95	642.50	631.08	4829.67	8415.49	0.992	0.974
C	473.50	425.37	420.17	4759.95	8261.86	0.898	0.887
D	927.07	1176.14	1038.42	5036.38	9460.32	1.269	1.120
E	573.19	602.06	563.05	4780.74	8589.89	1.050	0.982
F	418.67	413.02	393.65	4785.88	8471.63	0.987	0.940
Mean ratio						1.042	0.987

5. Conclusions

An experimental research on the behaviour of square and L-shaped section short and slender concrete-encased composite columns subjected to short-term axial load and biaxial bending has been presented in this paper. The complete experimental load-deflection behaviour of the composite column specimens has been attained in the test study.

An iterative theoretical method including slenderness effect is suggested to perform the ultimate strength analysis and to determine the complete load-deflection behaviour of composite columns. The proposed procedure is taken into account the nonlinear behaviour of the materials. The slenderness effect due to the additional eccentricity of the applied axial load is considered by The Moment Magnification

Method. The composite column specimens have been analysed with the computer program developed based on the proposed method. Good agreement has been achieved between the complete experimental and the theoretical load-deflection diagrams in the study. The theoretical and the experimental results indicate that the concrete strength and the maximum compressive fiber strain are the most effective parameters on the computation of the composite columns. In addition, it is important to note that the flexural rigidity has significantly effect on the computation of slender composite columns. Two flexural rigidity approaches have been proposed for the analysis of slender composite columns. The computed results using both flexural rigidity approaches show good agreement with the experimental results for most of the slender composite columns carried out in the presented study.

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