BEHAVIOR OF REINFORCED CONCRETE COLUMNS STRENGTHENED USING CFRP SHEETS UNDER SUSTAINED LOADING

سلوك الأعمدة الخرسانية المسلحة المقواه أثناء تحميلها بإستخدام ألياف الكربون

Hamdy K. Shehab El-Din,* Said M. Abd-Alla,* and Ahmed S. Eisa**

**Professor of Reinforced Concrete, Structural Dep., Faculty of Eng. Zagazig University*

***** Associate lecturer, Structural Dep., Faculty of Eng. Zagazig University***

الملخص العربي:

تناولت العديد من الأبحاث في الأونة الأخيرة دراسة تقوية وإصلاح المنشآت الخرسانية بإستخدام الألياف المركبة المستحدثة، وقد أظهرت العديد من هذه الدراسات أن العناصر الإنشائية مثل الأعمدة الخرسانية المسلحة مربعة المقطع تتحسن مقاومتها و كذلك ممطوليتها عند تقويتها بإستخدام شرائح الألياف المركبة المستحدثة، و على الرغم من العدد الكبير من الدراسات التي أجريت على سلوك الأعمدة الخرسانية المقواه بإستخدام الألياف المركبة المستحدثة فإن أغلب هذه الدراسات لم تضع في الإعتبار الأحمال الثابتة التي تكون الأعمدة معرضة لها أثناء عملية التصليح أو التقوية.

و يتضمن البحث دراسة عملية و تحليليه لسلوك الأعمدة الخرسانية المسلحة مربعة المقطع و المحملة رأسيا و جانبيا و مقواه بإستخدام شرائح ألياف الكربون المركبة المستحدثة أثناء تحميلها و كذلك بدون أحمال، و قد إستندت الدراسة العملية على النتائج المعملية التي تم إجراؤها على ١٢ عمود مسلح مربع المقطع (٢٠٠ مم×٢٠٠ مم) بإرتفاع ٢٥٠٠ مم، وكانت المتغيرات التي تم دراستها كالتالي:

١- نسب الأحمال الثابتة من الحمل الأقصى للأعمدة عند التقوية، و كانت قيمها (٠,٠٪ ، ٤٠٪ ، ٨٠٪).

٢- نسب الأحمال جانبية من الحمل الراسي للأعمدة، و كانت قيمها (٠,٠٪ ، ٥٪ ، ١٠٪).

ABSTRACT: This paper investigates experimentally the behavior of axially and laterally loaded square reinforced concrete columns wrapped with **CFRP** sheets with and without sustained loading. The experimental work includes twelve large scale square columns with cross section 200×200 mm and 2500 mm height. The parameters to be investigated are the percentage of sustained loads (40% and 80% of the ultimate load), and the lateral loads (equivalent to 5% and 10% of the axial load). The columns are kept loaded, until being tested up to failure under static axial compressive load in addition to the different values of the lateral loads.

Keywords: Column, strengthening, sustained loading, fiber-reinforced polymers (FRP).

INTRODUCTION

In most previous researches dealing with the repair of reinforced concrete structural elements, the load applied to the element, under study, is removed before the repair is done. Then after repairing the element is reloaded for testing. The results are then obtained, from which the conclusions are derived. This situation cannot resemble what really occurs in nature. It is virtually impossible to entirely remove the load acting on a structural element so as to strengthen that element. Therefore, in this research the strengthening of reinforced concrete elements taking the load applied on these elements into consideration has been studied. This case is more representative to the actual situation in existing structures. This research attempts to resemble the real conditions by assuming the partial load removal, or even strengthening at a specified applied load value [5].

Kaluarachchi [3] reported that when a reinforced concrete column is repaired under sustained service loading, the repair material carries a smaller portion of the applied load when compared to columns repaired without sustained loading. Thus, it is likely that the increase in axial capacity would be less if the columns were

Accepted December 17, 2009.

strengthened under sustained loading [4]. Various elements could be studied under the previously mentioned concept. In this research only reinforced concrete square columns subjected to axial compression loads and lateral loads are taken into consideration.

EXPERIMENTAL PROGRAM

Test specimens and loading arrangement

Twelve large scale square reinforced concrete columns were tested. All columns had square cross sections of (200×200 mm), overall height of 2500 mm, and a clear height of 2000 mm. Two enlarged reinforced concrete heads were used at the ends of each column with dimensions of (200×450 mm) to prevent any expected stress concentration at the column ends. The longitudinal steel reinforcement of the columns was four steel bars each of diameter 12 mm made of high tensile steel with ($fy/fult$=36/52) with a longitudinal steel reinforcement ratio, (μ=As/b.t) equal to 0.0113. Steel bars each of diameter 8 mm made of ordinary mild steel (24/35) were used as stirrups spaced every 200 mm with a volumetric ratio of 0.0040. Fig. (1) shows the details of test specimens. The test specimens were arranged into four groups each group consisted of three columns; one column was subjected to axial load only and the other two columns were subjected to different lateral loads (equivalent to 5% and 10% of the axial load). The groups details are shown in table (1), group (1) consisted of columns which were tested as control specimens without any application of the strengthening technique, group (2) consisted of columns which were strengthened by wrapping CFRP sheets before applying any loads (zero load level before the test), group (3) consisted of columns which were strengthened by wrapping CFRP sheets under loading (at 40% of the ultimate load during the test), and group (4) consisted of columns which were strengthened by wrapping CFRP sheets under loading (at 80% of the ultimate load during the test).

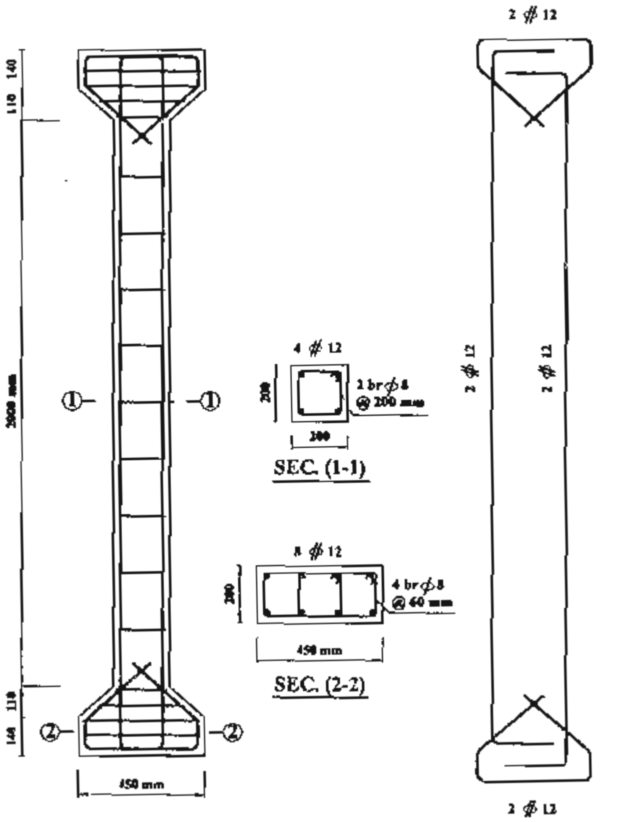

Fig. (1) Reinforcement details of tested columns

Table (1) Groups details and test program

Group	No.	Column	Lateral load (% of the axial load)	Description
1	1	C-0-0	0%	Control specimens without any application of the strengthening technique.
	2	C-0-5	5%	
	3	C-0-10	10%	
2	4	S-0-0	0%	Columns which were strengthened by wrapping CFRP sheets before applying any loads (zero load level before the test).
	5	S-0-5	5%	
	6	S-0-10	10%	
3	7	S-40-0	0%	Columns which were strengthened by wrapping CFRP sheets before applying any loads (at 40% of the ultimate load during the test).
	8	S-40-5	5%	
	9	S-40-10	10%	
4	10	S-80-0	0%	Columns which were strengthened by wrapping CFRP sheets before applying any loads (at 80% of the ultimate load during the test).
	11	S-80-5	5%	
	12	S-80-10	10%	

Materials

Locally produced materials were used. Fine and coarse aggregates were composed of harsh desert sand and crushed dolomite with two sizes having nominal maximum sizes 9.5mm and 16mm, respectively, combined together to meet **ASTM** grading. Ordinary Portland cement and tap drinking water were used. Two types of reinforcing bars were used, the first was locally produced high strength steel with (f_y/f_{ult}=360/520) used as longitudinal reinforcement, the second one was ordinary plain mild steel with (f_y/f_{ult}=240/350) used as stirrups.

Strengthening material (CFRP sheets and its resin)

Carbon fiber fabric strengthening system manufactured by **Sika Egypt** for Construction Chemicals under product name as **Sikawrap Hex®-230C/Sikadur®-330** was used which consisted of the **CFRP** sheets and its impregnating resin. The specifications of the product could be found in the manufacturing company (www.sika.com.eg); some of these technical specifications are as follows:

Sikawrap Hex®-230C

-Areal weight (± 10):220g/m^2
-Density:1.78g/cm^3
-Fabric design thickness (based on total carbon content):0.12mm
-Tensile strength of fibers (nominal):4100MPa
-Tensile E-modulus of fibers (nominal):231GPa
-Strain at break of fibers:1.7%

Sikadur®-330

-Density:1.31kg/lit
-Tensile strength:30MPa
-Tensile E-modulus in flexural:3800MPa
-Adhesive strength on concrete:4MPa

Application of CFRP strengthening system

The process for the field installation of **CFRP** sheets and its impregnating resin consisted of the following basic steps: ***(1)Concrete surface preparation*** (that was, cleaning, sealing cracks, and smoothing using a manual grinder), ***(2)Application of a primer coat (if needed)***, ***(3)Application of the resin*** (**Sikadur®-330** was used to apply the sheets over the columns. The epoxy two components were mixed in 4:1 ratio by mass, stirred mechanically in low speed to ensure the uniformity of the mix. The epoxy was mixed in 750 gm batches for each strengthened specimen. This amount was sufficient to apply the sheets over the entire column), and ***(4)Adhesion of the sheets*** (Ten laminates of **CFRP** sheets were used for each strengthened column with dimensions (900 mm length and 100 mm width), each laminate of the **CFRP** was wrapped around the column with an overlap of 25% of the circumference as shown in fig. (2). In the vertical direction, the column clear height (2000 mm) was covered by ten laminates of sheets in a symmetrical manner with 100 mm spacing between them. Wraps could be applied by two persons (the author and one helper); no special training was necessary to complete the job. The wrapping process could be completed in approximately an hour).

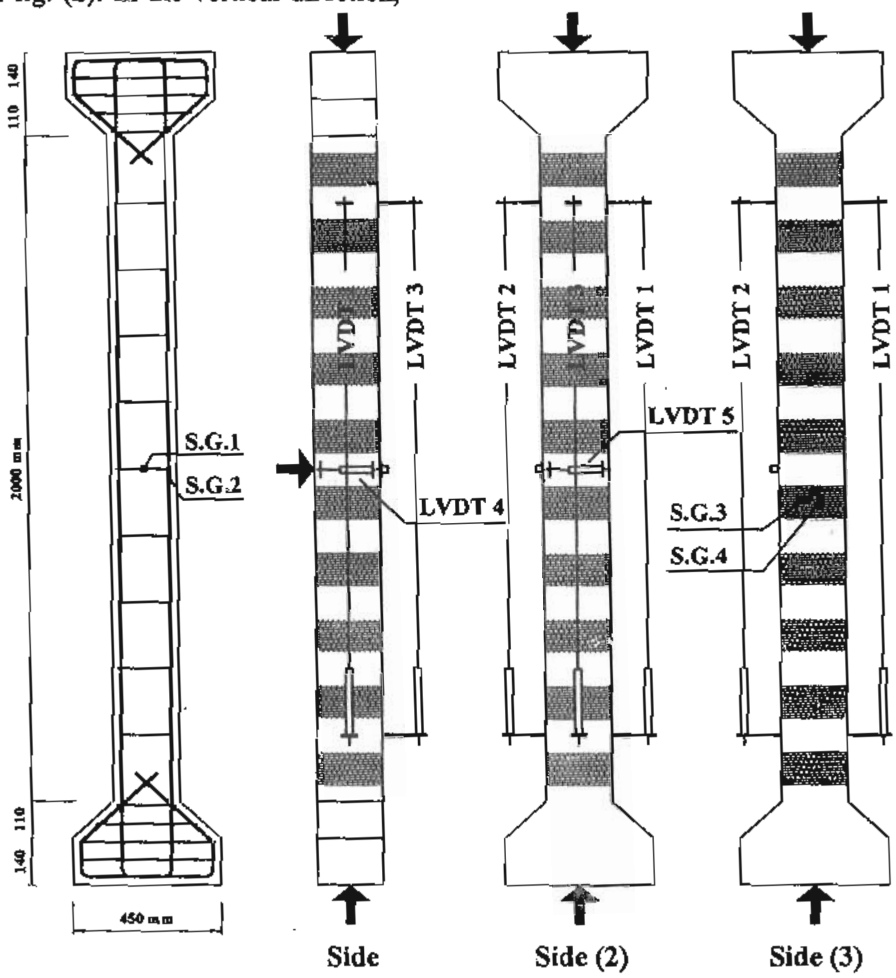

Fig. (2) CFRP sheets configuration and measuring instruments on strengthened columns

Testing and measurements

The columns were tested using a monotonic axial compression loading system at the columns ends using a hydraulic jack and a reaction frame of 400-ton capacity and also in some cases, a monotonic axial compression loading system at the columns mid heights as lateral loads was used in combination with the axial compression loading system. Fig. (3) shows the loading arrangement and the overall test setup. The axial and transverse strains of the specimens were measured by two different methods. The first method was the electrical strain gages produced by **KYOWA.ELECTRONIC,INSTRUMENTS CO., LTD., Tokyo, Japan**. The product type for the steel and the **CFRP** sheets were **KFG-5-120-C1-11** and **KFG-20-120-C1-11** respectively. The strain gages data were collected using a data logger system and lab view software. Two electrical strain gages were installed on the steel reinforcement; one strain gage was installed on a longitudinal bar (**S.G.2**) and the other was installed on a stirrup at the mid height of the column (**S.G.1**). Two electrical strain gages were installed on the **CFRP** sheets; one strain gage was installed in the fiber direction (**S.G.3**) and the other was installed in the perpendicular direction of the fiber direction (**S.G.4**) on the closest sheet to the mid height of the column as shown in fig. (3). Strains were also measured using Linear Variable Distance Transducers, **LVDT**, which has different lengths (50 and 100 mm). Three **LVDTs** were installed on three faces of each column to measure the longitudinal strain (**LVDTs** no. 1, 2, and 3) while two **LVDTs** were installed on two faces of each column at mid height to measure the transverse strain (**LVDTs** no. 4 and 5) as shown in fig.(2).

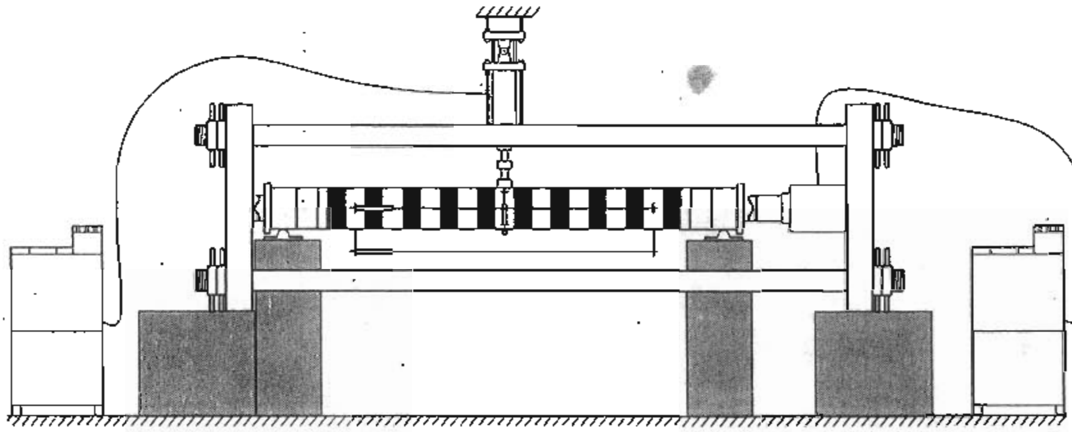

Fig. (3) Loading arrangement and test setup

TEST RESULTS AND DISCUSSION

Failure mode

The modes of failure of the tested columns are illustrated in table (2), three modes of failure were observed during the tests as shown in photos from (1) to (4). These modes of failure can be described as follows: ***(1)Compression failure mode"CF"*** was initiated by an inclined crack that occurred near the top third of the column at about 90% of the ultimate load. Sounds were heard during the middle stages of loading due to micro cracking and aggregates shifting. The concrete cover spalled off and the longitudinal steel reinforcement buckled between two adjacent stirrups, ***(2)Splitting failure mode"SF"*** that initiated by vertical and inclined cracks occurred near the top third of the column at about 90% of the ultimate load. Sounds were heard during the middle stages of loading due to micro cracking and aggregates shifting. The concrete cover spalled off and the longitudinal steel reinforcement buckled between two adjacent stirrups. The failure was progressive, the load decreased gradually after the concrete cover spalled off, ***(3)Rupture of CFRP sheets"RF"*** occurred by rupture of **CFRP** laminates at the corner of the columns. It was initiated by a vertical crack that occurred near the top third of the column between the **CFRP** laminates at about 90% of the ultimate load. Failure occurred simultaneously at the corners of two successive **CFRP** laminates. The **CFRP** laminates pulled off with the concrete cover and the steel reinforcement bars were exposed. After failure occurred, an inclined crack in the concrete was observed. Table (2) presents the test results and observed failure-modes.

Table (2) Test results and observed failure modes

Group	No.	Column	Ultimate load (KN)	Measured strains at ultimate load (%)					Observed failure mode
				Concrete		Long. Steel	Stirrups	CFRP	
				Side (1)*	Side (1)**				
1	1	C-0-0	787.8	0.2500	0.2500	0.4600	0.2100	----	CF
	2	C-0-5	758	0.2500	0.2550	0.4470	0.2340	----	SF
	3	C-0-10	723	0.2000	0.2880	0.4380	0.4350	----	SF
2	4	S-0-0	1141.4	0.3810	0.3810	0.4180	0.2400	0.1920	RF
	5	S-0-5	1109	0.3170	0.3300	0.4400	0.1890	0.1650	RF
	6	S-0-10	1035	0.3040	0.3100	0.4700	0.1460	0.3930	RF
3	7	S-40-0	971	0.3830	0.3830	0.5700	0.2403	0.1821	RF
	8	S-40-5	967.2	0.3500	0.3310	0.3970	0.1770	0.1890	RF
	9	S-40-10	948.4	0.3510	0.3030	0.3720	0.2274	0.2283	RF
4	10	S-80-0	955.6	0.3470	0.3470	0.4680	0.1440	0.2520	RF
	11	S-80-5	929	0.3540	0.3640	0.3280	0.1680	0.2790	RF
	12	S-80-10	892.5	0.3240	0.3440	0.4240	0.1740	0.3420	RF

* Side (1): The column side which is parallel to the applied lateral load direction.
Side (2): The column side which is perpendicular to the applied lateral load direction.

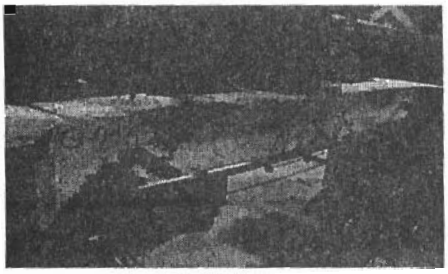

Photo (1) Failure of group 1

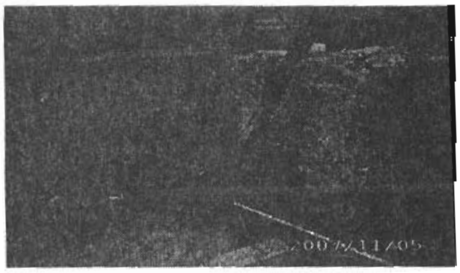

Photo (2) Failure of group 2

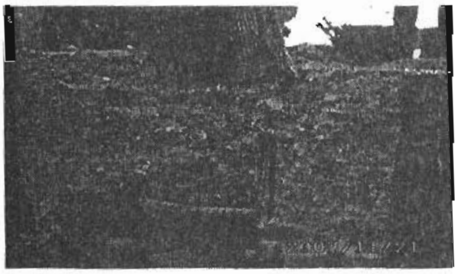

Photo (3) Failure of group 3

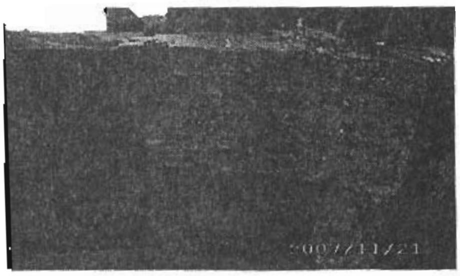

Photo (4) Failure of group 4

Effect of test variables and comparison of test results

The effect of strengthening load levels and the applied lateral loads on the tested columns and comparisons of the recorded experimental results of the tested columns are illustrated in figures from (4) to (23) in terms of ultimate load, load-longitudinal strain curves, and load-transverse strain curves for concrete, steel , and CFRP.

Observing the results listed in table (2) and the mentioned figures, the following can be noticed:

• Comparing the measured ultimate loads of the tested columns in both groups (1) and (2), the ultimate loads of the tested columns in group (2) increased by 45%, 46%, and 43% for columns (S-0-0, S-0-5, and S-0-10) respectively which is due to the confinement effect of applying the strengthening technique by wrapping **CFRP** sheets before applying any loads on the tested columns of this group.

• Comparing the measured ultimate loads of the tested columns in both groups (1) and (3), the ultimate loads of the tested columns in group (3) increased by 23.3%, 27.6%, and 31.2% for columns (S-40-0, S-40-5, and S-40-10) respectively, while comparing the measured ultimate loads of the tested columns in both groups (2) and (3), the ultimate loads of the tested columns in group (3) decreased by 14.9%, 12.8%, and 8.4% for columns (S-40-0, S-40-5, and S-40-10) respectively, as a result of the sustained loads.

• Comparing the measured ultimate loads of the tested columns in both groups (1) and (4), the ultimate loads of the tested columns in group (4) increased by 21.3%, 22.6%, and 23.4% for columns (S-80-0, S-80-5, and S-80-10), respectively, while comparing the measured ultimate loads of the tested columns in both groups (2) and (4), the ultimate loads of the tested columns in group (4) decreased by 16.3%, 16.2%, and 13.8% for columns (S-80-0, S-80-5, and S-80-10), respectively. Comparing the measured ultimate loads of the tested columns in both groups (3) and (4), the ultimate loads of the tested columns in group (4) decreased by 1.6%, 3.9%, and 5.9% for columns (S-80-0, S-80-5, and S-80-10), respectively, which is a result of applying the confinement under the sustained loads.

• The relationships between the applied load and both the longitudinal and transverse strains for concrete, steel, and **CFRP** was typical for all tested columns, a linear increase followed by a nonlinear relation until failure. The slope of the first part of the plotted figures was almost the same, being slightly sharper when strengthening by wrapping **CFRP** sheets before applying any loads on the tested columns while the sharpness degree decreased when strengthening under loading (at 40% and 80% of the ultimate load during the test).

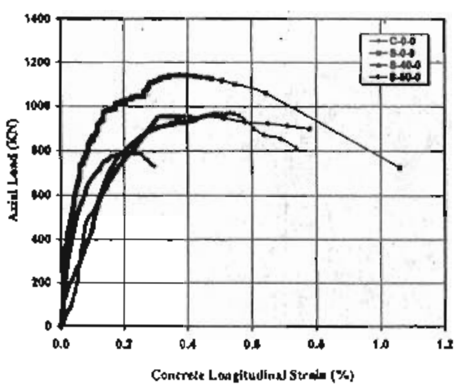

Fig. (4) Columns without lateral loads

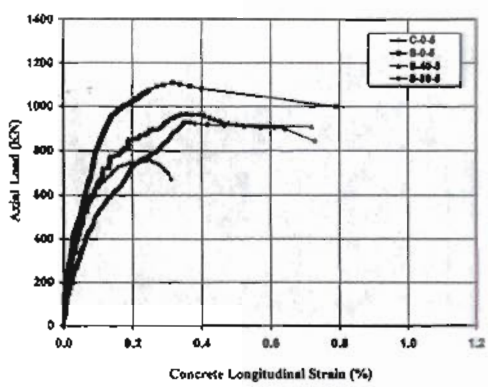

Fig. (5) Columns having lateral loads (5%)

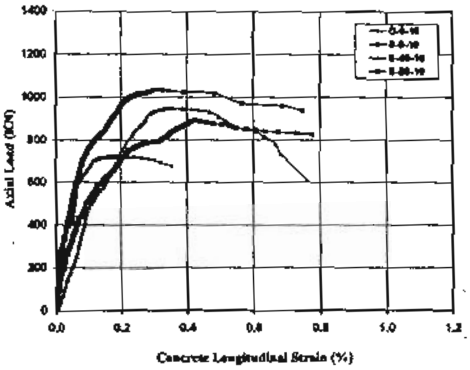

Fig. (6) Columns having lateral loads (10%)

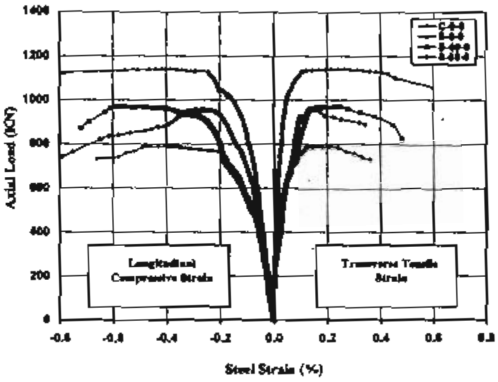

Fig. (7) Columns without lateral loads

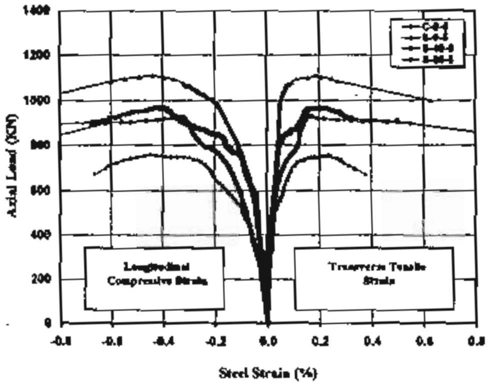

Fig. (8) Columns having lateral loads (5%)

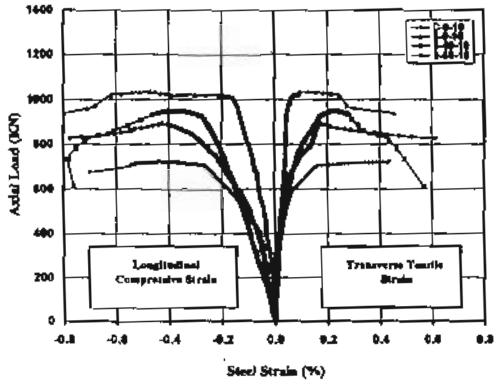

Fig. (9) Columns having lateral loads (10%)

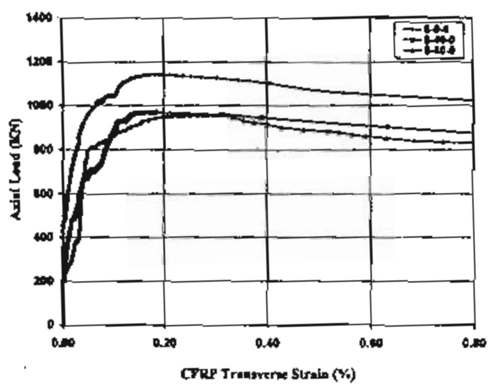

Fig. (10) Columns without lateral loads

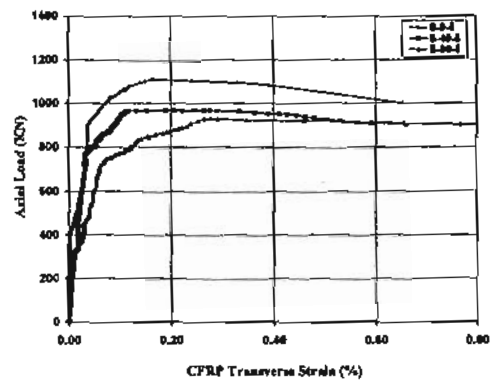

Fig. (11) Columns having lateral loads (5%)

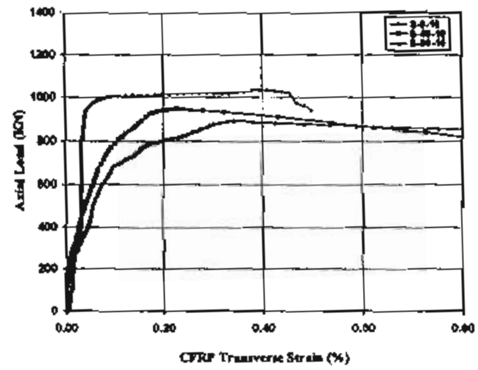

Fig. (12) Columns having lateral loads (10%)

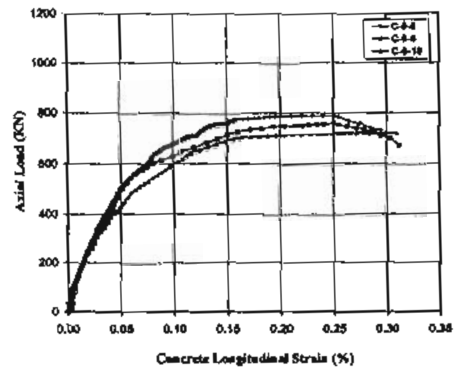

Fig. (13) Comparison of group (1)

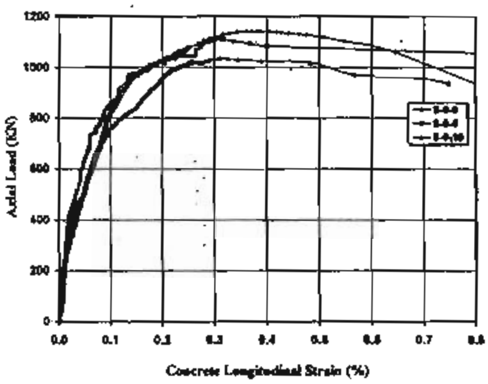

Fig. (14) Comparison of group (2)

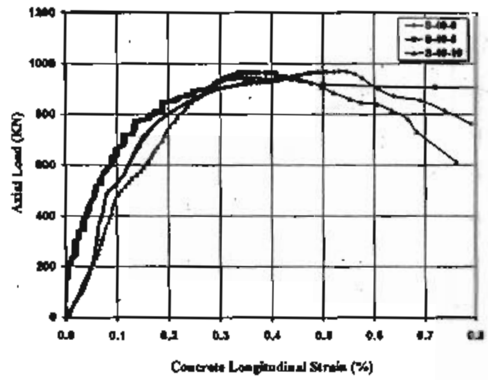

Fig. (15) Comparison of group (3)

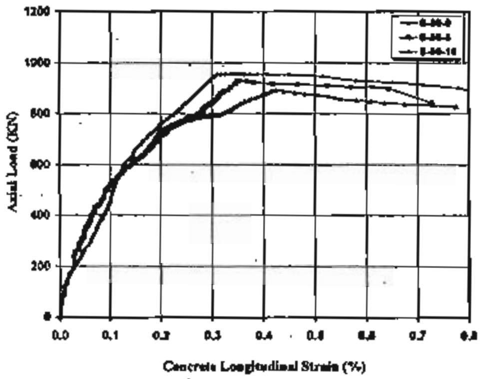

Fig. (16) Comparison of group (4)

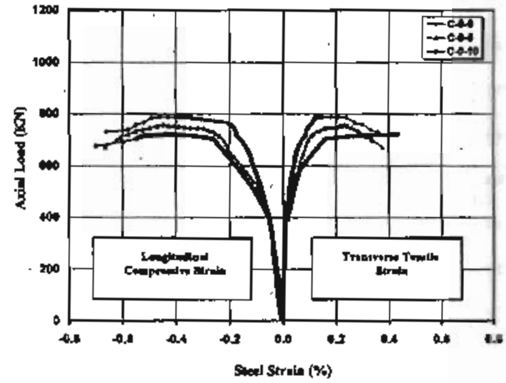

Fig. (17) Comparison of group (1)

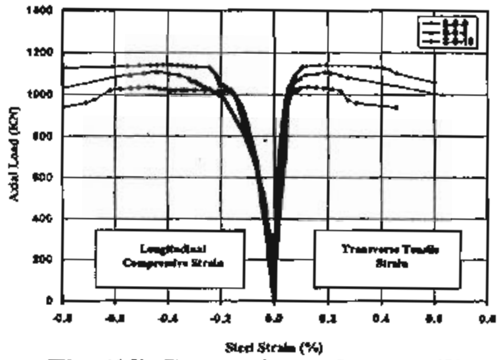

Fig. (18) Comparison of group (2)

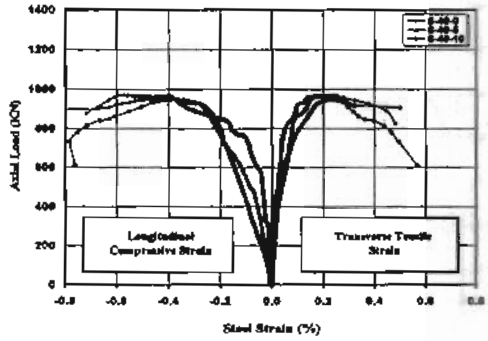

Fig. (19) Comparison of group (3)

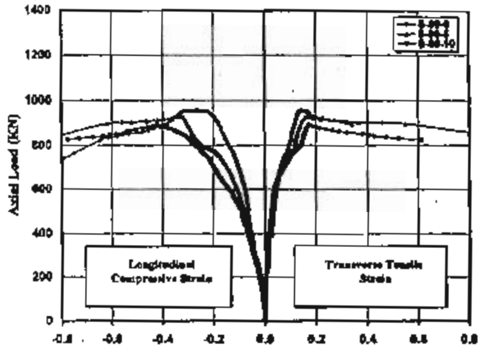

Fig. (20) Comparison of group (4)

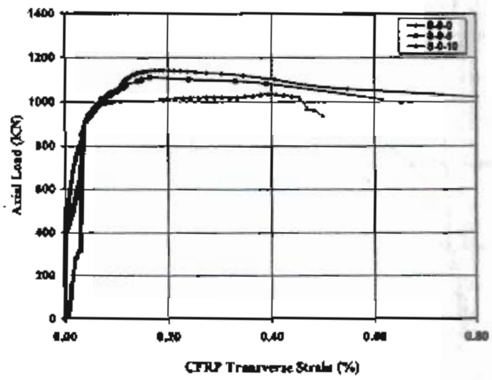

Fig. (21) Comparison of group (2)

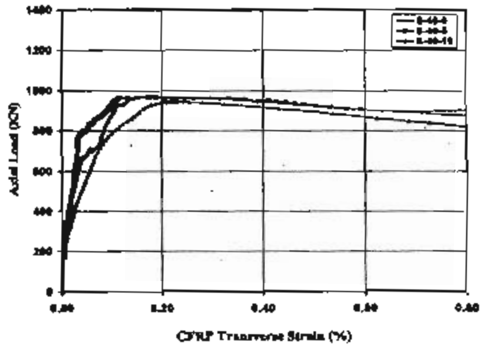

Fig. (22) Comparison of group (3)

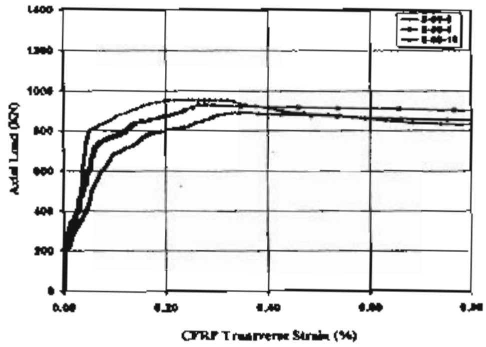

Fig. (23) Comparison of group (4)

CONCLUSIONS

Based on the test results and the discussions reported in this study, the following conclusions can be drawn:

1- The steel bars reached the yield strain before failure, which is due to the effect of the confinement provided by steel stirrups and **CFRP** sheets that increased the column capacity and the stress on the steel reinforcement.

2- The relationships between the applied load and both the longitudinal and transverse strains for concrete, steel, and **CFRP** was typical for all tested columns, a linear increase followed by a nonlinear relation until failure.

3- The slope of the first part of the plotted figures was almost the same, being slightly sharper when strengthening by wrapping **CFRP** sheets before applying any loads on the tested columns while the sharpness degree decreased when strengthening under loading (at 40% and 80% of the ultimate load during the test).

4- The ultimate loads decreased with the application and the increase of the lateral loads.

5- The relationships between the applied load and both the longitudinal and transverse strains for concrete, steel, and **CFRP** was typical for all tested columns, a linear increase followed by a nonlinear relation until failure.

6- The slope of the first part of the plotted figures was almost the same, being slightly steeper with the application of lateral loads.

7- The concrete longitudinal strains at ultimate loads decreased slightly with the application and the increase of the lateral loads.

8- The transverse strains measured in steel stirrups at ultimate loads were greater than the yield strain of stirrups steel and increased slightly with the application of lateral loads.

9- The measured transverse strains on the **CFRP** sheets at ultimate loads were less than the maximum tensile strain of the **CFRP** sheets and increased slightly with the application of lateral loads.

REFERENCES

[1] **ACI Committee 440,** "Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures," ACI 440.XR (to replace 440R), To TAC Denver 11/06.

[2] **ISIS Educational Module 6,** "Application and handling of FRP reinforcements for concrete," Prepared by ISIS Canada, A Canadian Network of Centres of Excellence, March, 2006.

[3] **Kaluarachchi DM.,** "Performance of repaired axially-loaded members," MEng thesis, National University of Singapore, Singapore, 1997.

[4] **Maalej, M., Tanwongsval, S., and Paramasivam, P.,** "Modelling of rectangular RC columns strengthened with FRP," Cement & Concrete Composites 25 (2003) 263–276.

[5] **Mansour, M. M. H.,** "Repair Of Reinforced Concrete Beams Under Flexural Loading," PhD thesis, Zagazig University, Faculty of Engineering, 2005.