

Nonlinear Finite Elements Analysis of Reinforced Concrete Columns Strengthened With Carbon Fiber Reinforced Polymer (CFRP)

Mazen Dewan Abdulla

Engineering College, University of Basrah

Mazend081@gmail.com

Zahraa Abbas Khaduer

Engineering College, University of Basrah

zahraabas809@gmail.com

Abstract:

This paper presents the results of a study to have better understanding of structural behavior of the reinforced concrete (RC) column wrapped by carbon fiber reinforced polymer (CFRP) sheets.

In this study, 3D F.E model has been presented using ANSYS computer program (Release 16.0) to analyze reinforced concrete columns strengthened with CFRP composites, to evaluate the gain in performance (strength and ductility) due to strengthening, and to study the effect of the most important parameters such as: compressive strength of concrete, modulus of elasticity of CFRP and corner radius of square columns.

Three dimensional eight-node brick element (SOLID65) was used to represent the concrete, three dimensional spar element (LINK180) represented the steel and using a three dimensional shell element (SHELL41) to represent the CFRP composites.

The present study has a comparison between the analytical results from the ANSYS finite element analysis with experimental data. The results of the study show that, external bonded CFRP sheets are very effective in enhancing the axial strength and ductility of the concrete columns. Inspection of the results shows that, there is good agreement between the ANSYS and the experimental test results.

Keywords: Carbon Fiber Reinforced Polymer; Columns; Confined concrete; Non-linear finite element analysis; Ductility.

الخلاصة:

تقدم هذه الورقة نتائج دراسة لفهم أفضل للسلوك الهيكلي لعمود من الخرسانة المسلحة (RC) ملفوف بالبوليمر المسلح بألياف الكربون (CFRP).

في هذه الدراسة تم إنشاء نماذج عناصر محددة ثلاثية الأبعاد باستخدام برنامج ANSYS (الإصدار 16) لتحليل الأعمدة الكونكريتية المقواة بالبوليمر المسلح بألياف الكربون وكذلك لتقييم الأداء المكتسب (المقاومة والمطيلية) المتأتي من هذه التقوية وأيضاً لدراسة تأثير العوامل الأكثر أهمية مثل: مقاومة انضغاط الكونكريت، معامل مرونة CFRP ونصف قطر زوايا مقطع العمود المربع.

عنصر طابوقي ثلاثي الأبعاد ثماني العقد (SOLID65) استخدم لتمثيل الكونكريت و عنصر نحيف ثلاثي الأبعاد (LINK180) لتمثيل حديد التسليح و استخدم عنصر قشري ثلاثي الأبعاد (SHELL41) لتمثيل البوليمر المسلح بألياف الكربون (CFRP).

في الدراسة الحالية تمت المقارنة بين النتائج التحليلية من برنامج ANSYS العناصر المحددة مع البيانات العملية. وأظهرت نتائج الدراسة أن شرائح CFRP الخارجية فعالة جداً في تحسين المقاومة المحورية والمطيلية (متانة) للأعمدة الخرسانية. ويظهر فحص النتائج أن هناك اتفاقاً جيداً بين ANSYS و نتائج الاختبار العملي **الكلمات المفتاحية:** البوليمر المسلح بألياف الكربون، الأعمدة، الخرسانة المحصورة، التحليل اللاخطي بالعناصر المحددة، المطيلية.

1 Introduction

An increasing number of reinforced concrete structures have reached the end of their service life, either due to deterioration of the concrete and reinforcements caused by environmental factors, or due to an increase in applied loads. These deteriorated structures may be structurally deficient or functionally obsolete, and most are now in serious need of extensive rehabilitation. Carbon fiber reinforced plastics sheets or

plates are well suited to this application because of their high strength-to-weight ratio, good fatigue properties, and excellent resistance to corrosion (Spoelstra *et.al.*, 1999). Their application in civil engineering structures has been growing rapidly in recent years, and is becoming an effective and promising solution for strengthening deteriorated concrete members.

Because CFRPs are quickly and easily applied, their use minimizes labor costs and can lead to significant savings in the overall costs of a project.(Mirmiran *et.al.*, 2000)

During the last decade, the use of FRP has been successfully promoted for external confinement of reinforced concrete (RC) columns all over the world. Several studies on the performance of FRP wrapped columns have been conducted, using both experimental and analytical approaches (Chaallal *et.al.*, 2003; Pan *et.al.*, 2007). Such strengthening technique has proved to be very effective in enhancing their ductility and axial load capacity. However, most of the available studies on the behavior of FRP confined concrete columns have concentrated on circular shaped columns with normal concrete strength. The data available for columns of square or rectangular cross sections have increased over recent years but are still limited (Rochete and Labossiere , 2000 ; Al-Salloum , 2007). Also the validation of these results and their applicability to large scale RC columns is of great practical interest. This field remains in its infancy stages and more research investigation is needed on this subject to study the effect of slenderness and that of concrete strength.

2-Mechanism Of Concrete Column Strengthening By Confinement

When FRP jackets or any confining device (steel plates, transverse reinforcing steel) are applied to the concrete column, no initial stresses are introduced in the confining device at low levels of stresses in the concrete; therefore the concrete is unconfined. But at the high levels of stresses approaching to the uniaxial concrete strength, the transverse strains become very high because of lateral expansion of concrete and progressive internal cracking; therefore, the concrete bears out against the confining device, and the last then applies a confining reaction to the concrete making it in triaxial compressive stress state and according to the behavior of the concrete in triaxial compressive stress state, the strength and the ductility of concrete are greatly increased. This type of confinement is passive and there are cases where an initial active confining pressure is present, as is the case when an expansive grout is injected between the column and an external jacket. The confinement in this case is generally quite small in comparison to the passive pressure generated by concrete dilation (Chaallal *et.al.*, 2003).

Passive confining pressures may be constant or variable through an axial load history. Constant confining pressure is generated by an elastic plastic confining material after yielding, as the confining provided by conventional mild transverse reinforcing steel. (Pessiki, Stephen, *et.al.*, 2001)

Tests have demonstrated that the confinement provided in a circular section of a concrete column is much effective than that for square and rectangular section, the reason for this difference in effectiveness is illustrated in Figure (1) which demonstrates that a circular section because of its shape will make the confinement device in hoop tension and make it provide a continuous confining pressure around the circumference resulting in complete confinement. On the other hand, the square or rectangular section makes the confinement device apply confining reaction only near the corners and the central region of the section and leaves the sides without confinement which leads to provide partial confinement for the column.

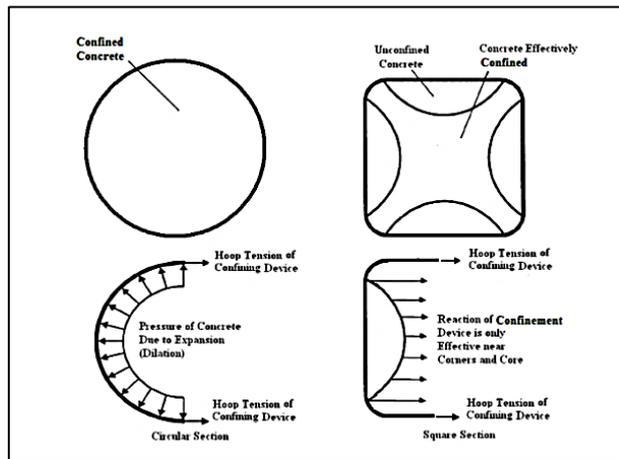
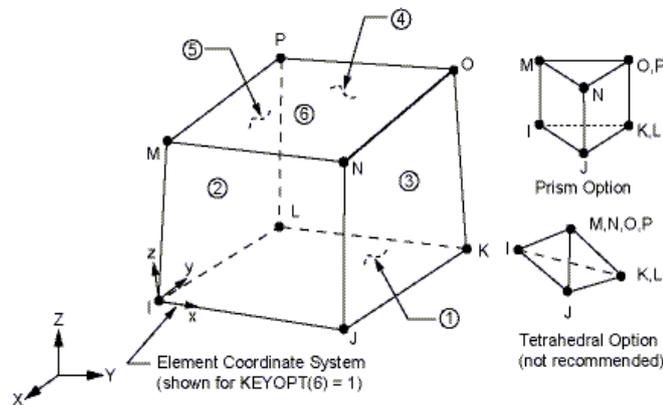


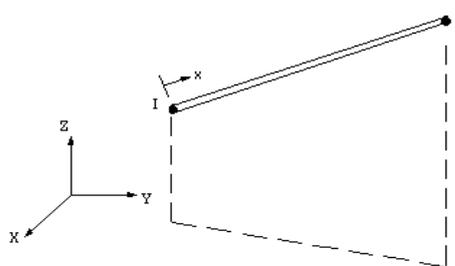
Figure1. The influence of confinement on circular and square sections.(Chaallal et.al., 2003)

2 Finite Element Representation of Strengthened RC Columns

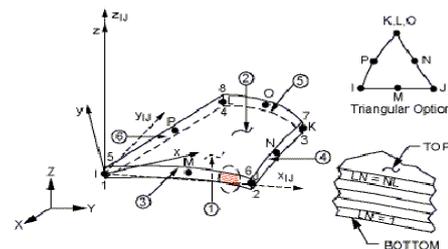
Although traditional empirical methods remain adequate for analysis of reinforced concrete members, the wide dissemination of computers and the development of the finite element method have provided means for analysis of much more complex systems in a much more realistic way, A nonlinear finite element analysis has been carried out for the analysis of reinforced concrete columns strengthen with CFRP composite. finite element program ANSYS (Version 16.0). Solid 65, Solid 185 , Link 180 and Shell 41 , elements are used to represent concrete, steel plates, main steel and stirrups reinforcing bars and carbon fiber (CFRP) composites respectively. The geometry, node locations, and the coordinate system for ANSYS elements are shown in Figure (2)



a. Brick Element SOLID 65.



b- link 180 3D Spar



c. Shell 41 Geometry.

Figure 2. Geometry of ANSYS elements, ANSYS (2016).

3.1 Nonlinear Solution Procedure in Ansys Computer Program

There are several numerical methods to solve nonlinear equations regardless of the source of nonlinearity; one of the most famous methods is Newton-Raphson method.

ANSYS program adopts Newton-Raphson method in solving nonlinear problems. In this method, equilibrium equation can be written as:

$$[K_i^T]\{\Delta u_i\} = \{F^a\} - \{F_i^{nr}\}$$

where:

$[K_i^T]$ = Tangent stiffness matrix

i=subscript representing the current equilibrium

$\{F_i^{nr}\}$ =vector of restoring loads corresponding to the element internal loads.

In this method, the load is subdivided into a series of load increments. The load increments can be applied over several load steps. Before each solution, the Newton-Raphson evaluates the out of balance load vector which is the difference between the restoring forces (the load corresponding to the element stresses) and the applied loads. The program then performs a linear solution, using the out of balance loads and the updated stiffness matrix, and checks for convergence. If a specified convergence criterion is not satisfied, the out of balance load vector is reevaluated, the stiffness matrix is updated, and a new solution is obtained. This iterative procedure continues.

A number of convergence enhancement and recovery features, such as line search, automatic load stepping, and bisection, can be activated to help the problem to converge. If the convergence cannot be achieved, then the program attempts to solve with a smaller load increment.

In some nonlinear static analyses, if Newton Raphson method is used alone, the tangent stiffness matrix may become singular (or non-unique), causing severe divergence difficulties. Such occurrences include nonlinear buckling analyses in which the structure either collapses completely or "snaps through" to another stable configuration. For such situations, an alternative iteration scheme must be activated, the arc length method, to help avoid bifurcation points and track unloading.

The arc-length method causes the Newton-Raphson equilibrium iterations to converge along an arc, thereby often preventing divergence, even when the slope of the load vs. deflection curve becomes zero or negative. This iteration method is represented schematically in Figure (3)

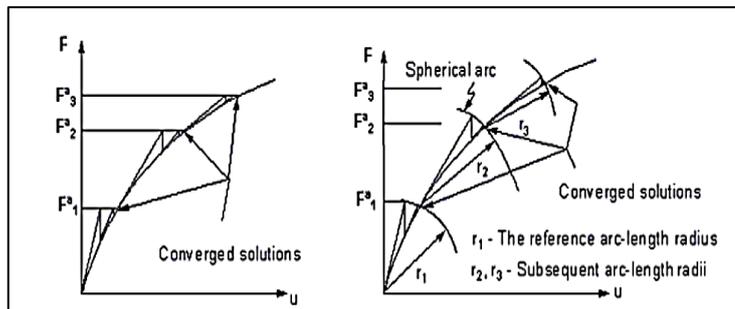


Figure 3. Newton-Raphson method vs. arc-length method

3.2 Material Characteristics:

Finite element models for CFRP confined columns are presented. First the material characteristics are identified, then material properties which are required to insert in software are defined. In this study, the ANSYS is used for modeling of concrete column, reinforcement and CFRP sheet. The nonlinear analysis is developed

by means of ANSYS/STANDARD to simulate the nonlinear behavior of the confined column. After whole model geometry definition, the material properties should be introduced. First, elastic behavior of material is set. Hence, the elastic parameters such as: Young's modulus of concrete, E_c and Poisson's ratio, ν , are inputted. From experimental results E_c is calculated as $E_c = 4700\sqrt{f'_c}$ where f'_c is given in MPa. The popular stress-strain relationship is used to make the uniaxial compressive simulation of the concrete column which is given by the following relationships (Desayi, Prakash, and Krishnan 1964) .

$$f'_c = \frac{\varepsilon E_c}{1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^2} \quad \dots\dots\dots (1)$$

$$\varepsilon_0 = \frac{2f'_c}{E_c} \quad \dots\dots\dots (2)$$

$$E_c = \frac{f'_c}{\varepsilon} \quad \dots\dots\dots (3)$$

Where:

f'_c = stress at any strain ε

ε = strain at stress f'_c

f'_c = ultimate compressive strength

ε_0 = strain at the ultimate compressive strength f'_c

Poisson's ratio of concrete is assumed to be $\nu_c=0.2$. Also an elastic, perfectly plastic behavior is considered for the steel bars as recommended in several previous researches. The elastic modulus, E_s and yield stress , f_y , as measured in experimental tests. A Poisson's ratio of 0.3 is used for the steel reinforcement. The perfect bond between steel bars and concrete is considered. Indeed, as the CFRP behavior is orthotropic, the CFRP material is inputted as a linear elastic orthotropic material in the model. Indeed, it is necessary to introduce properties of the CFRP for each direction separately.

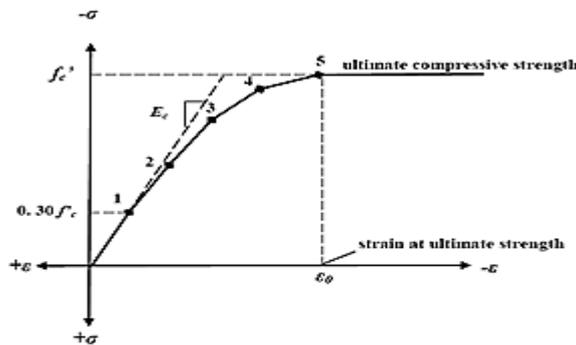


Figure 4. Stress-Strain relationship for concrete under uniaxial compression.

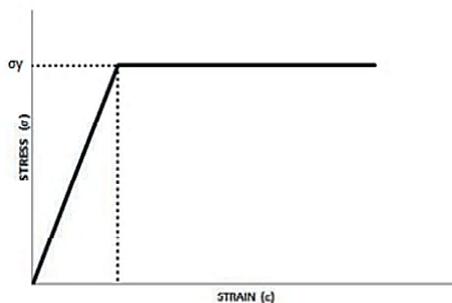


Figure 5. Stress-Strain relationship for steel as used in ANSYS.

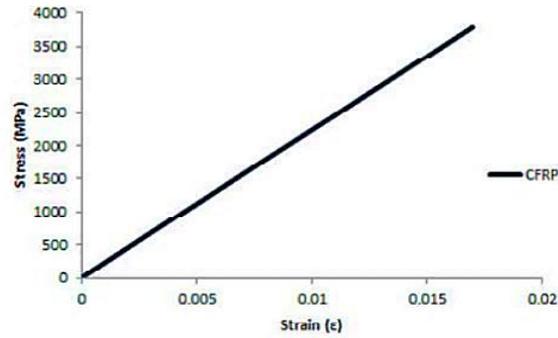


Figure 6. CFRP stress-strain relationship.

4 Methodology of the Study

In the present study, the structural behavior of reinforced concrete columns strengthened with carbon fiber reinforced polymers is simulated depends on available experimental works. Thirty seven column specimens were analyzed by using FEM and divided into four series .In each group of these columns verification study is done to check the validity of the theoretical results with experimental tests, then parametric study was done to investigate the effect of the most important parameter on behavior of RC columns strengthen with CFRP composites.

4.1 Series one: verification of short, square, plain Concrete Columns Strengthened with CFRP Wraps:

The column specimens analyzed by the FEM were chosen from the test conducted by (Rochette and Labossiere , 2000). A series of six columns specimens were chosen from this experimental test to be analyzed by FEM. This series only with square plain concrete columns to determine the amount of fibers confinement without contribution of lateral steel in confinement. Cross section dimension was 152×152 and 500 mm in height. Three parameters are established which include: different corner radius (5 ,25 and 38) , stiffness of the confinement (number of fiber layers) and type of confinement (CFRP and AFRP fiber) as explained in Table (1).

Table 1. Details of Specimens (Series 1)

<i>columns</i>	f'_c MPa	<i>B</i> mm	<i>R</i> mm	<i>R/B</i>	<i>H</i> mm	t_f CFRP	t_f AFRP
K1	35.8	152	0	0	500	--	--
K2	42	152	25	0.164	500	0.9	--
K3	35.8	152	38	0.25	500	1.5	--
K4	43	152	5	0.032	500	--	1.26
K5	43	152	25	0.164	500	--	3.78
K6	43	152	38	0.25	500	--	2.52

Where : *B* is the side length for square columns; *R* is the corner radius of the square cross section; *H* is the height of the columns; f'_c is the compressive strength for concrete ; t_f CFRP is the thickness of CFRP sheet; t_f AFRP is the thickness of Aramid fibers.

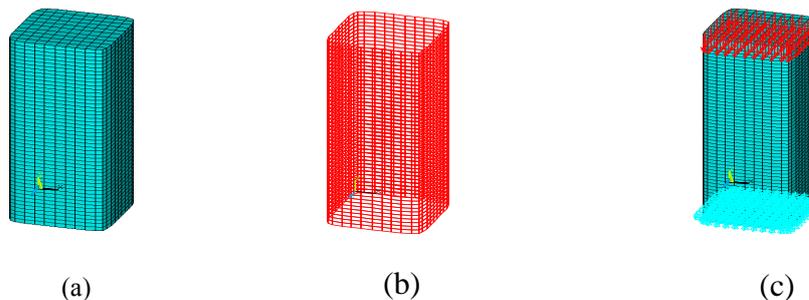


Figure 7. (a) Finite element model of column (concrete elements) (b) Mesh of CFRP (c) boundary condition and applied

4.1.1 Results of The Analysis:

The axial stress-axial strain curves at middle point in the height of columns K1, K2 ,...K6, obtained from the numerical analysis along with the experimental curves reported by [Rochette&Labossiere2000]are presented and compared in Figure (8). These figures show good agreement between the experimental and finite element axial stress- axial strain results. Table (2) shows that the computed ultimate load from the finite element analysis is slightly less than the actual experimental ultimate load of concrete columns confined with CFRP jackets. Figures (9) show results of axial strain using ANSYS program for (K1, K2 ,K3,K4 ,K5,and K6) columns. It can be seen that the ratio of the numerical to experimental axial strength and axial strain ranges between(0.92-0.98) and (0.95-1.07) respectively.

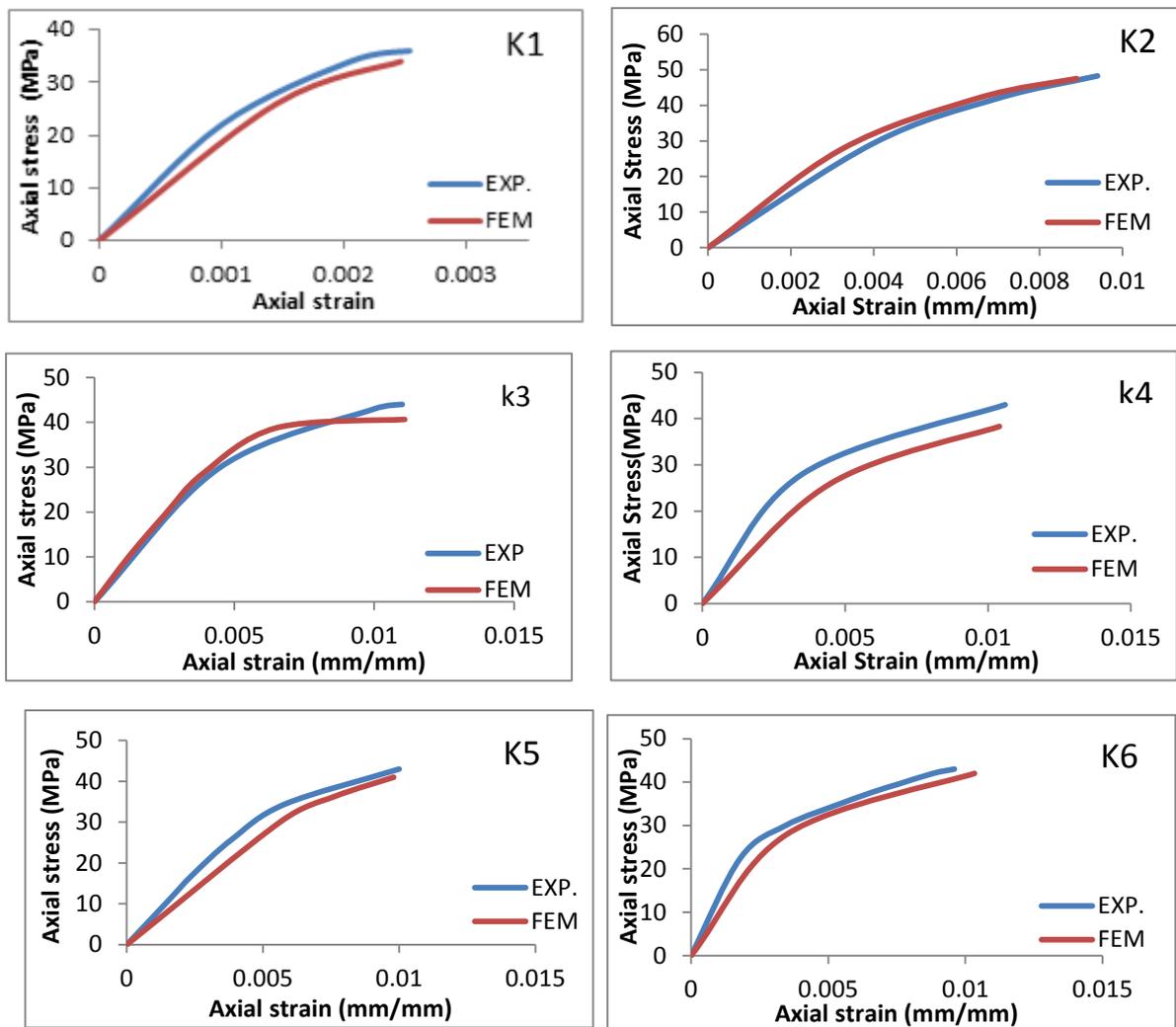


Figure 8. Experimental and numerical stress-strain curves of columns K1,K2,K3,K4,K5 and K6.

Table 2. Experimental and numerical results of ultimate load and axial strain (series 1).

columns	Ultimate load [KN]			Axial Strain		
	EXP.	FEM	FEM	EXP.	FEM	FEM
			EXP			EXP
K1	802	742	0.93	0.002533	0.002462	0.97
K2	1230	1185	0.96	0.0094	0.008897	0.95
K3	1221	1132	0.92	0.0108	0.011091	1.03
K4	1172	1153	0.98	0.0106	0.010383	0.98
K5	1182	1125	0.95	0.01	0.009816	0.98
K6	1175	1146	0.97	0.0096	0.010334	1.07

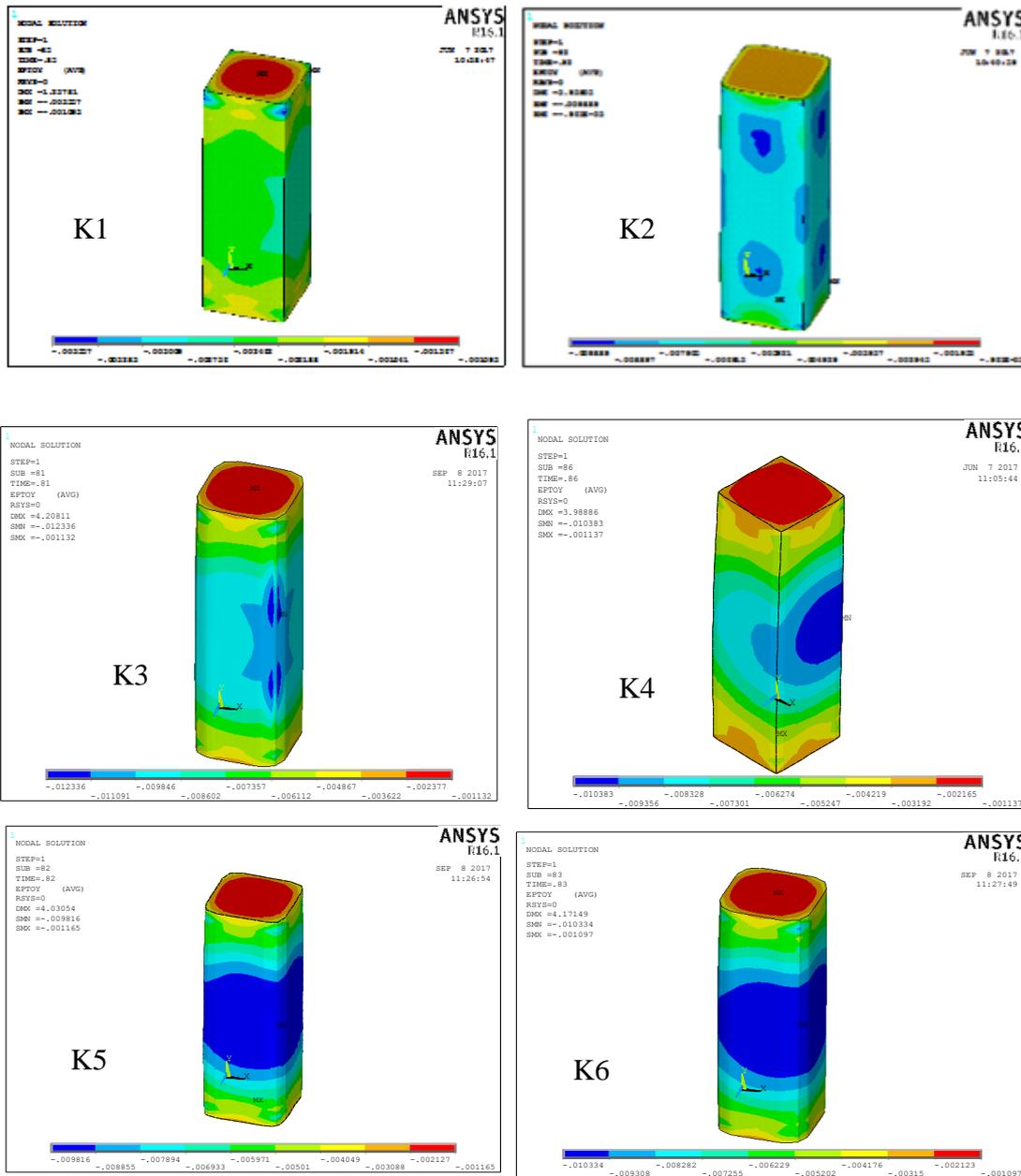


Figure 9. Variations in axial strain for columns (K1, K2, K3, K4, K5 and K6) respectively, using ANSYS

4.2 series two: verification of short, square and Reinforced Concrete Columns Strengthened with CFRP Wraps:

This experimental test was conducted by (Hadi *et.al.*,2012) to demonstrate the performance of carbon-fiber-reinforced polymer (CFRP)wrapped square reinforced concrete columns under eccentric loading. The influence of the number of CFRP layers and the magnitude of eccentricity were investigated(see table3). This series contain nine columns which were selected from the sixteen columns of the test to be analyzed by FEM.

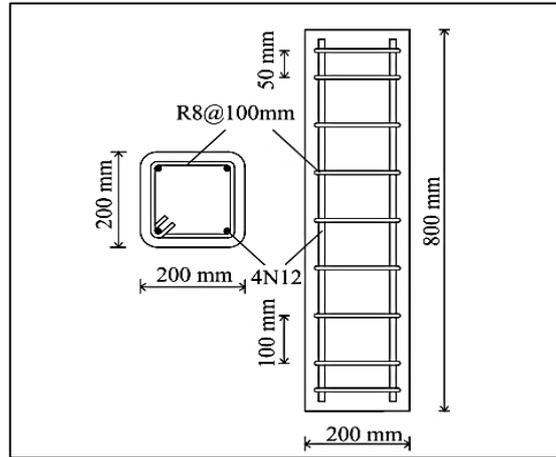


Figure10. Dimensions (mm) and steel reinforcement details

Table 3. Column details and steel reinforcement(series two)

Specimens	Side width mm	Height mm	Internal reinforcement	Number of FRP layers	eccentricity mm
EX1	200	800	4 ϕ 12 and ϕ 8 @100	None	0
EX2	200	800	mm		25
EX3	200	800			50
EX4	200	800	4 ϕ 12 and ϕ 8 @100	1 layer	0
EX5	200	800	mm		25
EX6	200	800			50
EX7	200	800	4 ϕ 12 and ϕ 8 @100	3 layer	0
EX8	200	800	mm		25
EX9	200	800			50

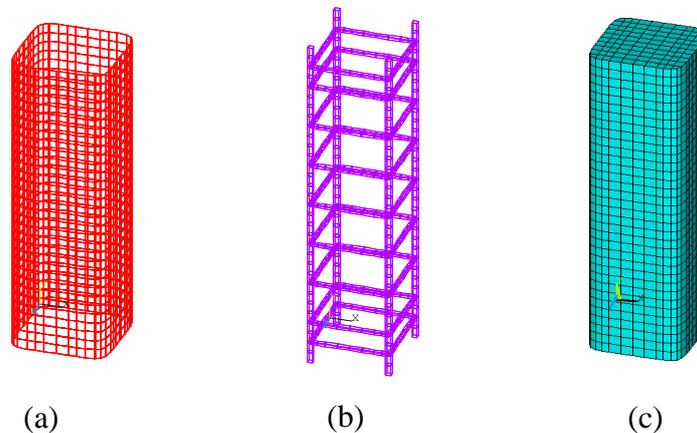


Figure 11. (a) Finite element model column (b) steel elements (c) Mesh of CFRP.

4.2.1 Results of The Analysis

The ultimate load and corresponding axial displacements were summarized in Table (4). (Hadi *et.al.*,2012) show in experimental study that the columns had a similar behavior before reaching the maximum load and explained clearly that the biggest maximum load and maximum axial displacement was achieved by wrapping the column with three layers of CFRP, thus wrapping columns with CFRP enhanced the performance of the columns by increasing their displacement at failure, meaning more ductility. This improvement in the performance of the concrete columns resulting from wrapping columns with CFRP was noted in the theoretical results using ANSYS program as shown in the performance of concentric columns (unwrapped EX1, wrapped with one layer of CFRP EX4, wrapped with three layers of CFRP EX7) in ultimate load and axial displacement (Table 4). An important advantage was also achieved for eccentric columns.

To describe the influence of eccentricity on the behavior of the columns, load-axial displacement were plotted as shown in figures (13). It can be clearly seen that the eccentricity of loading reduced the load carrying capacity and performance of the columns. ANSYS 's results as shown in figures (14).

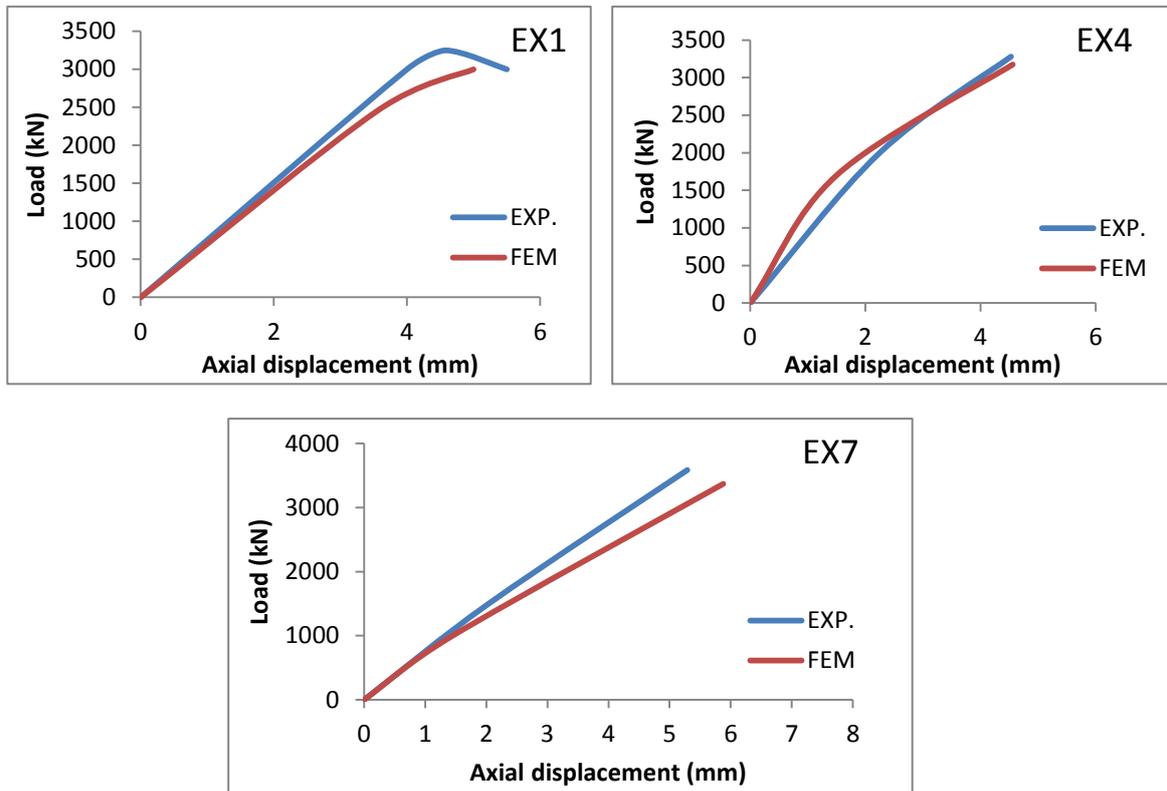


Figure 12. Experimental and numerical load-displacement curves for columns EX1,EX4 and EX7 under concentric loading.

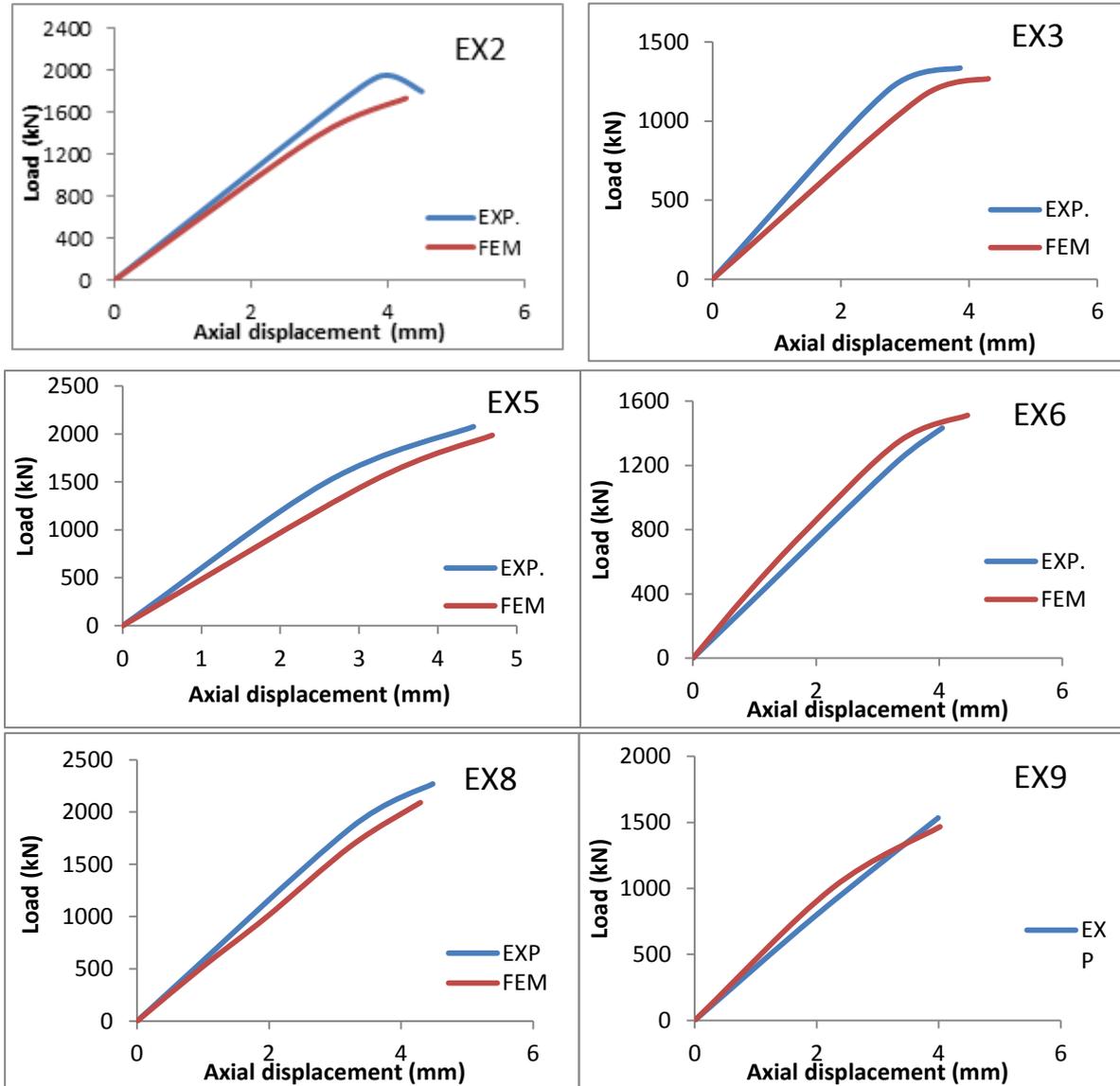
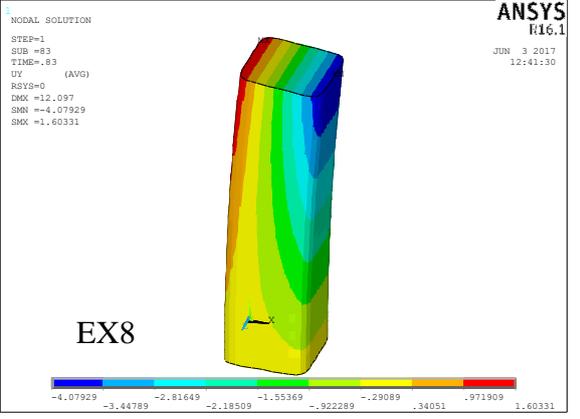
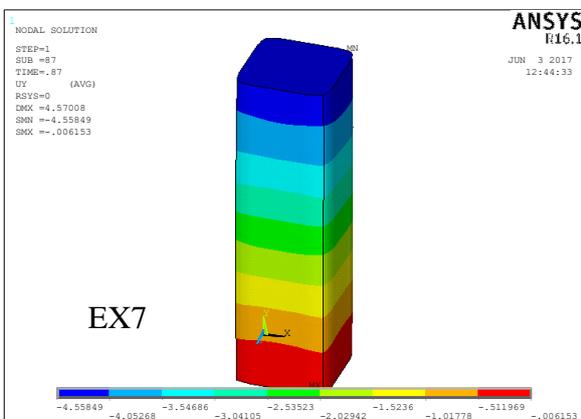
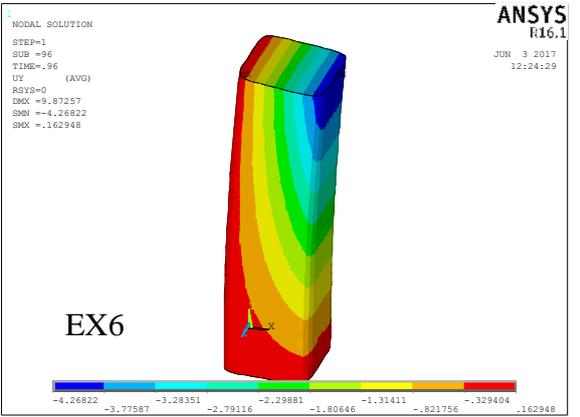
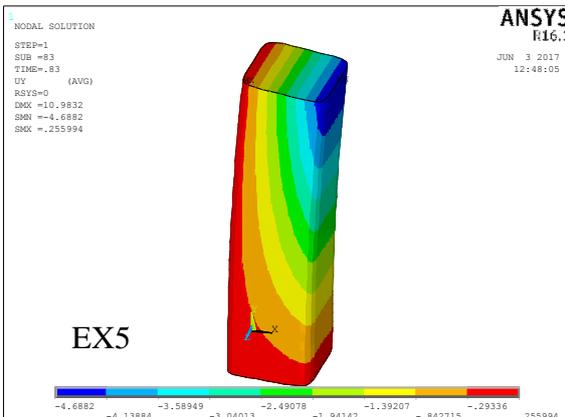
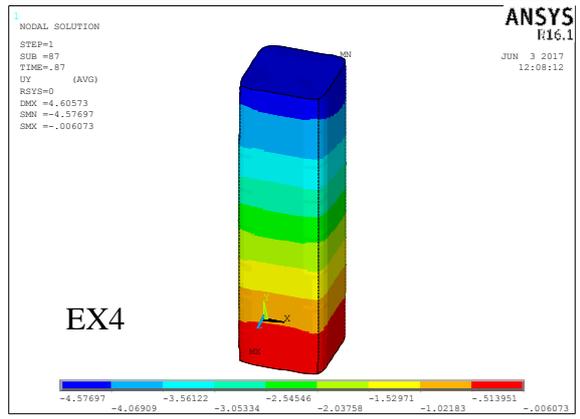
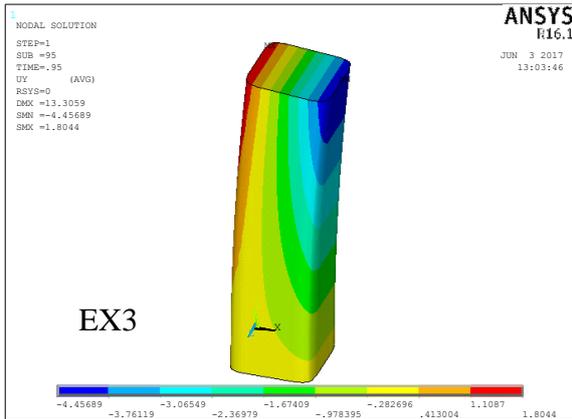
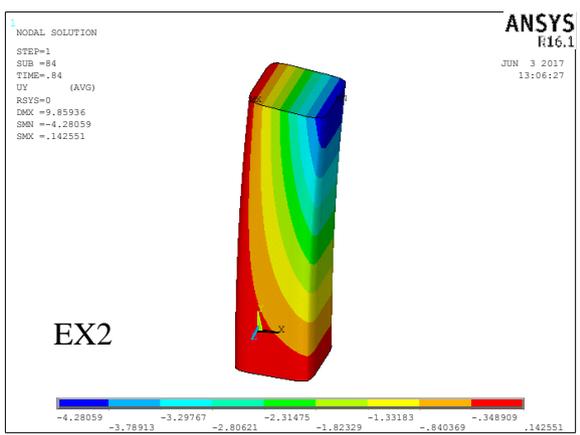
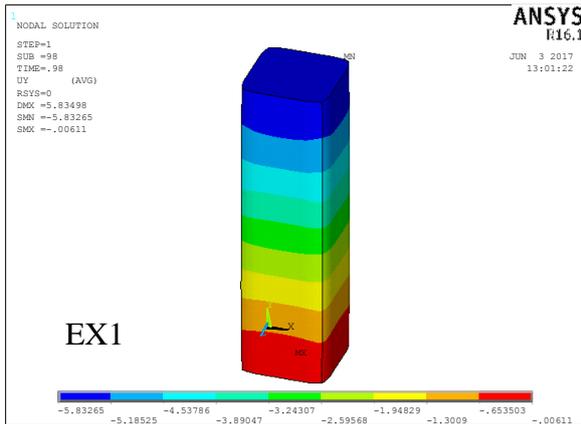


Figure 13. Experimental and numerical load-displacement curves for columns EX2, EX3, EX5, EX6 and EX8 under eccentric loading.

Table 4. Experimental and numerical results of ultimate load and axial displacement.

columns	Ultimate load [KN]			Axial Displacement		
	EXP.	FEM	FEM / EXP	EXP.	FEM	FEM / EXP
EX1	3248	3185	0.98	4.58	4.576	0.99
EX2	1950	1786	0.92	3.91	4.268	1.09
EX3	1336	1268	0.95	3.86	4.079	1.06
EX4	3279	3174	0.97	4.53	4.559	1.01
EX5	2076	1986	0.96	4.45	4.688	1.05
EX6	1433	1512	1.05	4.05	4.281	1.06
EX7	3585	3369	0.94	5.29	5.833	1.10
EX8	2269	2091	0.92	4.48	4.457	0.99
EX9	1534	1467	0.96	3.99	4.004	1.00



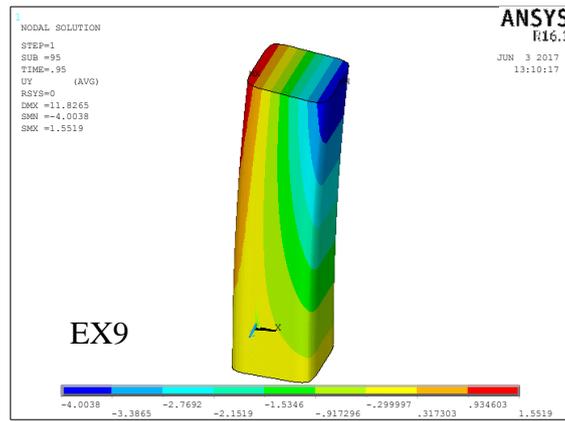


Figure 14. Variations in axial displacement in column (EX1,EX2,EX3,EX4,EX5,EX6,EX7,EX8 and EX9) using ANSYS.

4.2 Series three: verification of Rectangular Reinforced Concrete Columns Strengthened with CFRP Wraps:

This experimental test was conducted by (Harajli *et.al.*, 2006) to investigate the effectiveness of CFRP for various aspect ratios of the column rectangular sections and the development of stress-strain model. This series contains plain and reinforced rectangular columns wrapping with CFRP composites. Figure(15) shows cross sections and dimensions of specimens.

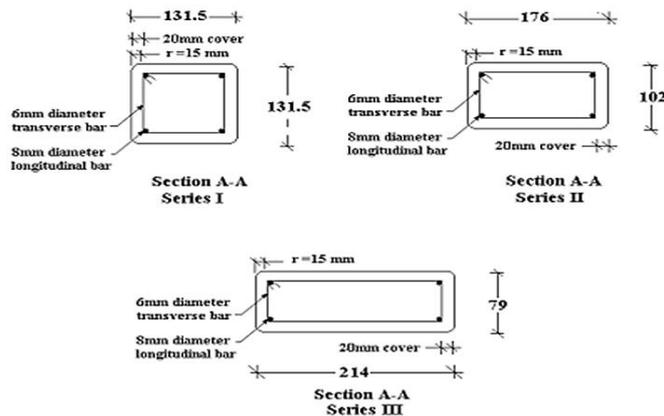


Figure 15. Dimensions and reinforcement details of reinforced concrete specimens tested by (Harajli *et.al.*, 2006).

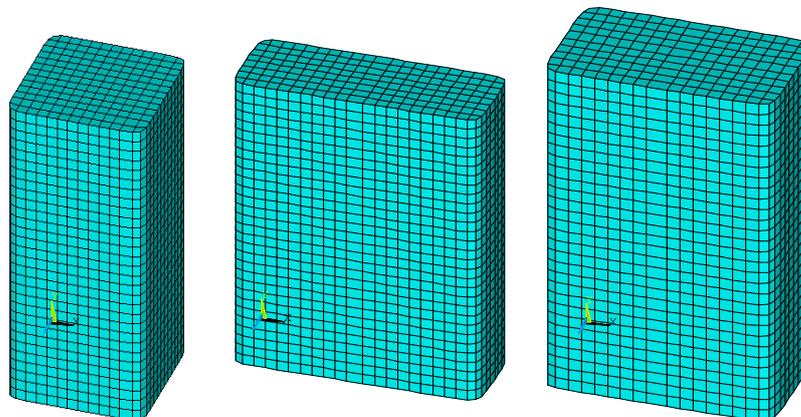
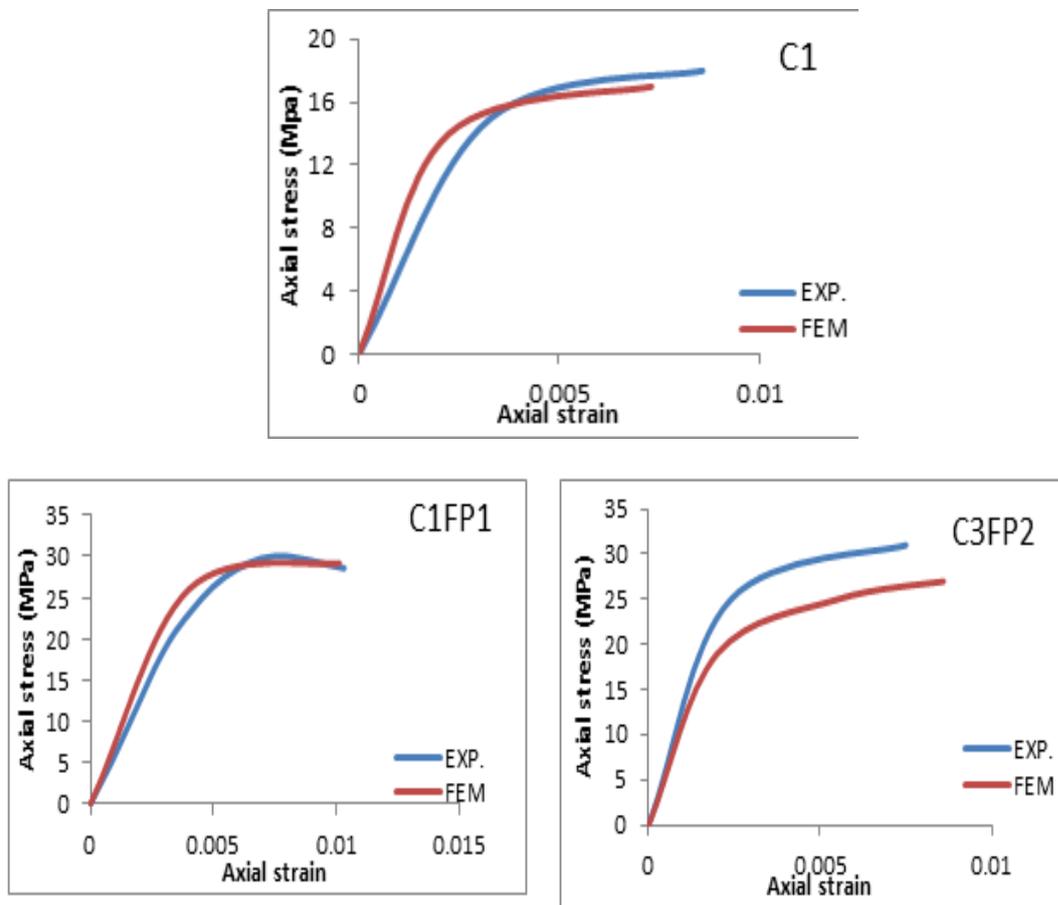


Figure 16. ANSYS modeling for specimens with aspect ratio (1,1.7,2.7).

4.3.1 Results of the Analysis:

The axial load-axial strain curves at middle point in the height of columns (C1, C1FP1, C2FP1, C3FP1, C1SFP1, C2SFP1 and C3SFP1) obtained from the numerical analysis along with the experimental curves as reported by (Harajli *et.al.*, 2006) are presented and compared in Figure(17). These figures show good agreement between the experimental and finite element analysis. Figures (18) show axial strain of (C1, C2FP1 and C3SFP1) columns with ANSYS. Table (5) shows the computed ultimate load and axial strain from the finite element analysis and the actual experimental ultimate load and axial strain of reinforced concrete columns confined with CFRP jackets. It can be seen that the ratio of the numerical to experimental axial load, axial strain ranges between (0.901-1.027), (0.85-1.14) respectively. These results prove the validation of the finite element models in the analysis of rectangular reinforced concrete columns strengthened with CFRP composites.



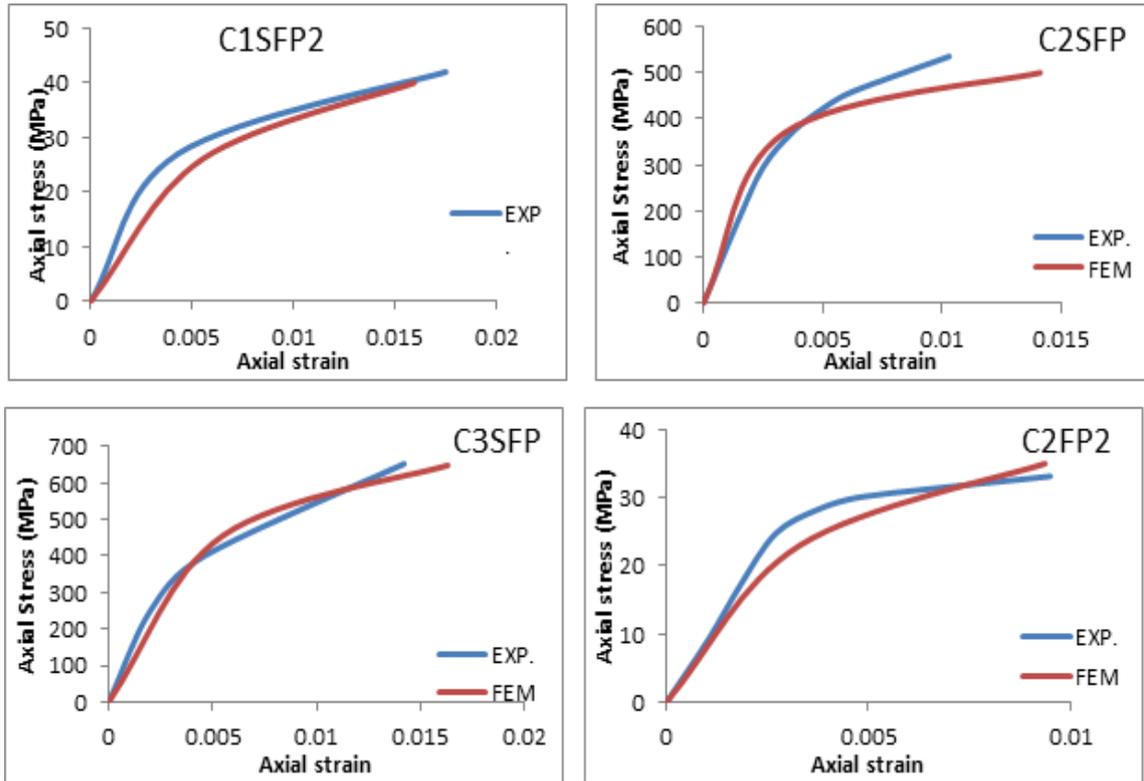


Figure 17. Experimental and numerical stress- strain curves for columns C1,C1SFP1,C2FP2,C3FP2,C1SFP2,C2SFP1andC3SFP1 respectively.

Table 5. Experimental and numerical results of ultimate load and axial strain(series three)

columns	Aspect ratio	Final load [kN]			Axial Strain		
		EXP.	FEM	$\frac{FEM}{EXP}$	EXP.	FEM	$\frac{FEM}{EXP}$
Columns with plain concrete ($f_c=18.3\text{MPa}$)							
C1	1	314	294	0.94	0.00859	0.00731	0.85
C1FP1	1	523	518	0.99	0.0103	0.0101	0.98
C2FP2	1.7	556.5	572	1.027	0.0095	0.00937	0.99
C3FP2	2.7	625.5	564	0.901	0.0075	0.00857	1.14
Columns with reinforced concrete ($f_c=15.2\text{MPa}$)							
C1SFP2	1	725	684	0.94	0.0175	0.01595	0.91
C2SFP1	1.7	535	494	0.92	0.0103	0.01047	1.02
C3SFP1	2.7	652	648	0.99	0.0142	0.01411	0.99

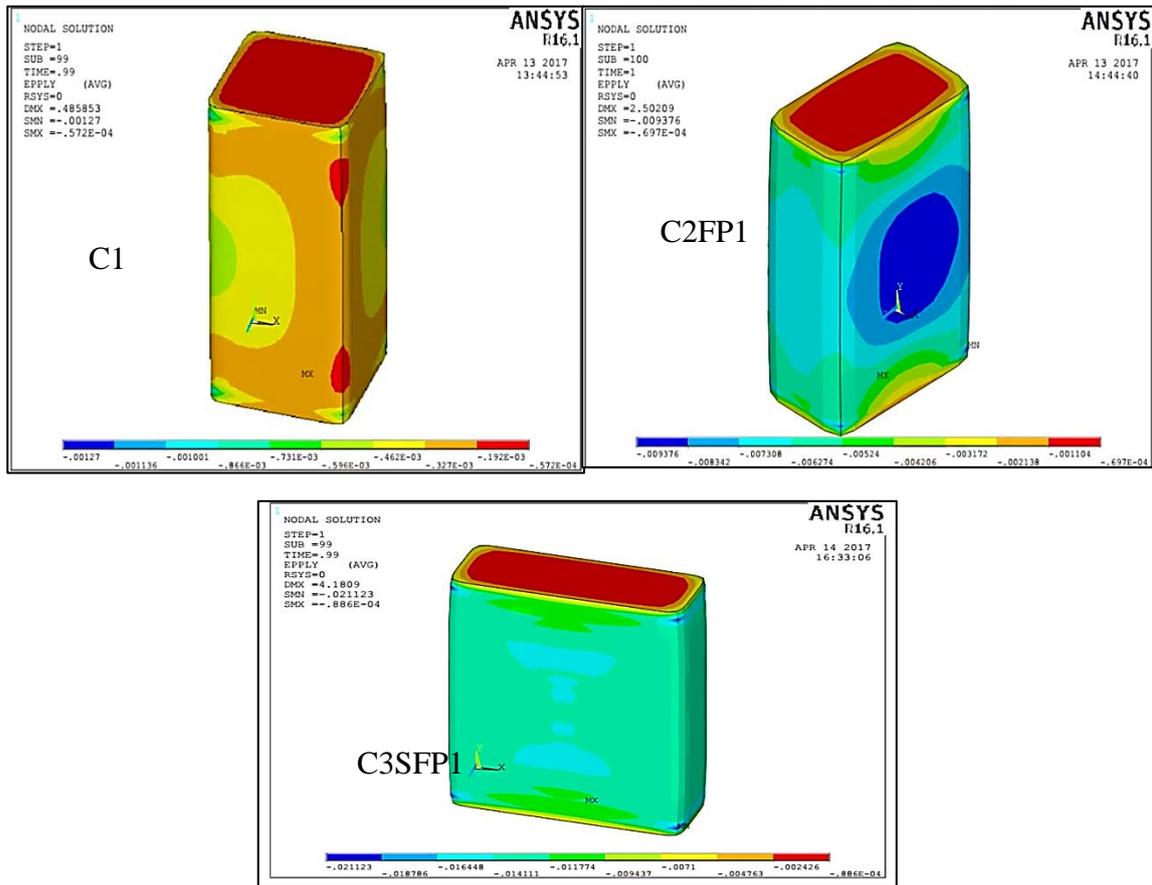


Figure 18. Variations in axial strain for some specimens in ANSYS (those tested by (Harajli *et.al.*, 2006).

4.4 series four: Verification of Long Rectangular Reinforced Concrete Columns.

In order to investigate the behavior of slender reinforced concrete (RC) columns sufficiently confined with FRP, more research work is needed. It is, therefore, useful to study the load carrying capacity of RC slender columns sufficiently confined with FRP and thus to understand the characteristics of the columns with a large slenderness ratio.

This series contains six RC columns wrapped with FRP were selected from experimental test (Pan *et.al.*, 2007) to modeled in finite element software ANSYS, details of specimens as shown in Table(6). The rectangular cross-section of the specimens was 120×150 mm, the slenderness ratio L/b was 4.5, 8, 10, 12.5, 14, 17.5, respectively as shown in figure (19).

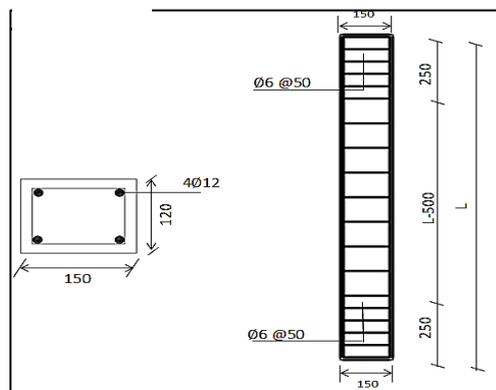


Figure 19. Details of the columns (tested by (Pan *et.al.*, 2007))

Table 6. columns description (series four).

Columns	f'_c (Mpa)	Slenderness ratio	Columns' height mm
Cln-1	36	4.5	675
Cln-2	36	8	1200
Cln-3	36	10	1500
Cln-4	36	12.5	1875
Cln-5	36	14	2100
Cln-6	36	17.5	2625

4.4.1 Results of The Analysis:

The load-axial displacement curves of columns Cln-1,Cln-2,Cln-3,Cln-4,Cln-5 and Cln-6 obtained from the numerical analysis along with the experimental curves reported by (Pan *et.al.*,2007). are presented and compared in Figure (20) These figures show good agreement between the experimental and finite element results. Table (7) shows that the computed ultimate load from the finite element analysis is slightly less than the actual experimental ultimate load of concrete columns confined with CFRP jackets. Figure (21) shows the results of axial displacement using ANSYS program for columns. It can be seen that the ratio of the numerical to experimental axial strength and axial displacement ranges between(0.92-0.98) and (0.95-1.07) respectively. These results prove the validation of the finite element models in the analysis of long columns strengthened with CFRP composites.

Table 7. Experimental and numerical results of ultimate load and axial displacement.

columns	Ultimate load [KN]			Axial displacement		
	EXP.	FEM	FEM / EXP	EXP.	FEM	FEM / EXP
Cln-1	1010	975	0.97	2.62	2.409	0.92
Cln-2	943	876	0.93	4.89	5.2087	1.07
Cln-3	900	874	0.97	5.37	5.347	0.99
Cln-4	800	766	0.96	6.93	6.8185	0.98
Cln-5	750	731	0.97	7.65	7.624	0.99
Cln-6	600	611	1.02	9.51	9.656	1.02

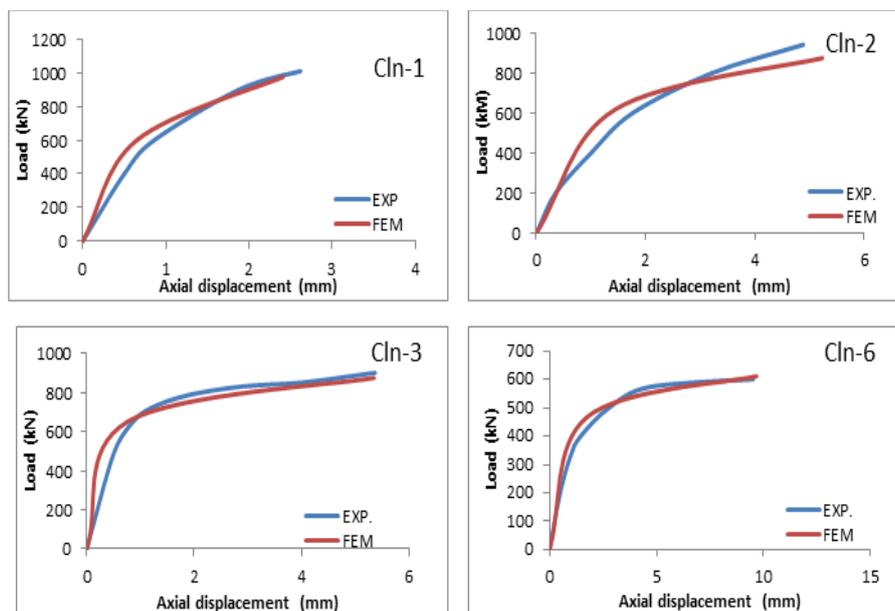


Figure 20. Experimental and numerical Load-axial displacement curve for columns

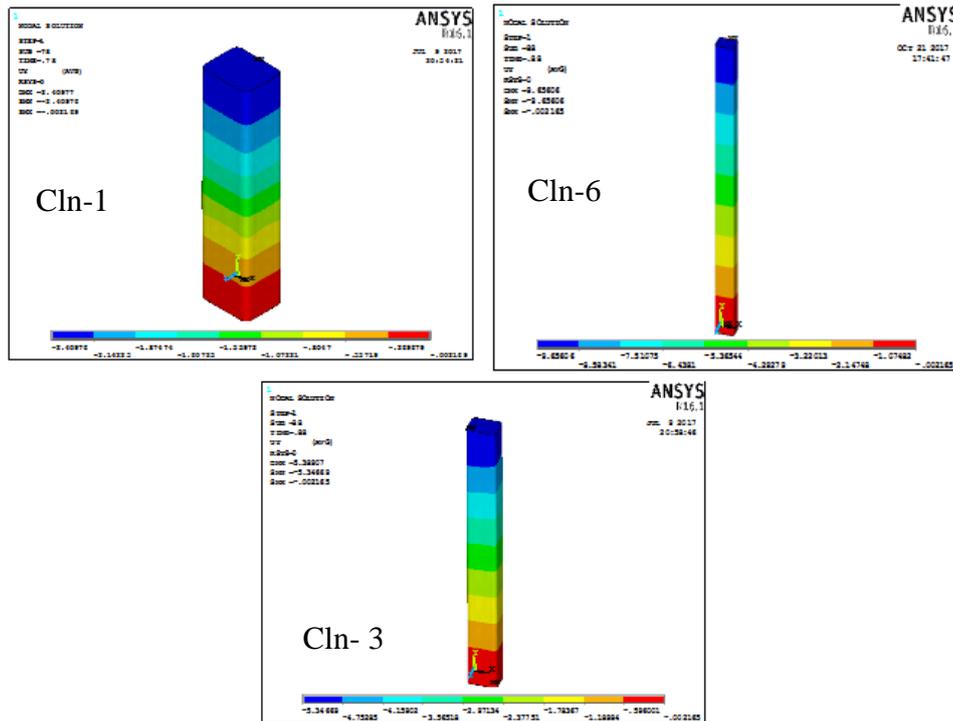


Figure 21. Variations in axial displacement for reinforced column using ANSYS.

5 - Parametric Study

Parametric study is conducted to investigate the effect of most important parameters on a number of concrete columns strengthened with CFRP which were analyzed by the nonlinear finite element analysis previously . These parameters include:

compressive strength of concrete, modulus of elasticity of CFRP and corner radius of square columns.

5.1 Effect of Columns' Compressive Strength:

To study the effect of Column's Compressive Strength on the behavior of square reinforced concrete columns strengthened with CFRP, square column was selected (C1SFP1 from the (Harajli , 2006)). Different concrete compressive strengths f_c (35,50 and 80MPa) were considered in addition to the original concrete compressive strength of experimental test (18.3 MPa for square C1SFP1).

Figure (22) reveals that as a concrete compressive strength is increased with values (35, 50 and 80MPa) for square controls (columns without strengthening with CFRP wraps), the axial strength of the columns increases with percentages (95.26, 145.58 and 218.3%) and the ductility decreases with percentages (15.91, 47.73 and 54.55%), as compared with the axial strength and ductility of the original state (f_c =18.3MPa). The decrease in ductility may belong to the tendency to the brittle behavior of concrete in higher concrete compressive strength. On the other hand, in state of square columns strengthened with CFRP wraps, as concrete compressive strength is increased with the same values above, the gain in axial strength was (77.78 , 87.88 ,63.27 and 62.26%) and the gain in ductility was (93.18 ,100 ,95.65 and 80%), as compared with the controls (without CFRP) respectively.

From the above results, it may be concluded that the increase of f_c for columns without strengthening, results in equal increase in strength but different decrease in ductility. On the other hand the increases in axial strength and ductility which come from strengthening with CFRP jackets for columns reduces with the increase in

concrete compressive strength, but the gain remains effective to enhance the compressive strength and ductility.

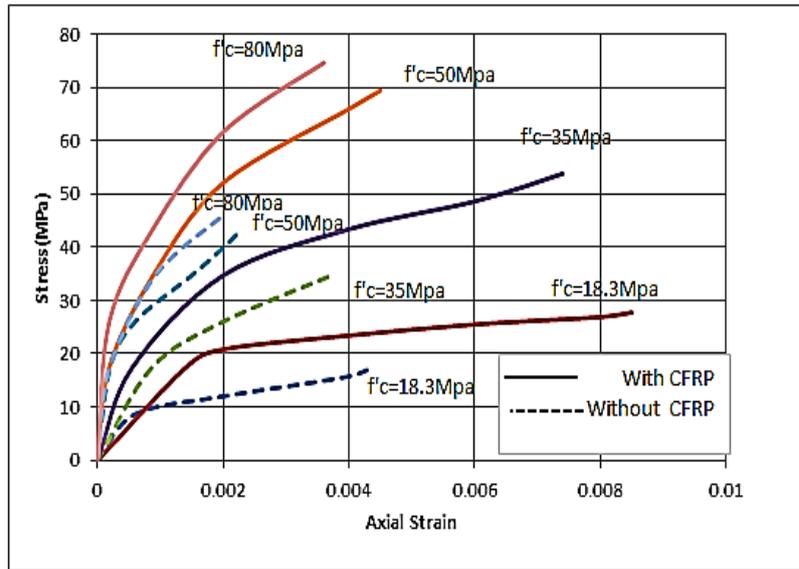


Figure 22. Stress-axial strain curves using finite element method for various f'_c for square columns (square C1SFP1) with and without CFRP wraps.

5.2 Effect of Modulus of Elasticity of CFRP:

To investigate the influence of the modulus of elasticity of CFRP composites, the same column used in the previous parametric studies was used here. Three values of modulus of elasticity (340,450 and 560 GPa) were selected from (ACI committee 440.22R-02) in addition to the original value (227 GPa).

It can be noted from Figure (23) that with the increase modulus of elasticity (227,340,450 and 560 GPa), the gained strength and ductility are (18.75, 50, 75 and 77.31%) and (47.5, 55, 70 and 112.5%), as compared with controls respectively.

From the above results, it may be concluded that the modulus of elasticity is an important parameter in strengthening square RC columns, and the increase in modulus of elasticity in high levels enhances the ductility significantly.

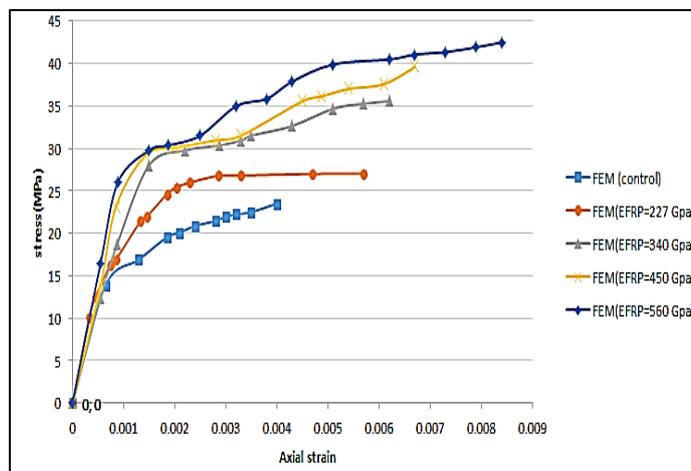
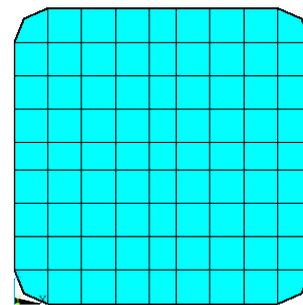
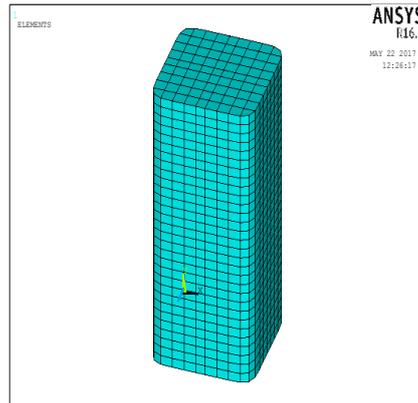


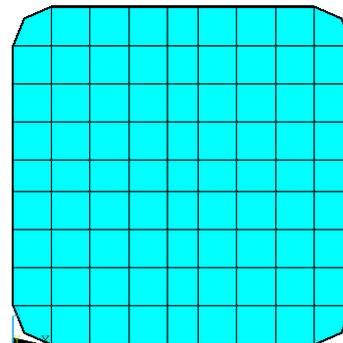
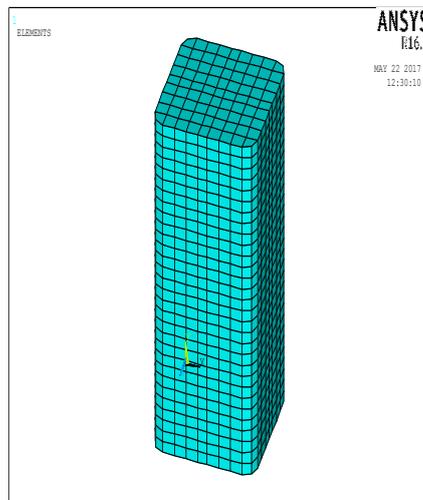
Figure 23. Stress-axial strain curves using FEM for various values of modulus of elasticity of CFRP composites for strengthening of square reinforced concrete column (square C1SFP1).

5.3 Effect of Ratio of Corner Radius to column side width ($\frac{R}{B}$) of Cross Section:

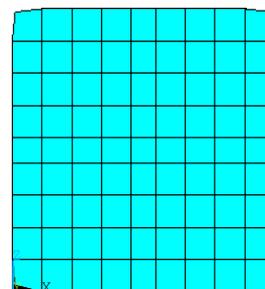
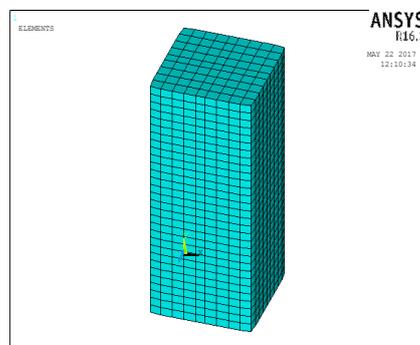
The column which was used in this parametric study was conducted from (Harajli *et.al.*, 2006) which verified previously to explain the effect of corner radius on the strengthening of RC column with CFRP. Three corner radii to column's side width were selected (0.0378, 0.1893 and 0.2878) (with keeping a suitable cover for the reinforcement steel) in addition to the original corner radius of experimental test column which was (15mm(0.1136)).Figure (24) show the finite element models of RC columns with selected values of corner radii.



Radius of corner =(5mm)



Radius of corner =(15mm)



Radius of corner =(25mm)

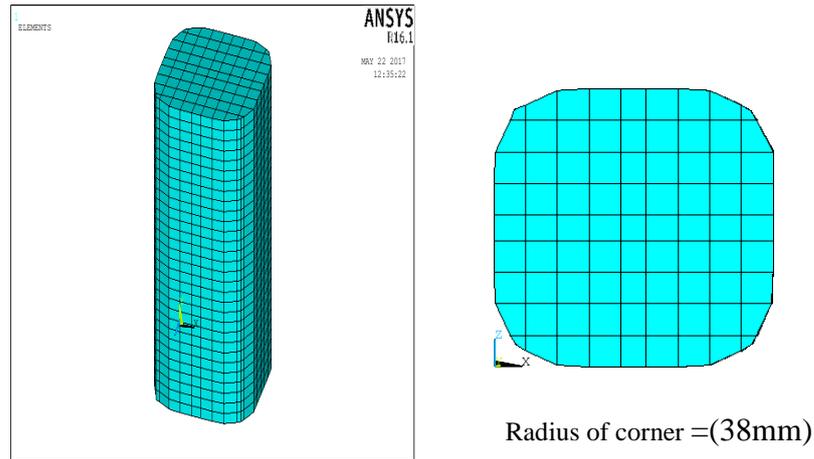


Figure 24. Finite element model of CFRP strengthened reinforced concrete columns.

This is attributed to the fact that the CFRP jacket delivers a higher confining stress as the corner sharpness decreases because of the expansion in hoop tension region, which arises in the corners and spreads towards the sides.

Figures (25,26,27), it is noted that the decrease in sharpness of the corners of the cross section by increasing the ratio of corner radius to column's side width with the values (0.0378, 0.1136, 0.1893 and 0.2878) results in percentage increases in axial strength of column strengthened with CFRP jacket, as compared with controls by about (80, 87.215, 118.75 and 146.67 %) respectively and percentage increases in ductility by (100.68, 186.34, 212.5 and 255.8%) respectively.

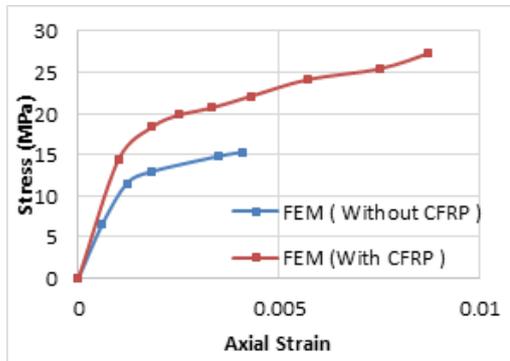


Figure 25. Axial stress-axial strain curves using FEM for reinforced concrete column with CFRP jacket and without CFRP jackets with radius of corner equal to (5mm).

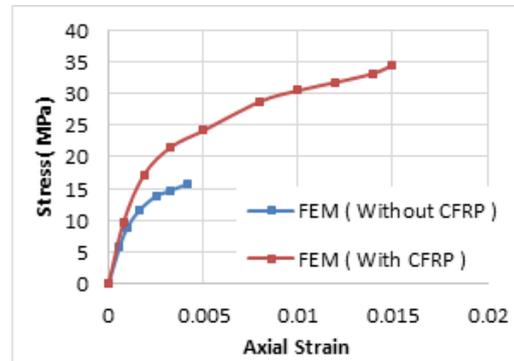


Figure 26. Axial stress-axial strain curves using FEM for reinforced concrete column with CFRP jacket and without CFRP jackets with radius of corner equal to (25mm)

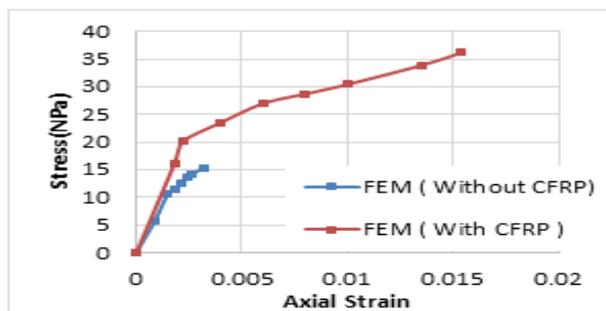


Figure 27. Axial stress-axial strain curves using FEM for reinforced concrete column with CFRP jacket and without CFRP jackets with radius of corner equal to (38mm).

6- Conclusions

Depending on the results of the nonlinear finite element analysis on the CFRP-strengthened reinforced concrete columns conducted throughout this study, the following conclusions can be made:

1. The general behavior of finite element stress-strain curves at mid height of the columns strengthened with CFRP jacket using ANSYS program shows good agreement with the available experimental stress-strain curves, and the analytical results have good convergence with the experimental results Therefore, the finite element models used in this study are suitable in analysis of this type of structure.
2. The strengthening, provided by the CFRP jacket system, improves both the load carrying capacity and the ductility of the reinforced concrete columns and this method of strengthening is seen to be applicable to different kinds of columns (circular, square and rectangular),but in different degrees.
3. The gain in strength and ductility for RC columns strengthened with CFRP decreases with the increase in concrete compressive strength (f_c).

when f_c is increased from (18.3 to 80MPa), the gained increase in strength decreases from (77.78 to 62.26%) and the ductility decreases from (100 to 80 %), as compared with the controls respectively.

4. The modulus of elasticity of CFRP is more effective in increasing the ductility. the increase in modulus of elasticity from (227 to 560GPa) results in an increase in gained strength (18.75 to 77.13%) and gained ductility (47.5 to 112.5%), as compared with the controls respectively
5. Reduction of corner sharpness of a square column cross-section by the increase in the corner radius is a very effective parameter in enhancing the gained increase in axial strength and ductility for the square RC column. When the $\frac{R}{B}$ is increased from (0.0378 to 0.2878mm), the gain in axial strength increases from (80 to 146.67%), and the gained ductility increases from (100.68 to 255.8%).

7- References

- ACI Committee. Copyright 2011. Building Code Requirements for Structural Concrete (ACI 318-11): American Concrete Institute.
- ANSYS. 2016. ANSYS Help. Release 16.0.
- Chaallal, Omar, Mohsen Shahawy, and Munzer Hassan. , 2003, "Performance of axially loaded short rectangular columns strengthened with carbon fiber-reinforced polymer wrapping." *Journal of Composites for Construction* 7.3: 200-208.
- Hadi, Muhammad NS, and Ida Bagus Rai Widiarsa. , 2012, "Axial and flexural performance of square RC columns wrapped with CFRP under eccentric loading." *Journal of Composites for Construction* 16.6: 640-649.
- Haider K. Osamah ,2013. Strength and Ductility of axially loaded RC short columns confined with CFRP and GFRP wraps. *American University*. M.Sc. Thesis.
- Harajli, Mohamed H., 2006,"Axial stress–strain relationship for FRP confined circular and rectangular concrete columns." *Cement and Concrete Composites* 28.10: 938-948.
- Mirmiran, Amir, Mohsen Shahawy, and Thomas Beitleman.,2001, "Slenderness limit for hybrid FRP-concrete columns." *Journal of Composites for Construction*5.1: 26-34.
- Murtada, A. I. , 2008. Reinforced concrete columns strengthened with carbon fiber reinforced polymer. *University of Mustansiriya*. M.Sc. Thesis.

- Pan J. L., T. Xu, and Z. J. Hu. , 2007, "Experimental investigation of load carrying capacity of the slender reinforced concrete columns wrapped with FRP." *Construction and Building Materials* 21.11: 1991-1996.
- Pessiki, Stephen *et.al.*, ,2001,"Axial behavior of reinforced concrete columns confined with FRP jackets." *Journal of Composites for Construction* 5.4: 237-245.
- Rochette, Pierre, and Pierre Labossiere. ,2000, "Axial testing of rectangular column models confined with composites." *Journal of composites for construction* 4.3: 129-136.
- Spoelstra, M. and Monti, G., August 1999 , "FRP-Confined Concrete Model", (ASCE) *Journal of Composites for Construction*, Vol.3, No.3, pp.143-15.