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Studies on carbon fiber polymer confined slender plain and steel fiber reinforced concrete columns

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ABSTRACT

This paper presents an experimental research to examine the behavior of carbon fiber reinforced polymer (CFRP) confined plain and steel fiber reinforced concrete columns. In this study, plain and steel fiber reinforced concrete columns were wrapped with CFRP material and experimentally tested to determine the effects of sheets on column behavior. It is revealed that the CFRP material is significantly effective on reinforced concrete columns with respect to strength, ductility and confinement. In addition, a numerical procedure is presented for the analysis of slender reinforced concrete columns confined with CFRP sheets subjected to combined axial load and biaxial bending. The CFRP confined slender reinforced concrete columns have been analyzed using geometric features and experimental parameters of concrete compressive strength, steel yield strength and CFRP material properties to predict the column structural behavior. The analysis and experimental results of CFRP confined slender plain and steel fiber reinforced concrete columns have been achieved in good accuracy in this study.

1. Introduction

Confinement effect and strength capacity are critical issues for reinforced concrete column members. Reinforced concrete columns behave more brittle with increasing concrete strength. Thus, columns require additional retrofit to improve the confinement and deformability features. Retrofitting of reinforced concrete columns by wrapping and bonding with CFRP has been increasingly used recently. The effectiveness of the use of CFRP sheet materials is seen especially in the seismic areas. The CFRP sheet can be easily applied on reinforced concrete columns and it provides cost economy and rapid construction. The mechanical properties of CFRP material is effective on reinforced concrete column behavior. The most effective parameters on the structural behavior of CFRP columns are the type of carbon fiber polymer, modulus and strength of the material, thickness of the fiber polymer, the number of CFRP layers, fiber orientation and also implementation of fiber polymer material.

The use of CFRP material improves confinement of the concrete core of plain and steel fiber slender reinforced concrete columns. In addition, CFRP jacketing is significantly effective to achieve strength capacity, ductility and stiffness of the structural members. Therefore, CFRP sheet wrapping to the reinforced concrete columns presents significant advantages in the field of civil engineering applications and constructions. Hence it is important to understand the structural behavior of plain and steel fiber reinforced concrete columns confined with carbon fiber reinforced polymer.

A number of research studies were conducted to determine the behavior of CFRP confined eccentrically loaded slender reinforced concrete columns and mechanical behavior of fiber reinforced polymer confined concrete. Mirmiran and Shahawy [1], Toutanji and Balaguru [2], Teng and Lam [3] and Sheikh [4] researched the structural behavior of columns confined with fiber composites. Samaan et al. [5] proposed a confinement model to predict the response of fiber reinforced polymer confined concrete in both the axial and lateral directions. Parvin and Wang [6] described the behavior of CFRP jacketed concrete columns subject to eccentric loading. Hadi [7] reported test results of fiber reinforced polymer wrapped normal strength concrete columns under eccentric loading. The results showed that wrapping a column with fiber reinforced polymer provided higher strength, ductility and energy absorption capacity. Barros et al. [8] presented a strengthening technique method by using CFRP material to improve the flexural capacity of columns subjected to bending and compression. Hadi [9] researched the behavior of eccentrically loaded reinforced concrete columns and steel fiber concrete columns wrapped with CFRP material. Malik and Foster [10] conducted experimental investigation to research the behavior of ultra-high strength

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concrete columns confined by carbon fiber reinforced polymer subjected to concentric and eccentric loading. Quiertant and Clement [11] examined the performance of eccentrically loaded columns externally strengthened with different carbon fiber reinforced polymer systems. Zaki [12,13] presented analysis and design techniques for retrofitting of reinforced concrete columns using CFRP under eccentrically applied axial load. Ozbakkaloglu et al. [14] studied on the comprehensive assessment of stress–strain relations of fiber reinforced polymer confined concrete available in the literature. Vincent and Ozbakkaloglu [15] studied on the effect of concrete compressive strength and confinement of fiber reinforced polymer confined concrete. Vincent and Ozbakkaloglu [16] reported the experimental results of the influence of fiber orientation of fiber reinforced polymer jacket and specimen end condition on the compressive behavior of fiber reinforced confined concrete. Ozbakkaloglu and Lim [17] presented a comprehensive test database constructed from the results of a large number of tests on fiber reinforced polymer confined concrete and a new design-oriented model was developed in the study. Punurai et al. [18] examined experimental and theoretical behavior of biaxially loaded slender reinforced concrete columns confined with carbon fiber reinforced polymer jackets. Alecci et al. [19] and Hu and Barbato [20] studied on the determination of the behavior of concrete columns confined with CFRP wraps. Hadi and Le [21] worked on the effect of fiber orientation on hollow core square reinforced concrete columns confined with CFRP tested under concentric and eccentric conditions. Rahai and Akbarpour [22] presented experimental study on rectangular reinforced concrete columns strengthened with carbon fiber reinforced polymer composites under axial load and biaxial bending. There is a lack of information particularly on steel fiber reinforced concrete columns wrapped with CFRP material. Thus, further research studies are necessary to better describe the structural behavior of CFRP confined plain and steel fiber reinforced concrete columns under combined axial load and biaxial bending including slenderness effect.

The main objective of this study is to determine the behavior of biaxially loaded CFRP confined slender plain and steel fiber reinforced concrete columns. A total of 16 both plain and steel fiber reinforced concrete column specimens were constructed with concrete strength in the range between 53.13 and 76.76 MPa. The column specimens were strengthened by CFRP sheets and experimentally tested to determine the column structural behavior. In addition, the tested column specimens have been analyzed to predict the ultimate strength capacity and load–deformation behavior of CFRP confined slender reinforced concrete columns. The nonlinear behavior of the stress–strain relations of the materials is used in the analysis procedure. In the study, the theoretical results have been compared with the test results and found to be in good agreement.

2. Experimental study

The purpose of this experimental research was to investigate the effects of CFRP material on the behavior of plain and steel fiber reinforced concrete columns. The test parameters were concrete compressive strength, load eccentricity, yield strength of reinforcing steel, CFRP sheet property, steel fiber and slenderness effect. The column strength capacity, load–deflection behavior and the effects of carbon fiber reinforced polymer material on the structural behavior of plain and steel fiber reinforced concrete columns were observed in the study.

2.1. Column specimens

The experimental work comprised sixteen square plain and steel fiber reinforced concrete columns. All the columns were 1300 mm in length. The cross section dimensions of the column specimens were 125 × 125 mm. The slenderness ratio (effective length to the radius of gyration of cross section) of the column specimens was 34.67 determined according to ACI Standard 318-08 [23]. In order to provide biaxial loading application, two 200 × 200 × 200 mm heavily reinforced concrete brackets were designed at column both ends. Fig. 1 illustrates the details and the reinforcement configuration of the test columns. Deformed bars were used for longitudinal and lateral reinforcement arrangements of test columns. The longitudinal reinforcements were 8 mm-diameter deformed bars located at each corner of the section. The lateral reinforcements were designed with 6 mm-diameter deformed bars were bent into 135° hooks at the ends. The lateral tie spacing was 100 mm and 50 mm on column section and on brackets, respectively. The yield strengths of longitudinal and lateral reinforcements were 550 MPa and 630 MPa, respectively.

2.2. Materials

The column specimens were constructed using CEM I 42.5 R type Portland cement, well dry and clean natural gravel aggregate. The maximum coarse aggregate size was 20 mm. Tap water and also super plasticizer were used in concrete mixtures. Steel fiber concrete was prepared with using RC 65/35 BN-type hooked steel fibers. The fiber length and diameter were 35 mm and 0.55 mm, respectively. The aspect ratio of steel fiber was 64, and the density of fibers was 7850 kg/m^3. The amounts of concrete mixture compositions of the column specimens are given in Table 1. Steel fibers were contained in concrete batches at the dosages of 0, 50 and 60 kg/m^3. In the experimental study, bi-directional carbon fiber reinforced polymer material namely SikaWrap Hex 300C 0/90 was used for strengthening of column specimens. For this type of sheet, the fibers were designed in two directions as longitudinal and transverse. The carbon fiber reinforced polymer material applied on column surface with Sikadur-330 adhesive.

2.3. Specimen preparation

The plain and steel fiber reinforced concrete column specimens were cast horizontally in a steel mold in the Structural Laboratory at Cukurova University in Adana. The specimens were compacted by using mechanical vibrator. For the determination of the concrete compressive strength and properties of plain and steel fiber concrete, at least three concrete cylinder specimens (150 mm in diameter and 300 mm in length) were cast from each concrete batches. The cylinders were subjected to the same curing conditions with the prepared column specimens.

In order to determine the effects of carbon fiber reinforced polymer material on reinforced concrete column behavior, the plain and steel fiber reinforced concrete column specimens were designed with no sheet, one layer and two layers wrapping configurations. The control plain and steel fiber column specimens of C1-0, C2-0, C1-0-SF and C2-0-SF were not wrapped with CFRP material. The other columns were strengthened by one layer and two layers of sheets applied on four sides of column surface (Table 2). In order to eliminate the stress concentration, the sharp corner of the column specimens was rounded before applying the CFRP sheets.

The cylinder specimens were tested in axial compression after two months on the day of column test. It was seen that the inclusion of steel fibers has significantly effect on concrete deformability ([24]). The cylinder compressive strength of unconfined concrete (f_c), the eccentricity (e_x,e_y) of column specimens, CFRP material design details are presented in Table 2. The average

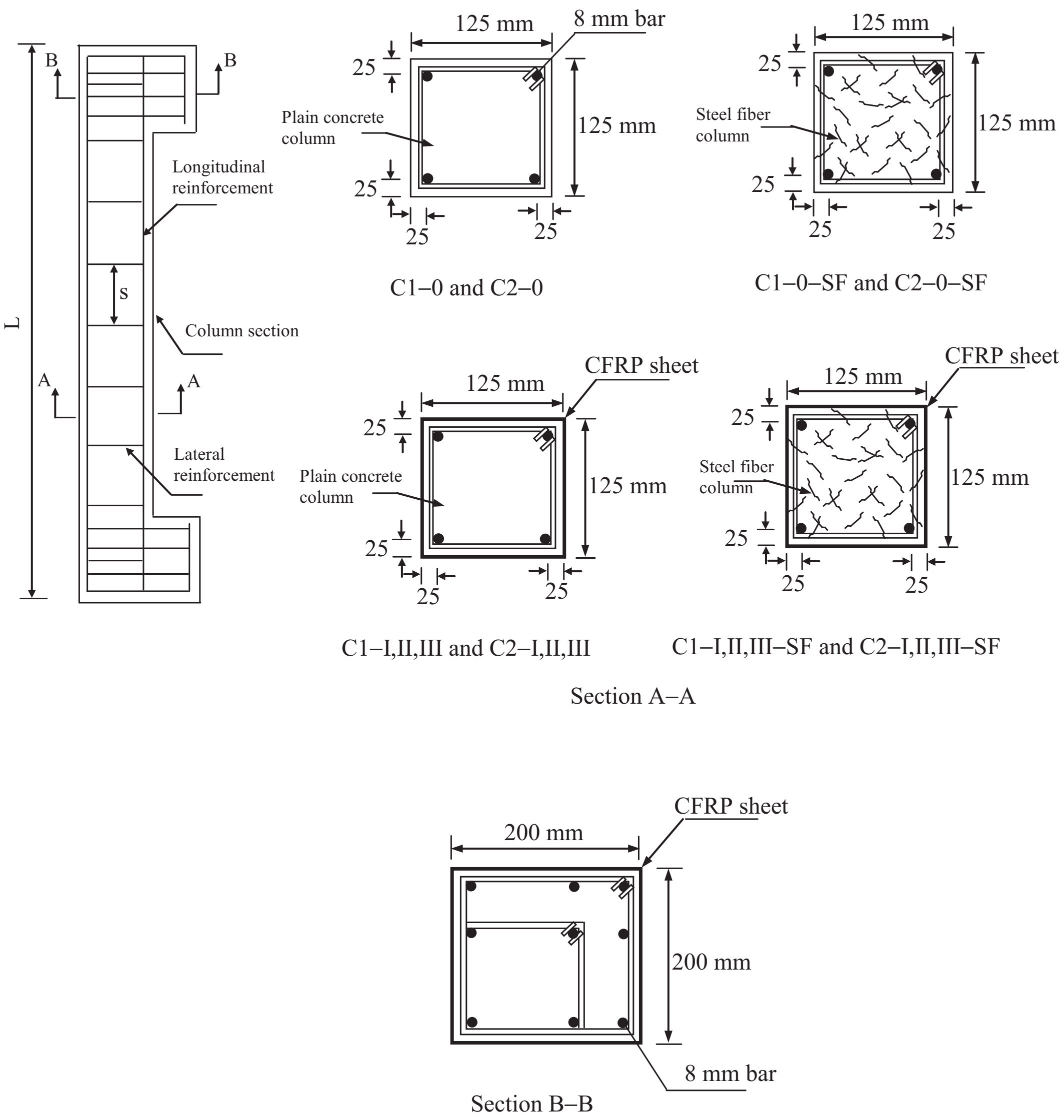

Fig. 1. Details of test specimens and reinforcement configuration.

Table 1
Concrete mix composition for test specimens.

Specimen no.	Gravel (kg/m^3)	Sand (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Plasticizer (kg/m^3)	Steel fiber (kg/m^3)
C1-0	1120	725	400	150	5	0
C1-I	1120	725	400	150	5	0
C1-II	1120	725	400	150	5	0
C1-III	1120	725	400	150	5	0
C1-0-SF	1110	720	400	150	5	50
C1-I-SF	1110	720	400	150	5	50
C1-II-SF	1110	720	400	150	5	50
C1-III-SF	1110	720	400	150	5	50
C2-0	1100	640	400	120	15	0
C2-I	1100	640	400	120	15	0
C2-II	1100	640	400	120	15	0
C2-III	1100	640	400	120	15	0
C2-0-SF	1090	630	400	120	15	60
C2-I-SF	1090	630	400	120	15	60
C2-II-SF	1090	630	400	120	15	60
C2-III-SF	1090	630	400	120	15	60

Table 2
Test details of specimens.

Specimen no.	f_c (MPa)	e_x (mm)	e_y (mm)	Sheet design
C1-0	64.66	40	40	No sheet
C1-I	58.98	40	40	One layer
C1-II	57.72	40	40	Two layers
C1-III	61.34	50	50	Two layers
C1-0-SF	65.20	40	40	No sheet
C1-I-SF	65.31	40	40	One layer
C1-II-SF	67.59	40	40	Two layers
C1-III-SF	65.48	50	50	Two layers
C2-0	76.76	50	50	No sheet
C2-I	74.87	50	50	One layer
C2-II	61.91	50	50	Two layers
C2-III	63.62	60	60	Two layers
C2-0-SF	64.37	50	50	No sheet
C2-I-SF	63.30	50	50	One layer
C2-II-SF	53.13	50	50	Two layers
C2-III-SF	57.53	60	60	Two layers

concrete compressive strength of column specimens varied from 53.13 to 76.76 MPa in the research study.

2.4. Test setup and procedure

The column specimens were vertically tested using a universal testing machine in the Structural Laboratory, at Cukurova University in Turkey. The column specimens were loaded with pinned end conditions. A data acquisition system was established to record the digital measurements during the tests. The lateral deformations of the column specimens were recorded with four linear variable differential transducers applied at column mid-height in both x and y directions. The biaxially applied axial load was measured with a 500 kN capacity load cell. The transducers and the load cell were calibrated before using in the test study. The test arrangement and instrumentations of the column tests are presented in Fig. 2.

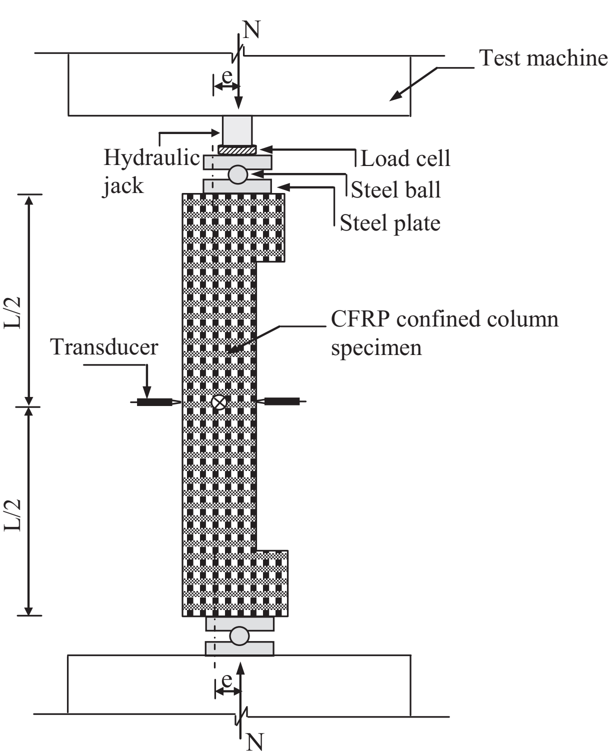

Fig. 2. Experimental setup.

The prepared column specimens were tested with different load eccentricities (Table 2). The load was applied to the specimens at small increment (1 kN/s) to obtain the complete load–deflection curves of the tested columns. During the tests, the load increments and corresponding lateral deformations in both x and y directions were measured and recorded by the data acquisition system.

2.5. Experimental results and discussion

Experimental behavior of plain and steel fiber reinforced concrete columns strengthened by CFPR sheets were investigated in the study. The axial load was applied to the column specimens monotonically in the tests. The plain reinforced concrete columns without CFRP material behaved in brittle manner due to the mechanical property of plain concrete specimens of C1-0 and C2-0. It is known that the addition of steel fibers considerably develops column ductility and deformability [24–26]. A good degree of deformations was observed for the steel fiber column specimens of C1-0-SF and C2-0-SF. It was observed that column failure and concrete crushing occurred at or close to mid-height of the tested columns. Lateral stiffness has been achieved for the plain and steel fiber reinforced concrete columns strengthened with CFRP material due to transverse sheets. Tensile cracks were observed in the tension side and the concrete crushing was occurred in the compression zone of the column specimens. It was seen that flexural cracking was delayed by confined bi-directional CFRP material. The failure was observed near the mid-height of the column specimens. At the time of failure, some of the longitudinal sheets were fractured in tension side after crushing of concrete occurred in the compressive side of the columns. Fig. 3(a and b) shows the typical failure mechanism of the tested CFRP confined slender reinforced concrete column specimens.

The experimental test results of columns have been presented in Table 3. It is known that the addition of steel fibers has improved confinement and deformability of tested column specimens. However, steel fibers have no effect on column strength capacity [24–26]. By comparing the control column specimens and CFRP confined columns, the CFRP sheets have increased the strength capacity of plain and steel fiber reinforced concrete columns. Comparative experimental axial load–lateral deflection diagrams of column specimens are illustrated in Fig. 4(a–f). The diagrams indicate that the CFRP wraps have considerable effect on load–deflection behavior of slender plain and steel fiber reinforced concrete columns. The CFRP material has improved ductility and deformability of plain and steel fiber reinforced concrete columns. It is seen in the diagrams that the ultimate load and deflection capacity of plain and steel fiber reinforced concrete columns have increased with increasing CFRP layers (Fig. 4(a–f)). In addition, the ultimate load capacities of reinforced concrete column specimens are significantly influenced by load eccentricity, concrete compressive strength, and slenderness effect. The photographs of all the specimens after experimental tests are shown in Fig. 5.

The complete experimental behavior of plain and steel fiber reinforced concrete columns strengthened with CFRP sheets has been observed in the present work. The obtained experimental findings have given significant knowledge to describe the structural behavior of carbon fiber reinforced polymer confined slender plain and steel fiber reinforced concrete columns.

3. Analytical research

A theoretical method to analyze the reinforced concrete columns under combined axial compression and biaxial bending have been previously presented in Tokgoz [24] and Dundar et al. [27]. The method has been expanded and modified here to determine

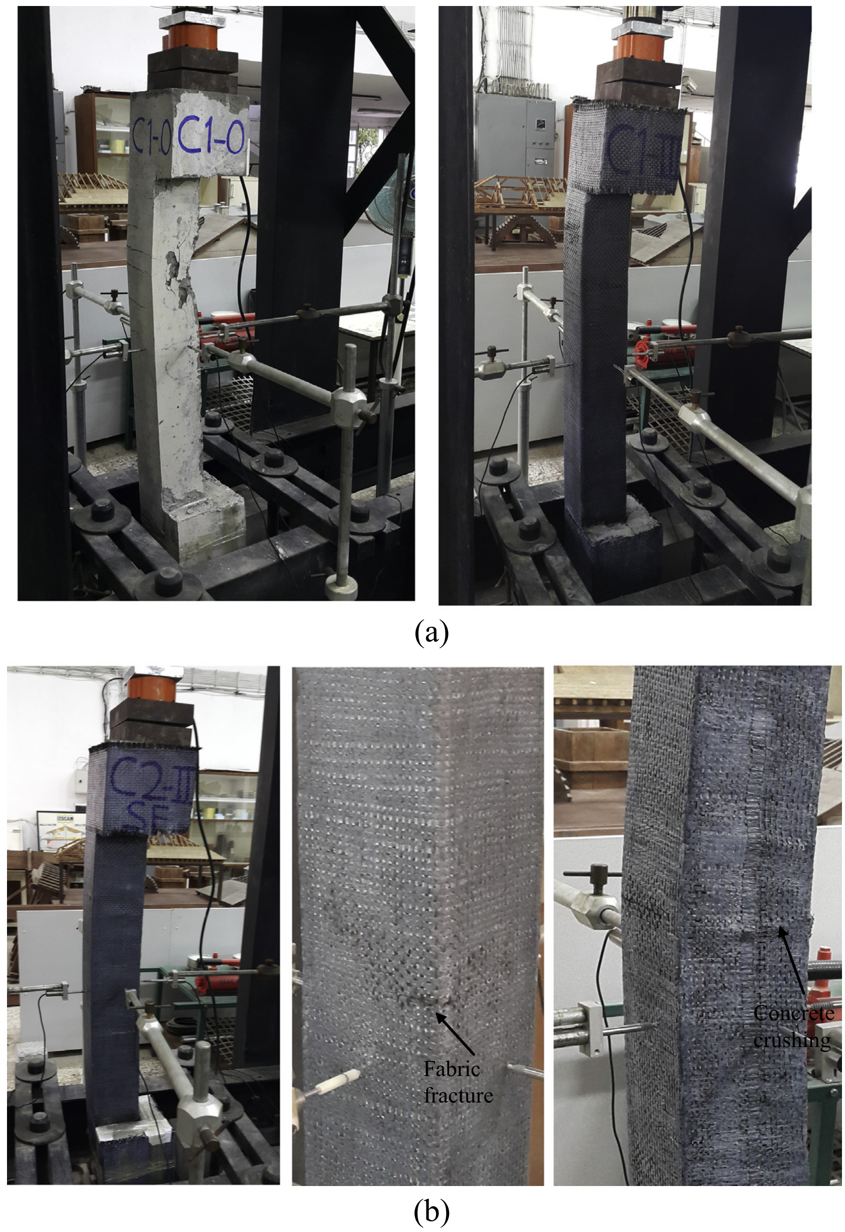

Fig. 3. (a and b) Typical failure mode of specimens.

the behavior of CFRP confined plain and steel fiber slender reinforced concrete columns. In the proposed procedure, the compression zone of the concrete section is divided into small elements for the computation of stress resultants of each element [24,27]. It is considered that CFRP sheets cannot take any compressive forces. On the other hand, CFRP material provides tensile forces in the case of longitudinal implementation. Thus, the CFRP sheets are divided into small elements in tension side to determine the tensile stresses using the material stress–strain law.

The analysis method is based on the following assumptions: (1) plane sections remain plane before and after bending, (2) nonlinear behavior of the materials are considered, (3) confined stress–strain relationship is proposed for concrete, (4) elastic–perfectly plastic stress–strain relationship is assumed for the reinforcing steel material, (4) the stress–strain relationship of the CFRP material is assumed to be linear elastic up to rupture, (5) tensile strength of concrete is neglected, (6) shrinkage and creep effects are excluded and perfect bond exists between steel, concrete and CFRP material, (7) axial and shear deformations are ignored.

3.1. Stress–strain relationship of the materials

3.1.1. Fiber reinforced polymer

The assumed stress–strain relationship of the CFRP material is shown in Fig. 6(a). The stress–strain diagram is expressed as follows:

$$\sigma_f = E_f \varepsilon_f \leqslant f_{fu} \quad \text{when} \quad 0 \leqslant \varepsilon_f \leqslant \varepsilon_{fu} \tag{1}$$

where σ_f and ε_f are the stress and strain of the CFRP sheet, respectively; and f_{fu} and ε_{fu} are the ultimate stress and the strain of the CFRP material, respectively. E_f is the modulus of elasticity of CFRP material and determined as:

$$E_f = \frac{f_{fu}}{\varepsilon_{fu}} \tag{2}$$

Table 3
Test and ultimate strength results of specimens.

Specimen no.		Ultimate strength results		Ratio
	N_{test} (kN)	N_u (kN)	M_{ux} & M_{uy} (kN cm)	
C1-0	203	199.66	935.68	0.984
C1-I	258	278.14	1418.56	1.078
C1-II	350	324.04	1545.15	0.926
C1-III	254	276.57	1607.75	1.089
C1-0-SF	220	205.26	960.35	0.933
C1-I-SF	299	298.95	1604.09	1.000
C1-II-SF	365	351.18	1698.42	0.962
C1-III-SF	273	285.54	1668.53	1.046
C2-0	155	157.87	885.68	1.019
C2-I	255	273.55	1790.12	1.073
C2-II	283	284.72	1660.54	1.006
C2-III	222	243.51	1675.19	1.097
C2-0-SF	162	150.64	846.78	0.930
C2-I-SF	234	249.81	1588.93	1.068
C2-II-SF	267	262.52	1512.96	0.983
C2-III-SF	225	231.19	1574.41	1.028
Mean ratio				1.014

3.1.2. Steel

The stress–strain relationship of steel is modeled as an elastic–plastic material and is given by:

$$\sigma_s = E_s \varepsilon_s \leqslant f_y \tag{3}$$

where σ_s and ε_s are the stress and strain of the steel material, respectively; E_s and f_y are the modulus of elasticity and yield strength of steel, as shown in Fig. 6(b).

3.1.3. Concrete

The complete theoretical stress–strain relationship of CFRP confined concrete was described by Samaan et al. [5] and Punurai et al. [18]. The suggested curve has an approximate bilinear shape and has no descending part (Fig. 6(c)). The empirical equation to represent the stress–strain behavior of CFRP confined concrete is expressed with the following equation (Punurai et al. [18]):

$$\sigma_c = \frac{(E_1 - E_2)\varepsilon_c}{\left[1 + \left(\frac{(E_1 - E_2)\varepsilon_c}{f_o}\right)^n\right]^{1/n}} + E_2\varepsilon_c \tag{4}$$

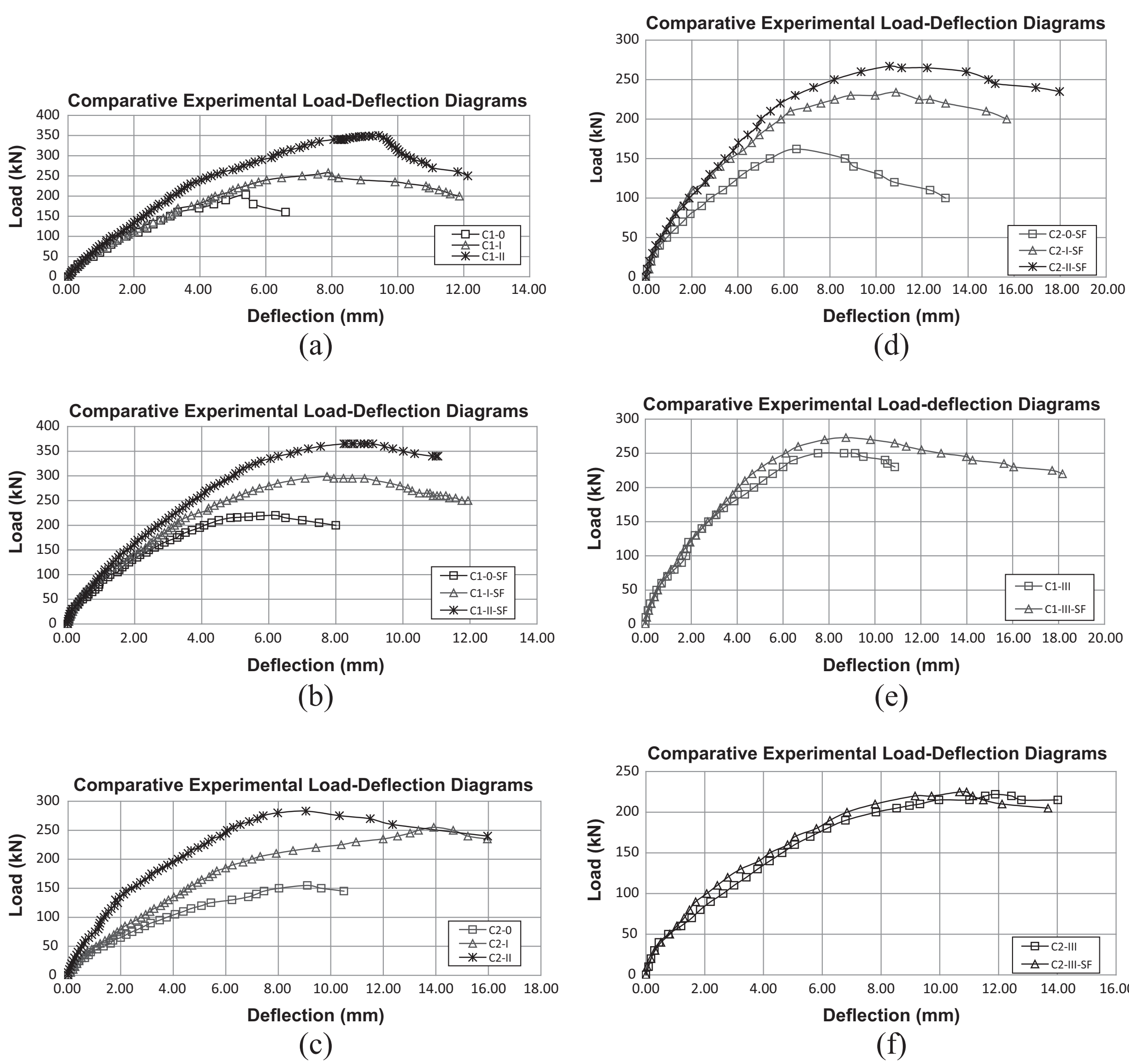

Fig. 4. (a–f) Comparative experimental axial load–lateral deflection diagrams.

Fig. 5. Tested specimens after failure.

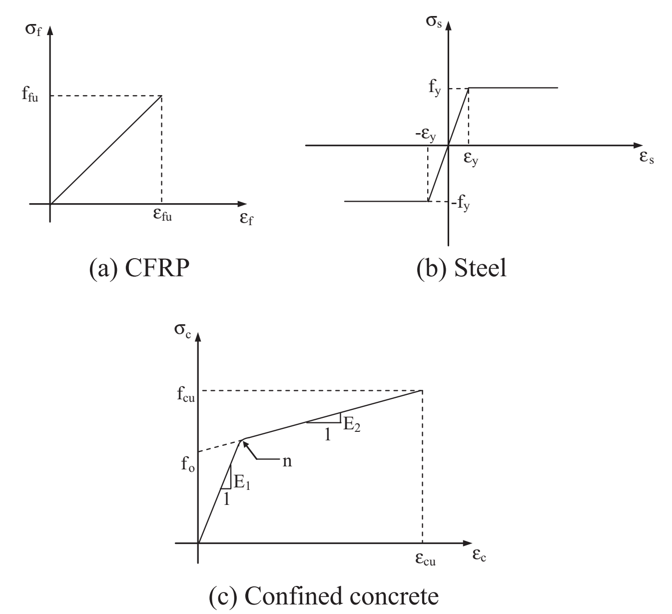

Fig. 6. (a–c) Idealized stress–strain curves of CFRP, steel and confined concrete.

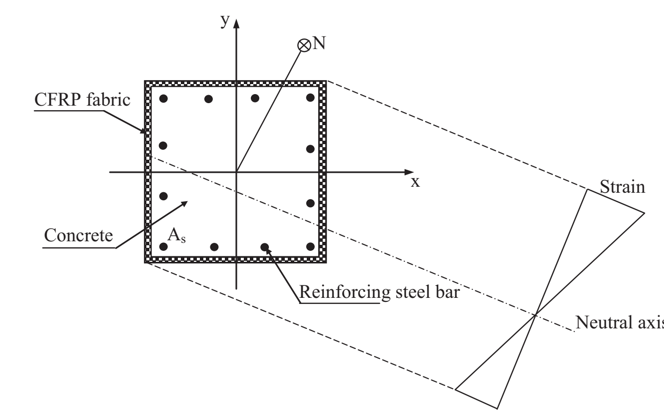

Fig. 7. Cross section and strain diagram of CFRP confined column section.

where σ_c and ε_c are stress and strain of the CFRP confined concrete in general, respectively; E_1 and E_2 are the first and the second slopes, respectively; f_o is the plastic stress at the intercept of the second slope with the stress axis; n is the curve shaped parameter. The shape of the proposed stress–strain diagram is illustrated in Fig. 6(c). In Fig. 6(c), ε_{cu} and f_{cu} are ultimate compressive fiber strain and compressive strength of confined concrete.

The modulus of E_1 is the first slope of the stress–strain curve and can be expressed as follows (ACI 318-08 [23]):

$$E_1 = 4730\sqrt{f_c} \tag{5}$$

E_2 is the second slope of stress–strain curve of CFRP confined concrete and assumed with the following:

$$E_2 = 189.21 f_c^{0.2} + 1.345\frac{E_f t_f}{D} \tag{6}$$

here E_f is the effective modulus of elasticity of dry FRP jacket, t_f is the thickness of dry FRP jacket, and D is the diameter of the concrete core. f_o is the stress at the intersection of the second slope with the stress axis. This parameter can be assumed with the following expression:

$$f_o = 0.85 f_c + 1.9 f_r + 6.89 \tag{7}$$

where f_r is the confining pressure of the FRP jacket. The parameter is written as:

$$f_r = \frac{2 f_f t_f}{D} \tag{8}$$

in which f_f is the hoop stress.

The ultimate stress (f_{cu}) and the corresponding strain (ε_{cu}) of the CFRP confined concrete can be expressed as follows:

$$f_{cu} = f_c + 6.14 f_r^{0.75} \tag{9}$$

$$\varepsilon_{cu} = \frac{f_{cu} - f_o}{E_2} \tag{10}$$

3.2. The equilibrium equations

Biaxially loaded CFRP confined column cross section is presented in Fig. 7. A comprehensive determination of the analysis procedure has been presented in companion papers reported by Tokgoz [24] and Dundar et al. [27].

The fundamental equilibrium equations for the axial load N, and the bending moments M_x and M_y of CFRP confined reinforced concrete columns are described as follows:

$$N = \sum A_c\sigma_c + \sum A_s\sigma_s + \sum A_{fp}\sigma_{fp} \tag{11}$$

$$M_x = \sum A_c\sigma_c y_c + \sum A_s\sigma_s y_s + \sum A_{fp}\sigma_{fp} y_{fp} \tag{12}$$

$$M_y = \sum A_c\sigma_c x_c + \sum A_s\sigma_s x_s + \sum A_{fp}\sigma_{fp} x_{fp} \tag{13}$$

where A_c, A_s and A_{fp} are the elemental area of concrete segment, area of reinforcing steel bar and elemental area of CFRP sheet, respectively; σ_c, σ_s and σ_{fp} are the concrete stress, reinforcing steel stress and CFRP material stress, respectively; (x_c,y_c), (x_s,y_s) and (x_{fp}, y_{fp}) indicate the distance between, respectively, the center of elemental area of concrete, reinforcing steel bar and the center of the elemental area of CFRP element, and the geometric center in x–y plane. The contribution of CFRP element forces is taken into account in the case of wrapping the sheet as the longitudinal implementation to the reinforced concrete column member. In the study, "The Simplified Stability Analysis Method" proposed by Rangan [28] has been used to analyze the slenderness effect of CFRP confined reinforced concrete columns. More details for the analysis procedure of reinforced concrete columns can be found in Tokgoz [24] and Dundar et al. [27].

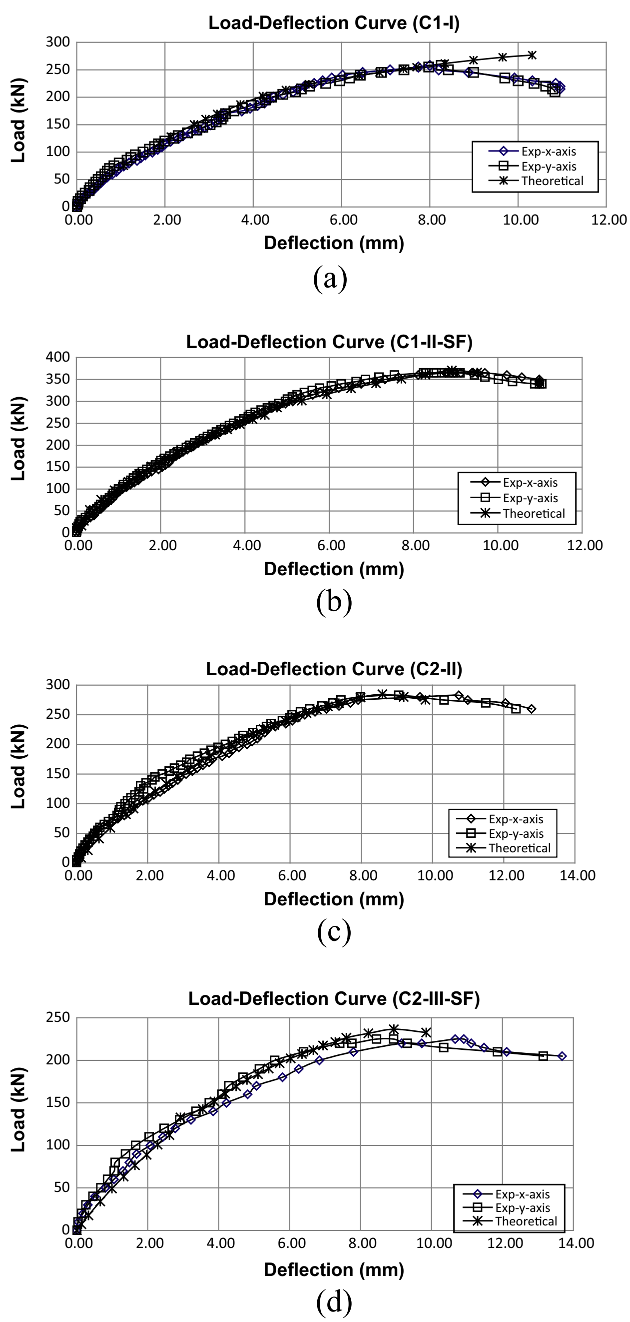

Fig. 8. (a–d) Typical experimental and theoretical axial load–lateral deflection diagrams of specimens.

4. Computer analysis of tested slender CFRP confined concrete columns

The tested columns have been analyzed by using a developed software program based on the proposed analysis method. The experimental properties of the column length, concrete compressive strength, and eccentricity of applied axial load and CFRP material design are presented in Table 2. Wrapping material namely "SikaWrap Hex 300C 0/90" is used for longitudinal and transverse sheets. The CFRP material properties of the thickness is 0.166 mm, the tensile strength is 3900 MPa, and the modulus of the elasticity is 230 GPa defined by the manufacturer.

In this study, the CFRP confined slender reinforced concrete columns were analyzed using the proposed stress–strain curves of the materials of confined concrete, steel and CFRP sheet. Besides this, the control column specimens (C1-0, C2-0, C1-0-SF and C2-0-SF) which had no CFRP sheet were analyzed based on the theory reported in Tokgoz [24]. The experimental loads (N_{test}), the analysis column strength results (N_u), and the comparative results of the column specimens are shown in Table 3. Comparative axial load–lateral deflection diagrams of column specimens are shown in Fig. 8(a–d).

The analysis results indicate that a good degree of accuracy is achieved between the experimental and the analytical results for the CFRP confined slender reinforced concrete columns. The predicted ultimate strength capacities (N_u) compare well with the test results of the slender reinforced concrete columns confined with CFRP sheets subjected to biaxial bending and axial load (Table 3). The average value of the predicted load to test load has been obtained as 1.014. In the analysis, the use of the stress–strain models proposed for concrete, steel and CFRP materials has provided good correlation. It is concluded that both longitudinal and transverse directional sheets have provided significant structural capacity. The analysis research revealed that the CFRP jacketing increases confinement, ductility and strength capacity of slender plain and steel fiber reinforced concrete columns.

5. Summary and conclusions

This paper has presented an experimental research to describe the structural behavior of CFRP confined slender plain and steel fiber reinforced concrete columns subject to combined axial compression and biaxial bending. The main test parameters are concrete compressive strength, steel fiber, load eccentricity, slenderness and carbon fiber polymer sheet. The tested column specimens have been analyzed with a proposed theoretical method considering the nonlinear behavior of the materials. The use of bi-directional (i.e., transverse and longitudinal) CFRP sheets have increased confinement, ductility and the ultimate strength capacity of plain and steel fiber slender reinforced concrete columns. In addition, the increase of sheet layers has increased the confinement and load carrying capacity of column specimens significantly. The results show that concrete compressive strength, load eccentricity and slenderness have considerable effect on CFRP confined plain and steel fiber reinforced concrete column behavior.

The assumed stress–strain diagram of the CFRP confined concrete has given reasonable accuracy in predicting the ultimate strength capacity and load–lateral deflection behavior of CFRP wrapped slender reinforced concrete columns. The comparisons between the test and the analysis results have indicated good accuracy for biaxially loaded plain and steel fiber reinforced concrete columns confined with CFRP sheets. The experimental and analysis results indicate that wrapping both transverse and longitudinal sheets has significantly improved the structural behavior for slender plain and steel fiber reinforced concrete columns under biaxial bending and axial load.

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