Experimental and Numerical Investigations on Behavior of Confined Steel Fiber Reinforced Concrete Columns Subjected to Axial and Eccentric Loading

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***Abstract* —** This paper investigates experimentally and numerically behavior of twelve Normal Concrete (NC) and Steel Fiber Reinforced Concrete (SFRC) columns, with cross section 150 mm×150 mm and 1800 mm height, when subjected to axial and eccentric compressive loads. The main parameters of the current study are the volume fraction of steel fiber (0%, 0.25% and 0.75%) and the eccentricity of the applied compressive loads (0 and 75 mm). Moreover, half of the specimens were partially wrapped with CFRP sheets in order to investigate the effect of confinement on columns axial behavior. Finite element models were conducted using ABAQUS to verify the experimental results and to investigate the effect of using CFRP as full confining technique. The variations of steel fiber percentages coupled with the CFRP partial confinement under eccentric loading, resulted in an increase in the compressive strain.

***Keywords* —** *Column · Strengthening · Fiber-Reinforced Polymers (FRP) · CFRP · Eccentric load*

I. INTRODUCTION

Recently, Fiber Reinforced Polymers (FRP) materials have been widely used in the retrofitting and strengthening of concrete members due to numerous advantages they provide, compared to traditional strengthening materials, such as high strength to weight ratio, corrosion resistance, and electromagnetic neutrality as well as the ease of installation [1-3]. Strengthening of reinforced concrete (RC) columns is one of the most common and effective applications of FRP materials in civil and construction engineering. FRP composites help improving both strength and ductility of retrofitted and strengthened columns [4-5]. Numerous studies have been carried out to investigate the effect of external confining, using FRP composites, on the behavior of reinforced concrete columns, the majority of these studies carried out using small scale specimens made of plain unreinforced normal strength concrete [6-11].

Cui and Sheikh [9] tested 112 concrete cylinders, with variable compressive strength up to 112 MPa, under monotonic compressive loading. Ductile failure and an increase in the ductility factor were observed due to the use of FRP jackets. Moreover, results revealed an increase in the energy absorption capacity as well as ductility with the increase of FRP confining layers, in addition, there was a reduction in the energy absorption with the increase of concrete strength. Vincent and Ozbakkaloglu [12] investigated the effect of concrete strength and confining using FRP on the behavior of high strength and ultra-high strength cylindrical concrete specimens. The results showed that using FRP confinement improves the ductility of the specimens under compression test. However, the thickness of FRP had a negligible effect on the reduction in the strain. Hadi and Li [13] experimentally investigated the effect of external confinement on the behavior of concrete columns when subjected to axial and eccentric loading. It was observed that, column's load capacity was increased by the external confining of concrete. The best confinement was obtained in case of using Carbon Fiber Reinforced Polymers (CFRP). The axial compressive behavior of square and rectangular concrete columns was experimentally studied and reported in [14]. Results showed that specimens can exhibit ductile behavior when sufficient confinement was provided. Moreover, FRP confinement thickness had no significant effect on the rupture strains. Yang et al. [15] studied the mechanical properties of rectangular high strength concrete columns confined with CFRP composites when subjected to eccentric compressive loading. Results revealed that the energy absorption and the ductility of CFRP strengthened columns were improved extensively compared to the reference specimens which showed brittle behavior accompanied with the traditional failure modes. Moreover, increasing the number of CFRP layers provided more enhancement to the overall behavior. Al Abadi et al. [5] investigated the effect of the compressive strength of concrete and confinement length on the behavior of partially confined columns. Results showed that the partial confinement arrangements improved the columns elastic stiffness and the ultimate strength capacity.

Based to the analysis of the available literature, most of studies, which focused on the behavior of confined concrete columns under compressive loading, were limited to small scale specimens made of unreinforced normal and high strength concrete, and there is still a gap regarding the behavior of other concrete types, such as Fiber Reinforced Concrete (FRC), under eccentric loading. The current study aimed at investigating experimentally and numerically the behavior of confined and unconfined normal concrete (NC) and steel fiber reinforced concrete (SFRC) columns, when subjected to axial and eccentric compressive loads. The volume fraction of steel fiber and the eccentricity of the applied compressive loads were the main parameters of the study.

II. EXPERIMENTAL PROGRAM

A. Specimen Details and Test Program

Twelve large scale reinforced concrete columns were prepared and tested. All columns had square cross sections of 150 mm×150 mm, overall height of 1800 mm, and a clear height of 1000 mm. Two enlarged reinforced concrete heads were used at the ends of each column with dimensions of 150 mm×450 mm to prevent any expected stress concentration at the column boundaries. Four high strength steel reinforcement bars (f_y/f_{ult}=36/52) with 12 mm diameter were used as longitudinal reinforcement, while column ties were mild steel smooth bars (24/35 with 8 mm diameter. The spacing between ties were set as 200 mm at the middle third and it was reduced to 50 mm at the ends to avoid localized damage. **Figure 1** shows the details of column specimens.

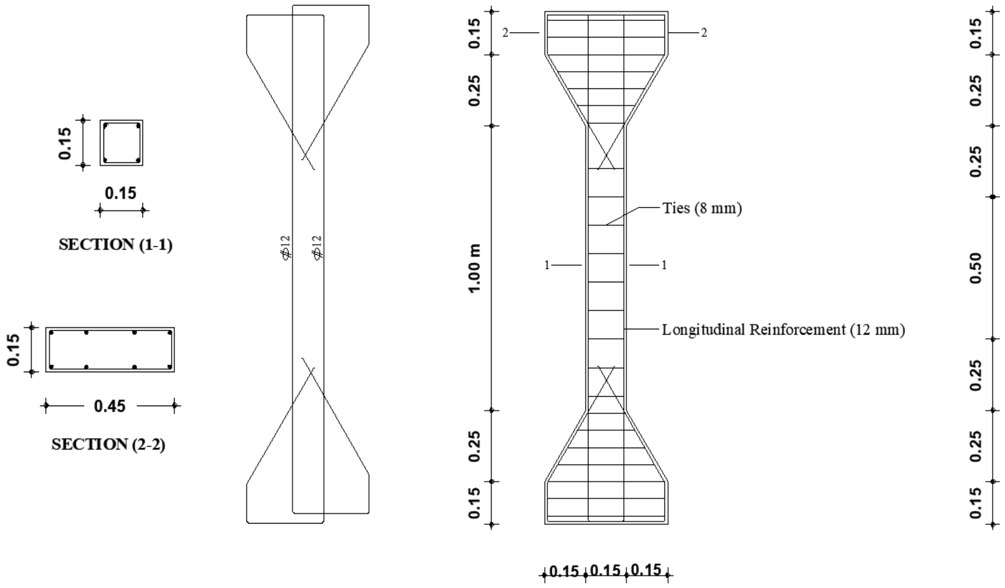


Figure 1. Details of Column Specimens (units in meter)

Table 1. Group Details

Group	Specimen	V_f (%)	CFRP Layers	Eccentricity (mm)
G1	C1	0	0	0
	C2	0	2	
	C3	0.25	0	
	C4	0.25	2	
	C5	0.75	0	
	C6	0.75	2	
G2	C7	0	0	75
	C8	0	2	
	C9	0.25	0	
	C10	0.25	2	
	C11	0.75	0	
	C12	0.75	2	

The test specimens were divided into two groups, each group consisted of six columns. Group details are shown in **Table 1**. The first group (G1) contains six control column specimens which were tested under non-eccentric axial compression load. The second group (G2) contains six columns, which were tested under eccentric axial compression load (75 mm eccentricity from the center of column). Each group has been prepared using different steel fibers volume fraction (0, 0.25%, and 0.75%) and two cases of confining (no CFRP and using 2 layers of CFRP). For the strengthened specimens, column's surface was well cleaned and smoothed using grinder, then the corners were finished as fillet with 15 mm, to avoid local failure of CFRP sheet at column's corners, then a two-component epoxy resin was mixed in a ratio 4:1 and applied to the external surface of the column. Finally, CFRP sheets were wrapped around the column with an overlap of 25% of the circumference as shown in **Figure 1**.

B. Material Properties and Mix Proportion

Harsh desert sand and crushed dolomite, locally produced, were used as fine and coarse aggregates, respectively. Two sizes of the dolomite were used, having maximum sizes of 9.5 and 16 mm. Then, coarse and fine aggregates were combined together to meet ASTM standards. In addition, Ordinary Portland cement and tap drinking water were used in casting. The concrete mix was designed to achieve a target compressive strength of 30 MPa after 28 days. The concrete mix composed of 1320 kg/m^3 of dolomite as coarse aggregate, 660 kg/m^3 of sand as fine aggregate, 300 kg/m^3 of cement, and the water content was 165 L/m^3.

Hooked end steel fibers were used in this study to increase anchorage. The length of the Steel fibers was 50 mm and the diameter was 0.80 mm. The provided steel fibers had a tensile strength of 1000 MPa and elastic modulus of 210,000 MPa. Steel fibers were used with different volume fractions (0%, 0.5%, and 0.75%). For strengthening, Carbon Fiber Reinforced Polymers (CFRP) fabric strengthening system, manufactured by Sika Inc. named Sikawrap Hex-230C/Sikadur-330, was used. The strengthen system consisted of the CFRP sheets and its impregnating resin. The thickness of CFRP sheets was 0.12 mm with a tensile strength of 4100 MPa and modulus of elasticity equal to 231 GPa. The tensile strength and modulus of elasticity of adhesive used in the study were 30 MPa and 3800 MPa, respectively.

C. Test Setup and Instrumentation

Columns were tested using a monotonic axial compression loading applied at column ends using a hydraulic jack and a reaction frame of 400-ton capacity. A schematic of the loading system and the hydraulic jack is illustrated in **Figure 2**. The axial compression force applied measured by a load cell directly connected to the hydraulic jack as shown in **Figure 3**. Moreover, a hinge was provided at the end of the specimens to allow in plane rotation and transfer the generated load by the machine to the surface of column during the test.

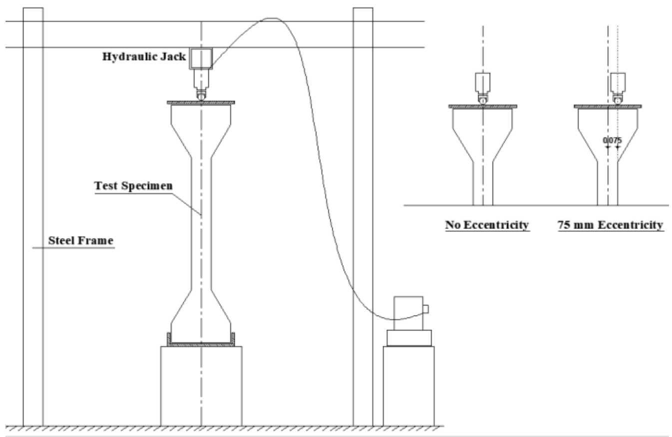


Figure 2. Schematic of the Loading System

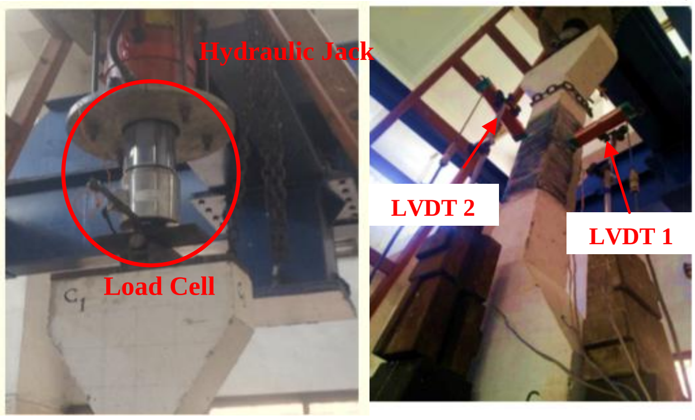


Figure 3. Test Setup

As shown in **Figure 3**, two LVDT were used to measure mid-height lateral displacement of the two perpendicular faces of the specimen. In addition, strain gauges were installed to measure both vertical and lateral strains during loading process. The load was applied gradually with a rate of 10 kN/minute till 80% of the theoretical estimated load, then was reduced to 5 kN/minute till the failure of the specimen.

III. RESULTS AND DISCUSSION

Table 2 shows a summary of the calculated results (failure load, maximum mid-height lateral displacement, and maximum tensile and compressive strain) for strengthened and un-strengthened reinforced concrete column specimens.

Table 2. Column Specimens under Compression Load Results

Group	Specimen	Failure Load (KN)	Lateral Displacement (mm)	Compressive Strain	Tensile Strain
G1	C1	363	0.50	0.0031	---
	C2	403	0.20	0.0024	---
	C3	370	0.45	0.0027	---
	C4	412	0.18	0.0020	---
	C5	384	0.40	0.0023	---
	C6	428	0.13	0.0014	---
G2	C7	205	2.80	0.0036	0.00050
	C8	254	1.50	0.0040	0.00052
	C9	229	2.40	0.0032	0.00070
	C10	286	1.27	0.0038	0.00073
	C11	254	1.80	0.0027	0.00085
	C12	315	0.85	0.0035	0.00091

A. Failure Modes

(a) (b)

Figure 4. Failure Mode of un-Strengthened Columns;

a) No Eccentricity, and b) Eccentric Loading

(a) (b)

Figure 5. Failure Mode of Strengthened Columns;

a) No Eccentricity, and b) Eccentric Loading

Two Modes of failure were observed as shown in Figure 4 and Figure 5. In case of non-eccentric load, the column is under pure compression, then the failure mode was the typical concrete crushing. On the other hand, concrete cover separation in the tension side accompanied by crushing in the compression side was the failure mode observed in case of eccentric load. The main difference, in the failure characteristic between strengthened and un-strengthened specimens is the position of failure. Un-strengthened specimens failed in the middle third, while strengthened ones failed out of the strengthened zone.

B. Load-Displacement Response

As shown in **Table 2,** using steel fibers increase the failure load by a percentage up to 6% and have a considerable effect in case of eccentric loading with an increase by a percentage up to 24%. It was observed that, when the load applied with no eccentricity, the failure load increased by 2% to 6%, when the steel fibers volume fraction varied from 0.25% to 0.75%, respectively (C1, C2 versus C3, C4 and C5, C6). On the other hand, when the load applied with an eccentricity of 75 mm, the failure load increased by 12% to 24%, when the steel fibers volume fraction varied from 0.25% to 0.75%, respectively (C7, C8 versus C9, C10 and C11, C12).

Using two layers of CFRP as partial confinement increase the failure load by 12% in case of axial load, and this percentage is increased to become 24%, when the load applied with 75 mm eccentricity. **Figure 6** shows failure load results of column specimens.

When the load applied with an eccentricity, the failure load decreased by 43%, however, this percentage becomes 36% when using CFRP as partial confinement. It was observed that, when the load applied with an eccentricity of 75 mm in case of un-strengthened columns, the failure load reduced by 43%, 38%, and 33%, when the steel fibers volume fraction varied from 0%,0.25%, and 0.75%, respectively (C1 vs C7, C3 vs C9, and C5 vs C11). On the other hand, when the load applied with an eccentricity of 75 mm in case of strengthened columns, the failure load reduced by 36%, 30%, and 26%, when the steel fibers volume fraction varied from 0%,0.25%, and 0.75%, respectively (C2 vs C8, C4 vs C10, and C6 vs C12).

The displacement at the mid height of the column mainly depends on the mode of failure. For columns in the first group (G1), the failure was typical concrete crushing, therefore the columns failed without undergoing any considerable lateral deformations. On the other hand, for columns in the second group (G2), the eccentric load resulted in a considerable lateral displacement. However, increasing steel fibers volume fraction would bridge micro-cracks and reduce the lateral displacement. In addition, using CFRP as partial confinement significantly decreases lateral displacement. As shown in **Table 2**, increasing steel fibers volume fraction from 0% to 0.25%, and 0.75%, decreased the lateral displacement by 14%, and 35%, respectively (C7 versus C9 and C11). In addition, using two layers of CFRP as partial confinement decreased the lateral displacement by 46%, 47%, and 52%, when the steel fibers volume fraction varied from 0%,0.25%, and 0.75%, respectively (C7 vs C8, C9 vs C10, and C11 vs C12). **Figure 7** shows lateral displacement results of column specimens.

According to the values of the load (monitored using load cell) and the corresponding displacement (monitored using LVDT), Load- Displacement curves were plotted, **Figure 8.** It can be obviously concluded that, increasing the failure load, by using CFRP or increasing steel fibers volume fraction, was accompanied by a reduction in the lateral displacement.

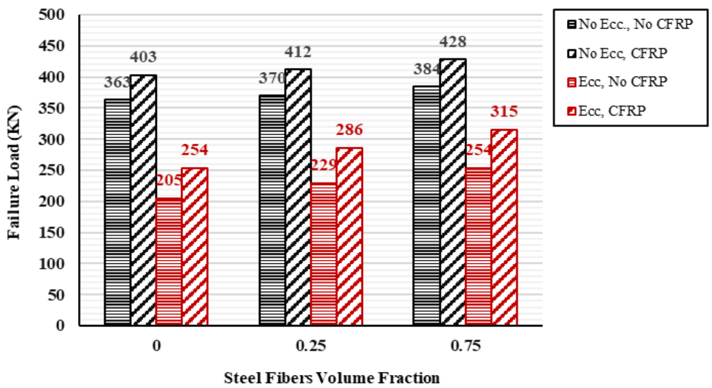


Figure 6. Failure Loads

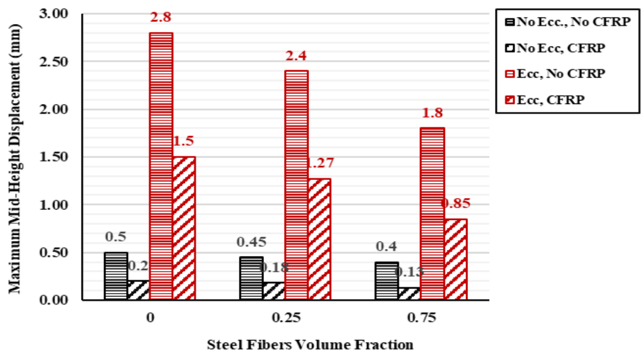
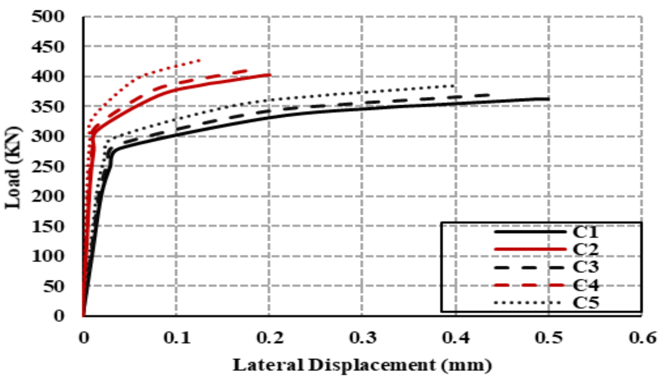
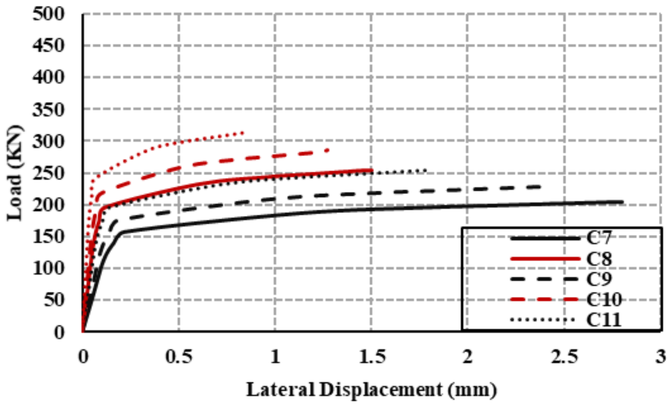


Figure 7. Maximum Mid-Height Lateral Displacement



a) No Eccentricity (G1)



b) Eccentric Loading (G2)

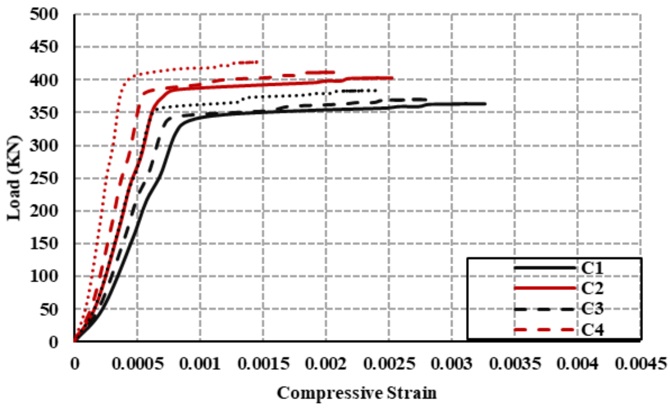
Figure 8. Load-Displacement Relationship under Compression Load;

a) No Eccentricity (G1), and b) Eccentric loading (G2)

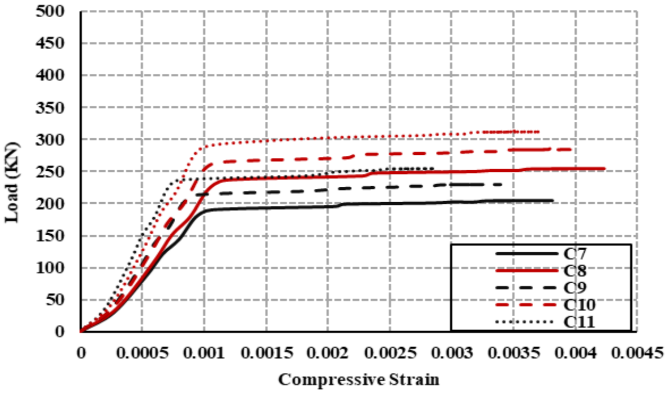
C. Strain Analysis

Increasing steel fibers volume fraction up to 0.75% reduces compressive strain by 25%. Moreover, using CFRP as partial confinement decreases compressive strain by 39% at 0.75% steel fibers volume fraction. **Figure 9** shows the experimental load versus compressive strain relationship. For group G1 specimens **(Figure 9a),** using two layers of CFRP as partial confinement decreased the compressive strain by 22%, 26%, and 39%, when the steel fibers volume fraction varied from 0%,0.25%, and 0.75%, respectively (C1 vs C2, C3 vs C4, and C5 vs C6). In addition, the effect of increasing steel fibers ratio can be observed by comparing specimens C1, C3, and C5 in case of un-strengthened columns, and C2, C4, and C6 for specimens confined with CFRP sheets. It was observed that, increasing the steel fibers ratio from 0% to 0.25%, reduced the strain at failure load by 13%, this ratio was found to be 25% when the steel fibers ratio increased from 0% to 0.75%. For strengthened columns, the reduction in the compressive strain at failure load was 16% and 41% when the steel fibers ratio increased from 0% to 0.25% and from 0% to 0.75%, respectively.

In the case of specimens subjected to eccentric axial loading **(Figure 9b),** failure modes show a compressive strain at the side of the load and a tensile strain at the other side, in addition, the compressive strain is higher compared with no eccentricity cases. It was observed that, when the load applied with an eccentricity of 75 mm, the compressive strain increased by 11% and 25%, in case of unconfined specimens (C7 vs C9 and C11), and by 5% and 12%, in case of confined specimens (C8 vs C10 and C12), when the steel fibers volume fraction varied from 0% to 0.25%, and 0.75%, respectively.



a) No Eccentricity (G1)



b) Eccentric Loading (G2)

Figure 9. Load-Strain Curves under Compression Load;

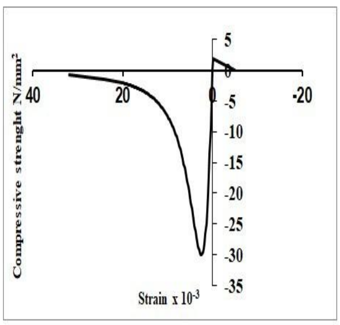
a) *No Eccentricity (G1), and b) Eccentric loading (G2)*

IV. NUMERICAL SIMULATION

Nonlinear three-dimensional finite element model was developed using the finite element (FE) program ABAQUS CAE 6.14 [16]. This simulation process aims to numerically investigate the response of the reinforced concrete column specimens, which were tested experimentally as mentioned in the Experimental Work section. All the constitutive materials were simulated using the appropriate elements provided in ABAQUS library. Concrete damage plasticity (CDP) was selected to simulate the inelastic behavior of concrete material. The CDP model parameters were defined using the experimental results (compressive and splitting tensile tests). Reinforcing steel was assumed to be elastoplastic material. The material properties input values were identical to experimental work. **Figure 10** shows the uniaxial stress strain curves for concrete and reinforcing steel used in the FE model.

An eight-node linear brick, reduced integration, hourglass control element (C3D8R), was used for modeling concrete, while a two-node linear 3-D truss (T3D2) element was used for both steel bars and stirrups. The CFRP sheets were modeled using an 8 nodes quadrilateral in plane general purpose continuum shell, reduced integration (SC8R) as shown in **Figure 11.**

The interface between reinforcement steel and the concrete was simulated using the embedded constraint. The truss elements of steel reinforcement lied embedded into the host concrete elements. In addition, fixed boundary conditions were applied at the base of the FE models. According to sensitivity study, suitable FE mesh with a maximum size of 20 mm was selected. The validity of the FE models was carefully verified against the experimental results and showed a good agreement.



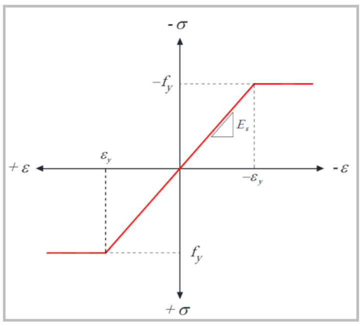


Figure 10. Uniaxial Stress-Strain Curves used in FEM;

a) Concrete; and b) Steel Reinforcement

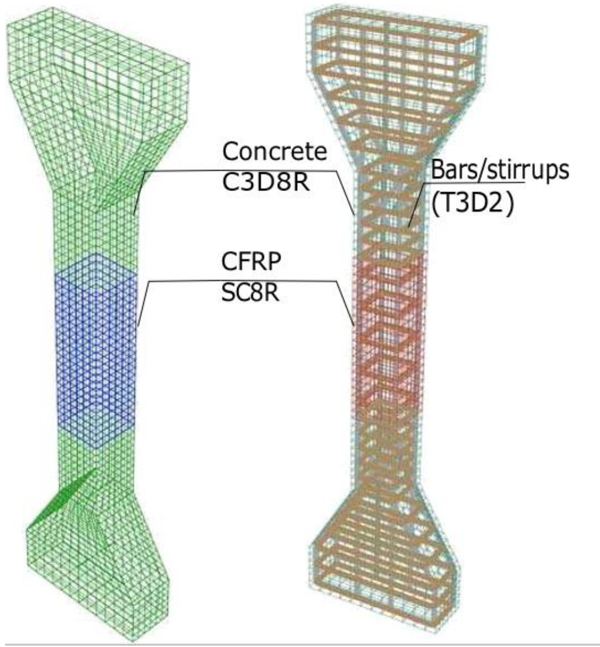


Figure 11. 3D Finite Element Model

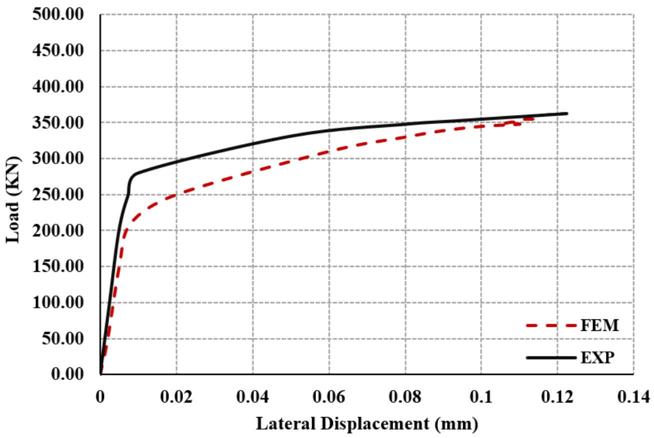
A. Numerical Results and Validation

Relationship curves for Load-Mid-Height Lateral Displacement and Load- Strain resulted from the FE analysis were compared with the experimental work results and showed a similar behavior, as shown in **Figure 12**. For the purpose of clarification, the peak loads obtained from both experimental tests and FE modeling are introduced in **Table 3**, the results show good agreement between both experimental works and numerical models with maximum difference does not exceeds 10%.

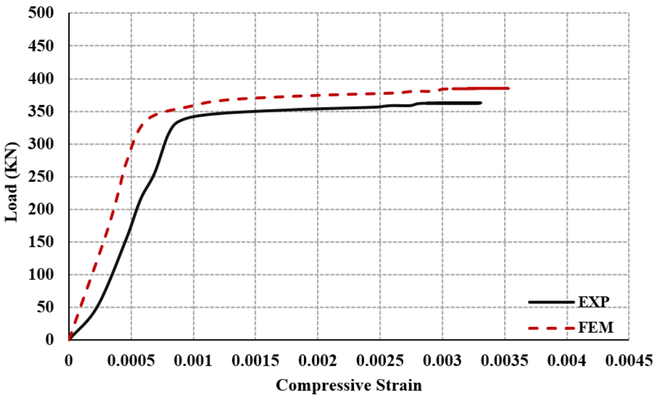
The plastic strain (PEEQ) results obtained from the numerical simulation **(Figures 13 and 14)** showed clearly the two modes of failure, that were observed during the experimental work.

Table 3: Comparison Study between FEA and Experimental Results

Specimen	Peak Load (KN)			Maximum Displacement (mm)		
	EXP	FEM	Diff. %	EXP	FEM	Diff. %
C1	363	384	6	0.50	0.54	7
C2	403	435	8	0.20	0.21	3
C3	370	381	3	0.45	0.46	3
C4	412	428	4	0.18	0.19	6
C5	384	418	9	0.40	0.41	2
C6	428	457	7	0.13	0.14	8
C7	205	211	3	2.80	2.94	5
C8	254	269	6	1.50	1.59	6
C9	229	245	7	2.40	2.47	3
C10	286	294	3	1.27	1.32	4
C11	254	261	3	1.80	1.89	5
C12	315	321	2	0.85	0.88	4



a) Validation of Load-Displacement Curve for C1



b) Validation of Load-Strain Curve for C1

Figure 12. Validation of C1 FE Model;
a) Load-Displacement Curve, and b) Load-Compressive Strain Curve

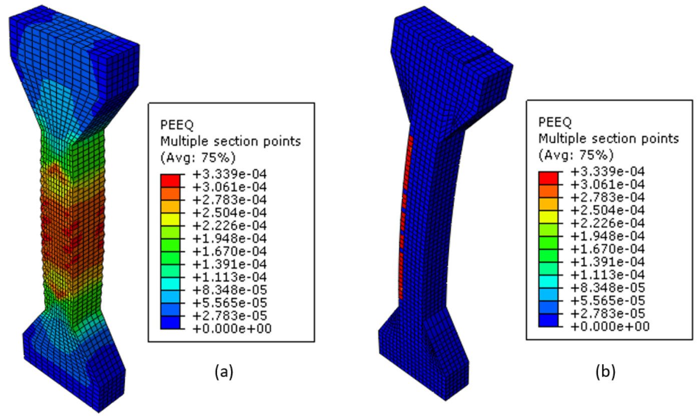


Figure 13. PEEQ results of un-strengthened Columns;
a) No Eccentricity, and b) Eccentric Loading

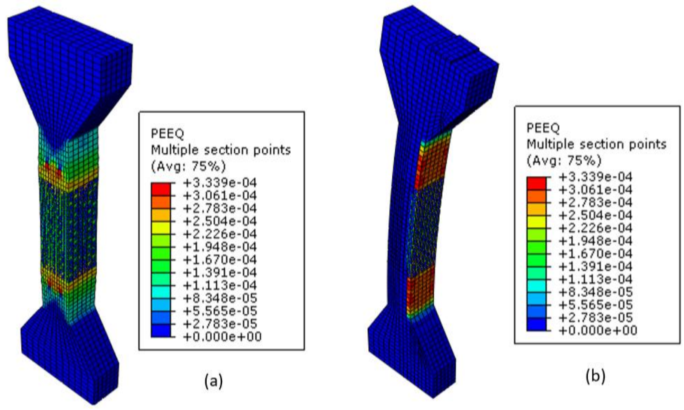


Figure 14. PEEQ results of strengthened Columns;
a) No Eccentricity, and b) Eccentric Loading

B. Parametric Study

The finite element program was extended further to study the effect of full confining, using two layers of CFRP, in the cases of eccentric and non-eccentric loads, when the steel fibers volume fraction varied from 0%, 0.25%, and 0.75%.

The results are presented in Table 4. It can be concluded that, steel fibers have similar effects on the failure load, lateral displacement, and compressive strain as mentioned before. In addition, using two layers of CFRP as full confinement have superior effects, compared to partial confining, with an increase in the failure load by 32% and 45%, instead of 12% and 24%, when the eccentricity varied from 0 to 75 mm, respectively, as shown in Figure 15.

As mentioned before, partially confined specimens failed out of the strengthened zone, therefore the maximum displacement and the maximum compressive strain moves out of strengthened zone. Based on the validated model, using CFRP as full confinement resulted in a uniform stress distribution among the column height, therefore, the mid-height displacement increased by about 75%, in cases of un-eccentric loading (C13 vs C2, C14 vs C4, C15 vs C6), and about 15% for the cases of eccentric loading (C16 vs C8, C17 vs C10, and C18 vs C12).

Table 4: Fully Confined Column Specimens FE Models Results

	V_f	Ecc.	Failure Load (KN)	Lateral Displacement (mm)	Compressive Strain	Tensile Strain
C13	0	0	479	0.35	0.0027	---
C14	0.25	0	488	0.31	0.0022	---
C15	0.75	0	507	0.22	0.0016	---
C16	0	75	298	1.72	0.0048	0.00055
C17	0.25	75	332	1.45	0.0046	0.00079
C18	0.75	75	368	0.98	0.0043	0.00100

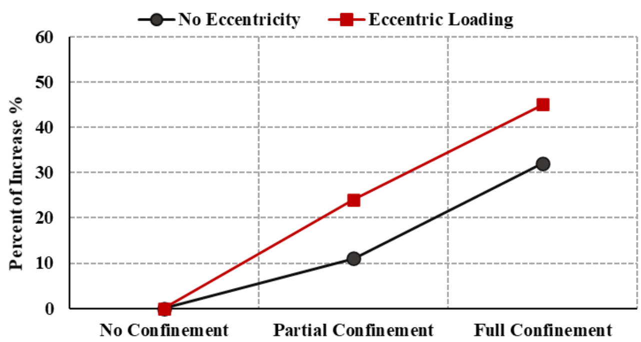


Figure 15. Effect of CFRP on the Peak Load

CONCLUSION

In the present paper, experimental and numerical study were conducted to investigate the behavior of RC columns with square cross sections under non-eccentric and eccentric compression force (75 mm eccentricity). Cases of ordinary and fibrous concrete columns, unconfined or confined using CFRP, in the presence of longitudinal and transverse steel reinforcements were examined. The paper highlighted the influence of varying steel fibers volume fraction (0%, 0.25%, and 0.75%), and the effect of partial and full confining using 2 layers of CFRP. The results can be summarized as follow:

1. Using steel fibers increase the failure load by a percentage up to 6% and have a considerable effect in case of eccentric loading with an increase by a percentage up to 24%. In addition, using two layers of CFRP as partial confinement increase the failure load by 12% in case of axial load, and this percentage is increased to become 24%, when the load applied with 75 mm eccentricity.
2. When the load applied with an eccentricity, the failure load decreased by 43%, however, this percentage becomes 36% when using CFRP as partial confinement.
3. The displacement at the mid height of the column mainly depends on the mode of failure. For uneccentric loads, the failure was typical concrete crushing, therefore the columns failed without undergoing any considerable lateral deformations. On the other hand, for eccentric loading, a considerable lateral displacement has occurred. However, increasing steel fibers volume fraction would bridge micro-cracks and reduce the lateral displacement. In addition, using CFRP as partial confinement significantly decreases lateral displacement.
4. Increasing steel fibers volume fraction up to 0.75% reduces compressive strain by 25%. Moreover, using CFRP as partial confinement decreases compressive strain by 39% at 0.75% steel fibers volume fraction.
5. In the case of specimens subjected to eccentric axial loading, failure modes show a compressive strain at the side of the load and a tensile strain at the other side and this compressive strain is higher than no eccentricity cases.
6. Based on the numerical model results, in case of full confining using CFRP, steel fibers still have similar effects on the failure load, lateral displacement, and compressive strain as mentioned before. In addition, using two layers of CFRP as full confinement have superior effects, compared to partial confining, with an increase in the failure load by 32% and 45%, instead of 12% and 24%, when the eccentricity varied from 0 to 75 mm, respectively.

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