Efficiency of CFRP wrapping on RC columns under concentric and eccentric loading

Said M. Allam and Tarek I. Ebeido
Structural Eng. Dept., Faculty of Engineering, Alexandria University, Alexandria, Egypt

The behaviour of reinforced concrete columns wrapped using Carbon Fiber Reinforced Polymer (CFRP) sheets is studied in this paper. An experimental program was conducted including testing twenty two reinforced concrete columns having the same slenderness ratio but different cross sectional shapes and dimensions. Tested columns were divided into two main groups. In the first group, ten columns were tested under monotonic concentric loading. The effects of cross sectional shape and rectangularity ratio on the efficiency of CFRP wrapping in enhancing column behaviour were investigated. In the second group, the effect of load eccentricity ratio on the efficiency of CFRP wrapping in enhancing the behaviour of circular and square columns was studied. Test results showed that using CFRP wrapping greatly enhanced the ultimate load capacity and ductility of reinforced concrete columns subjected to concentric loads. The maximum enhancement observed was in the case of circular columns. Less enhancement was obtained in the case of square columns. However, the efficiency of CFRP decreased dramatically in the case of rectangular columns, especially for columns having large rectangularity ratio. Furthermore, in the case of reinforced concrete columns subjected to eccentric loads using CFRP enhanced both the ultimate load capacity and ductility of columns. Such enhancement decreases with the increase in the eccentricity ratio. Finally, based on a theoretical study a method is proposed to predict the ultimate load capacity of reinforced concrete columns wrapped with CFRP. Results obtained from the proposed method showed excellent correlation with the experimental results.

يقدم هذا البحث دراسة معملية لسلوك الأعمدة الملفوفة بألياف الكربون وذلك من خلال برنامج معملي يتضمن اختبار عدد اثنان وعشرون عينة من أعمدة من الخرسانة المسلحة لها نفس نسبة الارتفاع إلي العرض ولكن بقطاعات عرضية ذات أشكال ونسب استطالة مختلفة وذلك من خلال مجموعتين رئيسيتين. المجموعة الأولي تناولت تأثير كل من تغير شكل قطاع العمود و كذلك نسبة استطالته علي كفاءة التقوية المستفادة من الإحاطة بألياف الكربون وذلك تحت تأثير الأحمال المحورية بينما تناولت المجموعة الثانية دراسة تأثير لامحورية التحميل علي سلوك كل من الأعمدة الدائرية والمربعة المقواه بألياف الكربون في جانب الشد الي جانب الإحاطة أيضا بألياف الكربون. وقد أظهرت النتائج المعملية أن الإحاطة الخارجية بألياف الكربون للأعمدة الخرسانية المسلحة يؤدي الي تحسين كل من الحمل الاقصي و الممطولية لهذه الأعمدة وذلك تحت تأثير الأحمال المحورية و أن العمود الدائري يعطي أعلي النتائج في هذا التحسن مقارنة بالأعمدة ذات القطاع المربع والقطاع المستطيل وأن زيادة درجة الإستطالة في الأعمدة تؤدي الي الإنخفاض الكبير في درجة هذا التحسن. بالنسبة للأعمدة الدائرية و الأعمدة المربعة فقد أظهرت النتائج أيضا أن هناك تحسنا في كل من الحمل الاقصي والممطولية ناتجة من الإحاطة بألياف الكربون وذلك تحت تأثير الحمل اللامحوري وأن هذا التحسن يقل مع زيادة درجة اللامحورية. اخيرا و بناء علي دراسه نظريه تم اقتراح طريقه لحساب الحمل الاقصي للاعمده الخرسانيه المسلحه الملفوفه بالياف الكربون. و قد كانت نتائج الطريقه المقترحه متوافقه بصوره ممتازه مع النتائج المعمليه.

Keywords: CFRP wrapping, Reinforced concrete, Columns, Concentric loading, Eccentric loading

1. Introduction

The technique of external confinement of existing reinforced concrete columns to improve their strength and ductility has attracted many researchers in the last few decades. Several methods have been proposed for the external confinement of columns such as the conventional methods of using external reinforced concrete jacket [1] or grout-injected steel jacket. These two conventional methods can enhance the axial capacity of the original column. However, the use of external reinforced concrete jacket causes a passive confinement whereas the use of grout-injected steel jacket causes an active one. Recently,

Alexandria Engineering Journal Vol. 41 (2002), No. 3, 499-512
© Faculty of Engineering Alexandria University, Egypt.

the application of circumferential wrapping with Fiber Reinforced Polymers (FRP) as a new technique for external confinement of reinforced concrete columns has been widely used [2-8]. Such technique is relatively easy to apply in comparison to conventional methods. These composite wraps are thin, light, flexible, non-corrosive, and can be easily applied to columns with any shapes using suitable epoxies [2].

Extensive experimental studies were found in the literature which considered the use of FRP composites to upgrade concrete columns. Through these investigations the external confinement was achieved either by direct external wrapping [2-6] or by using concrete filled FRP tubes [7 and 8]. Also, comparisons were made between using carbon fiber or glass fiber composite materials. Such comparisons revealed that carbon fiber has a greater energy-absorbing capacity than that of glass fiber. This results in an increase in the ultimate axial load capacity and ductility for columns wrapped with carbon fiber than that wrapped with the same volume of straps of glass fiber [9].

Through previous investigations several parameters were studied such as: column cross-sectional shape; column length-to-diameter ratio; concrete strength; longitudinal steel reinforcement percent; effect of corner radius in the case of non-circular columns; and number of FRP layers. From these investigations the following conclusions were drawn: (i) the effect of FRP is less significant in the case of square columns than that in the case of circular ones [8]; (ii) for FRP wrapped columns the effect of changing the length-to-diameter ratio within the range between 2:1 and 5:1 is not significant on either strength or ductility of column [8]; (iii) both concrete strength and concrete damage affect the axial strength of wrapped columns due to the change in concrete modulus of elasticity [2]; (iv) the variation in the longitudinal steel reinforcement percent or in the volume of stirrups with moderate spacing has a marginal effect on the axial strength of wrapped columns [2]; (v) the efficiency of FRP wrapping increases significantly with an increase in the ratio of radius of corner to side length for both square and rectangular columns [4]; and, (vi) an excessive confinement of columns using large numbers of FRP layers leads to a very sudden and destructive failures [4].

Recently, the behavior of FRP wrapped reinforced concrete columns subjected to eccentric loads was investigated [6]. In this study, columns having square cross-section were considered. However, the columns had very small dimensions (108x108x305 mm). Also, the eccentricity ratios used were very small ($e/h = 0.07$ and 0.14). The study concluded that the efficiency of FRP wrapping technique is reduced in the case of columns subjected to eccentric loads. Furthermore, it was recommended in the study that more research should be conducted in the case of columns subjected to eccentric loads.

The theoretical studies found in the literature regarding the confinement of concrete columns using FRP composites have concentrated on circular columns and several stress-strain models were proposed [9-13]. Very little theoretical studies considered modeling of non-circular columns [14]. All proposed models were mainly based on the equilibrium between the tendency of concrete to dilate and the volumetric strain of the wrapping material. The finite element method was also applied to model reinforced concrete columns wrapped with FRP composites [15].

The above presented summarized literature review revealed that some important aspects regarding the effect of FRP wrapping on the behavior of reinforced concrete columns are not well covered. The previous investigations have concentrated on circular columns rather than square or rectangular ones. The effect of column cross section rectangularity ratio on the efficiency of FRP wrapping was not clearly evaluated. Furthermore, the effect of FRP wrapping on the behavior of columns subjected to eccentric loads was studied only considering very small values of eccentricity ratio.

In this paper, an experimental study was conducted on reinforced concrete columns wrapped with Carbon Fiber Reinforced Polymer sheets (CFRP). Columns with circular, square, and rectangular cross-sections were considered in the study. For rectangular columns the effect of rectangularity ratio on the efficiency of CFRP wrapping in enhancing column behavior was studied. Through the experimental study columns were tested under the effect of either concentric or eccentric loads. The eccentricity ratio was varied in order to study the effect of such ratio on the efficiency of CFRP wrapping. Furthermore, based on a theoretical study a simplified method was proposed to predict the ultimate load capacity of reinforced concrete columns wrapped with CFRP.

2. Experimental study

The main objective of the experimental study conducted in this paper was to study the effect of column cross-sectional shape and rectangularity ratio on the efficiency of CFRP wrapping in enhancing reinforced concrete columns behavior. Another important objective of the experimental study was to investigate the behavior of CFRP wrapped reinforced concrete columns with different shapes subjected to eccentric loads. The details of the experimental program conducted will be presented in the following sections.

2.1. Column details

Twenty two reinforced concrete columns were tested in the experimental program. All columns had a total length of 1300 mm. The clear length was 1000 mm and the columns were provided with two end heads each of 150 mm length. The cross-sectional dimensions of column heads were greater than that for the column cross-section by 70 mm from all sides. The objective of providing columns with end heads was to prevent premature local failure at column ends.

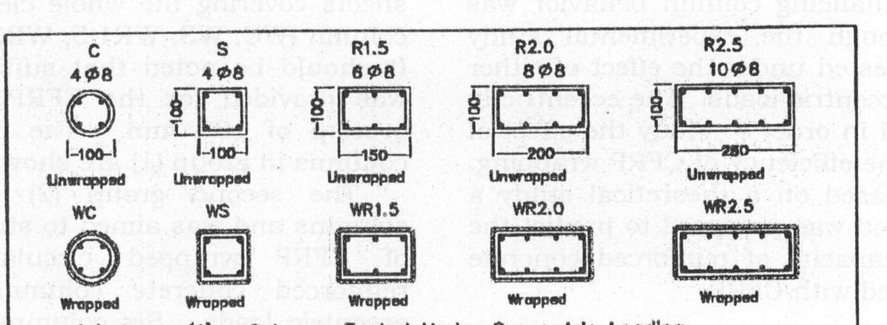
Tested columns were divided into two main groups. The first group (1) included ten columns and was directed to study the effect of column cross-sectional shape and rectangularity ratio on the efficiency of CFRP wrapping in enhancing column behavior in the case of concentric loads. Five columns were tested in their original condition without CFRP wrapping (C, S, R1.5, R2.0, and R2.5). In order to detect the effect of CFRP wrapping five similar columns were tested after circumferential wrapping with a single layer of unidirectional carbon fiber reinforced polymer sheets covering the whole clear height of the column (WC, WS, WR1.5, WR2.0, and WR2.5). It should be noted that sufficient anchorage was provided for the CFRP wraps with an overlap of 100 mm. The details of tested columns in group (1) are shown in fig. 1-a.

The second group (2) included twelve columns and was aimed to study the behavior of CFRP wrapped circular and square reinforced concrete columns subjected to eccentric loads. Six columns were tested in their original condition without CFRP wrapping (ECO.125, ECO.25, ECO.50, ESO.125, ESO.25, and ESO.50). Six similar columns having the same dimensions and reinforcement details (WECO.125, WECO.25, WECO.50, WESO.125, WESO.25, and WESO.50) were tested but after wrapping with CFRP sheets in the same manner explained for group (1). However, for these columns in group (2) before applying the circumferential wraps CFRP sheets were also applied at the column tension side in the longitudinal direction covering the whole clear height of the column. The width of this layer was 100 mm. The eccentricity ratios considered were e/h = 0.125, 0.25, and 0.5. The details of tested columns in group (2) are shown in fig. 1-b.

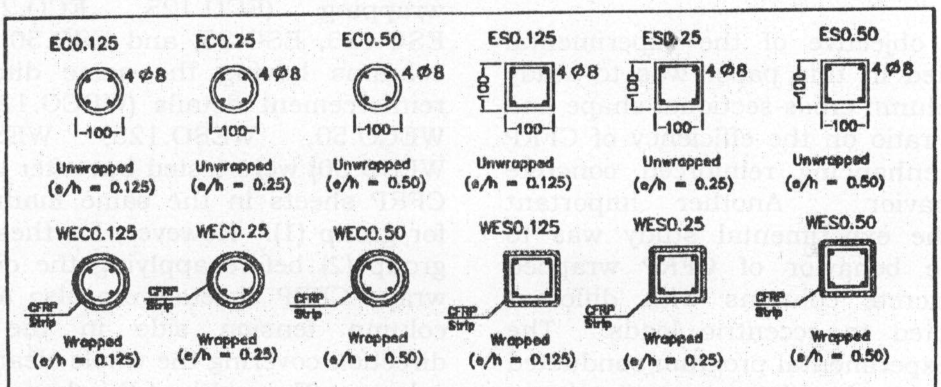
All tested columns were reinforced in the longitudinal direction using 8 mm diameter bars of mild steel. The number of longitudinal bars were varied according to column cross sectional area and the longitudinal reinforcement percent was fixed for all tested columns at 2%. All tested columns were provided with lateral stirrups of diameter 6 mm mild steel (see fig. 1-c).

2.2. Materials

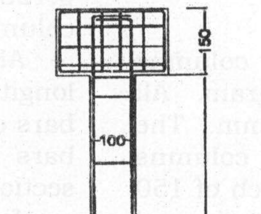
The concrete mix used for all tested columns consisted of ordinary Portland cement, natural sand, and broken stones with 20 mm maximum size , and the mix proportions were 1.0: 1.6: 2.55, respectively by weight. The water cement ratio w/c was in the range of 0.4. In order to determine concrete strength standard cubes 150x150x150 mm were cast from each concrete batch. These cubes were tested in the same day of testing the corresponding column.



(a) Group (1) : Columns Tested Under Concentric Loading



(b) Group (2) : Columns Tested Under Eccentric Loading



(c) Long. section

(All Dimensions are in MM)

Fig. 1. Details of tested columns.

The average concrete cube compressive strength was 35 MPa. The 8 mm diameter bars mild steel used as longitudinal reinforcement for tested columns had a yield and ultimate strength of 250 and 400 MPa, respectively. The 6 mm diameter bars mild steel used as lateral stirrups for tested columns had a yield and ultimate strength of 235 and360 MPa, respectively.

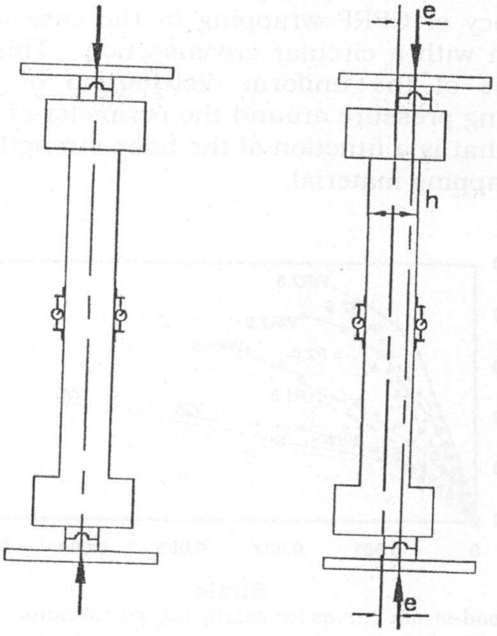
The high strength carbon fiber reinforced polymer sheets (CFRP) used for wrapping columns were supplied by Sika Egypt under the commercial name (Sikawrap Hex-230C). The thickness of the CFRP sheets was 0.13 mm. The tensile strength and modulus of elasticity of CFRP sheets were 3500 and 230000 MPa, respectively. It should be noted that these mentioned properties of the CFRP sheets were taken from the product data sheet provided by Sika Egypt company.

2.3. Columns preparation, instrumentation, and loading setup

After casting, columns were kept in room temperature and cured for 28 days. Then the application of CFRP wrapping was performed. Column surfaces were first roughened thoroughly using mechanical metallic brush and then were cleaned using compressed air in order to remove any dust from concrete surface. Following that, two-component epoxy adhesive (Sikadur 330) was mixed according to the proportions recommended by the manufacturer. The epoxy adhesive mix was then applied on the cleaned concrete surface of columns, and the CFRP sheets were applied on top of the epoxy adhesive layer. The CFRP sheets were pressed against the concrete surface, and then another layer of epoxy adhesive was applied on top of the CFRP sheets. After the application of CFRP sheets, columns were left for two weeks before testing in order to ensure that the epoxy adhesive gained its full strength.

For all tested columns, longitudinal strain was measured at the column mid height. This was done by using mechanical dial gauges with travel sensitivity of 0.01 mm. The strains were measured at both two opposite sides of the column as shown in fig. 2. The gauge length was 105 mm. The axial strain was then calculated by dividing the change in the dial gauge reading by the gauge length.

All columns were tested using a 3000 kN capacity universal testing machine. In order to allow column ends to rotate freely, two plates were placed between the column end and the testing machine platen. As shown in fig. 2, one of the two plates was made with a spherical surface whereas the second plate was made with a spherical groove, thus allowing free rotation between the two plates.



(a) Concentric Loading

(b) Eccentric Loading

Fig. 2. Loading set-up.

3. Test results and discussions

Test results including ultimate load capacity and the corresponding stain at ultimate load are presented in tables 1 and 2 for concentrically and eccentrically loaded columns, respectively. The relationships between load and axial strain for concentrically loaded columns are shown in fig. 3. The load- compressive strain relationships are presented in figs. 4 and 5 for eccentrically loaded circular and square columns. Failure modes of all tested columns are presented in figs. 6 and 7.

3.1. Ultimate load capacity

The ultimate load capacity is presented in table 1 for all columns in group (1) that were tested under concentric loads. The table also presents the percent enhancement in the ultimate load capacity for columns wrapped with CFRP sheets over those for corresponding unwrapped columns. It can be observed from the results that the maximum enhancement was obtained in the case of a column having a circular cross section (column WC compared to C). Such maximum enhancement in the ultimate load capacity reflects the great efficiency of CFRP wrapping in the case of a column with a circular cross-section. This is because of the uniform distribution of the confining pressure around the perimeter of the circle that is a function of the hoop strength of the wrapping material.

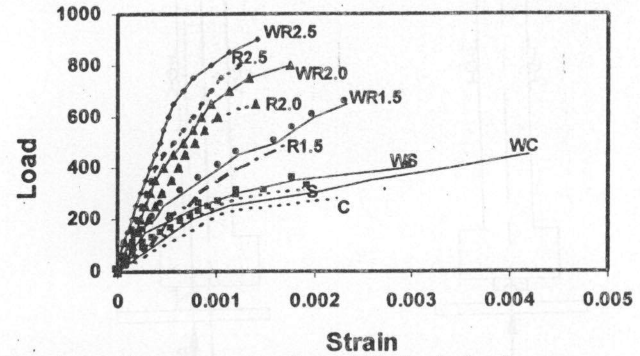


Fig. 3. Load-strain curves for axially loaded columns.

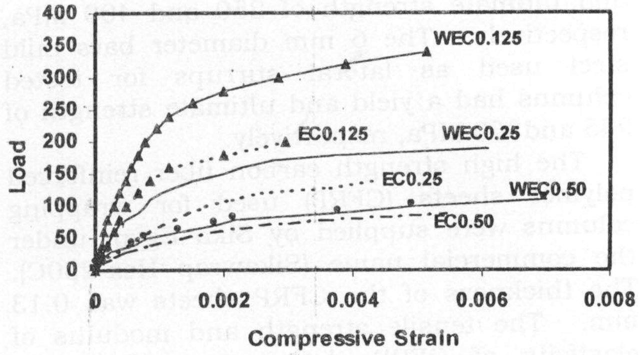


Fig.4. Load versus compressive strain for circular columns with different eccentricity ratios.

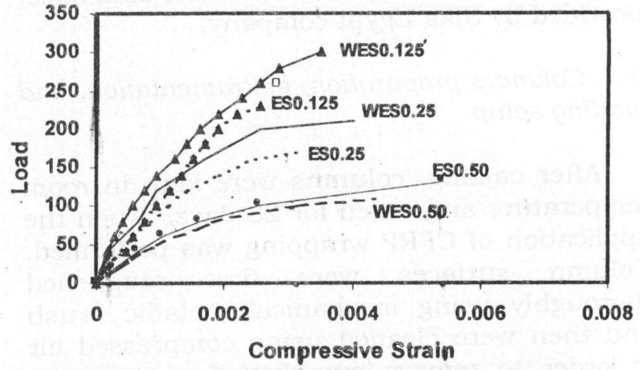
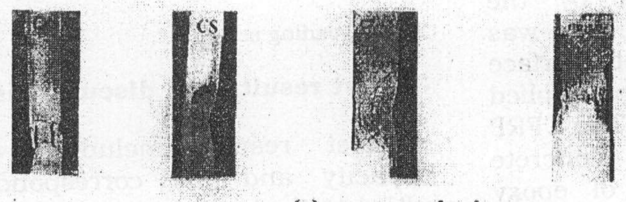
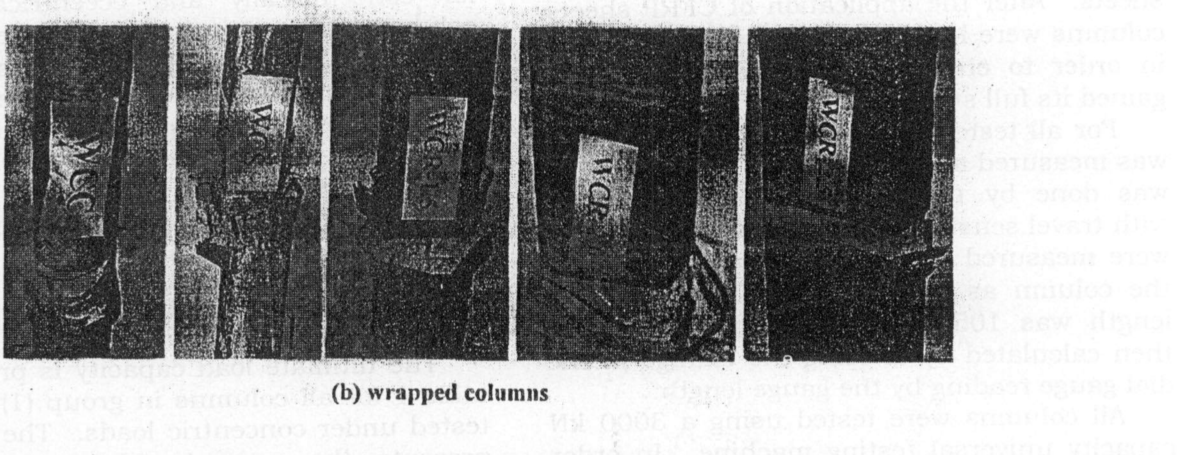


Fig. 5. Load versus compressive strain for square columns with different eccentricity ratios.

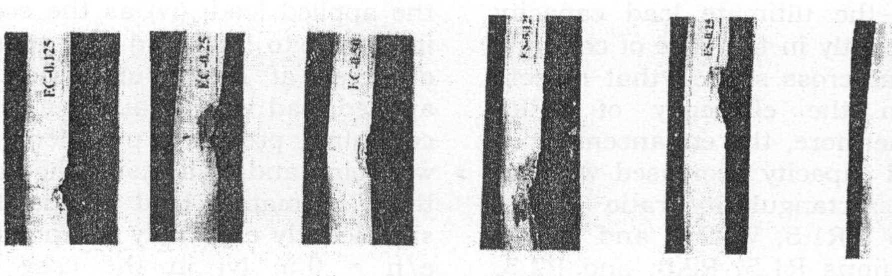


(a) unwrapped columns

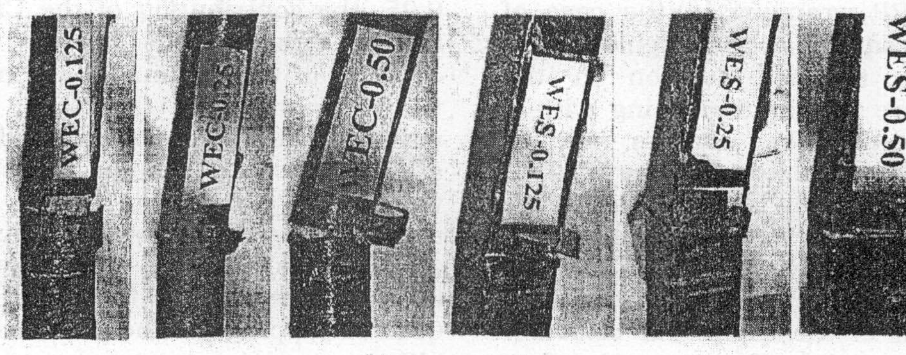


(b) wrapped columns

Fig. 6. Failure modes of columns tested under concentric loading.



(a) unwrapped columns



(b) wrapped columns

Fig. 7. Failure modes of columns tested under eccentric loading.

Table 1
Experimental results for columns tested under concentric loading

Column	Ultimate load (P_u) (kN)	Axial strain at ultimate load (ε_{cu})	Enhancement in the ultimate load (P_u) (%)	Increase in the axial strain at ultimate load(ε_{cu}) (%)
C	280	0.00224	--	--
S	320	0.00195	--	--
R1.5	470	0.00171	--	--
R2.0	650	0.00140	--	--
R2.5	800	0.00120	--	--
WC	480	0.00419	71	87
WS	460	0.00300	44	54
WR1.5	610	0.00233	30	36
WR2.0	800	0.00176	23	26
WR2.5	950	0.00145	19	21

However, less enhancement in the ultimate load capacity was obtained in the case of a column having a square cross-section (column WS compared to S). The enhancement in the ultimate load capacity decreased significantly in the case of columns having rectangular cross section that reflects the decrease in the efficiency of CFRP wrapping. Furthermore, the enhancement in the ultimate load capacity decreased with an increase in the rectangularity ratio of the column (columns WR1.5, WR2.0, and WR2.5 compared to columns R1.5, R2.0, and R2.5, respectively). This significant decrease in the efficiency of CFRP wrapping in the case of columns having square or rectangular cross sections is due to the variation in the confining pressure distribution being with a maximum value at the corners and a minimum value between edges. The dilation of concrete during loading results in a passive pressure from wrapping material that causes confinement to the cross section. The confining pressure at the corners is due to the membrane action in the transverse direction of wrapping material. However, at other points the confining pressure depends on the flexural rigidity of wrapping material.

Table 2 shows the ultimate load capacity for circular and square columns in group (2), tested under eccentric loads. The table also presents the percent enhancement in the ultimate load capacity for columns wrapped with CFRP sheets in comparison to those for corresponding unwrapped columns. It should be noted that in this case of eccentrically loaded columns, wrapped columns were also strengthened with another layer of CFRP sheets at the column side far from the applied load (tension side). Examining the results presented in table 2, the following can be observed: (i) the efficiency of CFRP wrapping is greater in the case of circular columns than that in the case of square columns; (ii) the enhancement in the ultimate load capacity due to CFRP wrapping decreased with the increase in the eccentricity ratio, for both circular and square columns; (iii) the maximum enhancement in the ultimate load capacity is observed in the case of least eccentricity ratio e/h = 0.125, for both circular and square columns. At this eccentricity ratio a triangular compressive strain distribution was observed with a maximum value at the column side near to the applied load and a value nearly equals to zero at the side far from the applied load; (iv) as the eccentricity ratio increased to 0.25 and 0.5, tensile strain was observed at the column side far from the applied load which caused a reduction in the confining pressure provided by the CFRP wrapping and as a result the enhancement in the ultimate load capacity decreased significantly especially at an eccentricity ratio e/h = 0.5; (v) in the case of small and moderate eccentricity ratio e/h = 0.125 and 0.25, the contribution of the CFRP wrapping to the enhancement in the ultimate load capacity of the column is much greater than the contribution of the CFRP strengthening sheet attached to the column side far from the applied load; and (vi) in the case of higher values of eccentricity ratio e/h = 0.5, significant tensile strain was observed at the column side far from the applied load which led to a decrease in the contribution of the CFRP wrapping to the enhancement in the ultimate load capacity of the column and also an increase in the contribution of the CFRP strengthening sheet attached to the column side far from the applied load.

3.2. Load-strain behavior and ductility

Fig. 3 shows load-axial strain relationships for all columns in group (1), tested under concentric loads. The effects of column cross-sectional shape and the rectangularity ratio on the load strain behavior are presented over the complete range of loading up to the column failure. It can be observed from the figure that for all tested circular, square, and rectangular columns, the load strain relationship is always linear up to a certain point at which a non linear relationship takes place up to failure. This was observed for both cases of unwrapped and wrapped columns. Moreover, it is seen from the figure that as the cross sectional area becomes larger, the strain at a given load decreases significantly although the ultimate load capacity increases. This can be explained by the increase in the column stiffness as the cross sectional area increases. It can be also observed that the use of CFRP wrapping results in an increase in the axial strain at ultimate load for all tested columns which reflects an enhancement in the column ductility.

Table 2
Experimental results for columns tested under eccentric loading

Column	Eccentricity ratio (e/h)	Ultimate load, P_u (kN)	Compressive strain at ultimate load (ε_{cu})	Enhancement in the ultimate load, P_u (%)	Increase in the compressive strain at ultimate load , ε_{cu}(%)
EC0.125	0.125	200	0.00295	--	--
EC0.25	0.250	140	0.00433	--	--
EC0.5	0.500	90	0.00548	--	--
WEC0.125	0.125	330	0.00514	65	74
WEC0.25	0.250	190	0.00610	36	41
WEC0.50	0.500	110	0.00700	22	28
ES0.125	0.125	230	0.00257	--	--
ES0.25	0.250	170	0.00314	--	--
ES0.50	0.500	110	0.00438	--	--
WES0.125	0.125	310	0.00360	35	40
WES0.25	0.250	210	0.00405	24	29
WES0.50	0.500	130	0.00543	18	24

The values of axial strain at ultimate load are presented in table 1 for all columns in group (1), tested under concentric loads. The table also presents the percent increase in the strain at ultimate load for columns wrapped with CFRP sheets over that for the corresponding unwrapped columns. It can be observed from the results presented in the table that the maximum increase in the value of the strain at ultimate load as a result of CFRP wrapping was obtained in the case of columns having circular cross-section. However, less increase in the value of strain at ultimate load as a result of CFRP wrapping is observed in the case of columns having square and rectangular cross-sections. Furthermore, in the case of rectangular columns the increase in the values of strain at ultimate load is reduced as the rectangularity ratio increases.

These findings about the effect of CFRP wrapping on the axial strain at ultimate load can be explained by the fact that the increase in such axial strain is a function of the volumetric change in the wrapping material. This volumetric change depends on the lateral strain in the wrapping material. This lateral strain increases in the case of columns having a circular cross-section. However, in the case of square columns, the presence of straight sides results in a decrease in the lateral strain due to the stress concentration at corners. Furthermore, in the case of rectangular columns, the long straight sides results in a further decrease in the lateral strain due to the flexural behavior of wrapping material. It should be noted that the percent increase in the axial strain at ultimate load as a result of using CFRP wrapping is greater than the percent enhancement in the corresponding ultimate load capacity, as shown in table 1. This can be attributed to the energy dissipation through the elongation of the wrapping material during loading.

Figs. 4 and 5 show load-compressive strain relationships for both circular and square eccentrically loaded columns, respectively. The relationships show the effect of CFRP wrapping on the compressive strain behavior for tested columns with different eccentricity ratios. It should be noted that such compressive strain was measured at the mid height of the column side near to the applied load. Table 2 presents the values of the compressive strain at ultimate load for all columns tested under eccentric loads. The table also presents the percent increase in the strain at ultimate load for columns wrapped with CFRP sheets along with CFRP strengthening sheets at the column side far from the applied load over that for the corresponding unwrapped columns.

A comparison of the load strain behavior presented in the figures for unwrapped and wrapped circular and square columns revealed that: (i) the compressive strain for wrapped column is always smaller than that for the corresponding unwrapped column up to a load representing the ultimate load capacity of unwrapped column; (ii) comparing the compressive strain at ultimate load for unwrapped with that for corresponding wrapped column it can be seen that the presence of CFRP wrapping increased such strain and therefore the ductility of the column increased; (iii) this increase in the compressive strain at ultimate load is more significant in the case of circular columns than that in the case of square ones; and, (iv) the increase in the compressive strain at ultimate load due to CFRP wrapping became less significant as the eccentricity ratio increased. This is because when the eccentricity ratio increases the strain at the column side far from the applied load becomes a tensile one. The presence of such strain decreases the effect of confinement. Therefore, the increase in the strain at ultimate load and thus the column ductility decreased. At a high value of eccentricity ratio e/h = 0.5 the increase in the strain at ultimate load due to CFRP wrapping became marginal. In this case the increase in the compressive strain at ultimate load is only due to the presence of the CFRP strengthening sheet at the column face far from the applied load.

Generally, it can be concluded herein that the efficiency of CFRP wrapping in increasing the strain at ultimate load and hence the column ductility is only significant in the case of concentric loads or in the case of eccentric loads but with a small value of eccentricity ratio.

3.3. Failure modes

Fig. 6-a presents failure modes for unwrapped columns tested under concentric loads. Longitudinal cracks first formed within the middle third of the column height. This was followed by spalling of concrete cover. Finally concrete crushing occurred accompanied by buckling of longitudinal reinforcement bars. Such buckling always occurred within the bars unsupported length between the stirrups. However, for columns wrapped with CFRP sheets and tested under concentric loads different failure modes were observed as shown in fig. 6-b. First sounds were heard due to concrete microcracking and shifting of aggregates within the concrete inside the wrapping material. As the axial applied load further increased the confining pressure also increased until the lateral tensile stress in the CFRP sheets reached a value equals to its ultimate tensile strength. At this point, a sudden rupture of CFRP sheets took place that resulted in a sudden loss in the concrete confinement that led to an explosive crushing of the concrete core. It should be noted that for square and rectangular wrapped columns, the rupture of CFRP sheets was always observed at the corner of the column. This is due to the concentration of stresses at the corners.

Different failure modes were observed in the case of columns tested under eccentric loads. Fig. 7-a shows the failure modes of unwrapped columns. For the case of small value of eccentricity ratio e/h = 0.125, no cracks were observed during loading at the column side far from the load. At failure, explosive concrete crushing occurred at the column side near the load accompanied by outward bucking of longitudinal reinforcement bears. At, the column side far from the load, two cracks were observed at failure due to the overall buckling of column. In the case of eccentrically loaded columns with eccentricity ratio e/h 0.25 and 0.5, cracks formed at the column side far from the load at loads representing 80% and 35% of the ultimate load capacity, respectively. As the applied load increases cracks became wider, especially in the case of e/h = 0.5, until failure took place by concrete crushing at the column side near the load. It should be noted that the failure was ductile in the case of e/h = 0.5.

Fig. 7-b presents failure modes for eccentrically loaded CFRP wrapped columns. It was observed that in the case of eccentricity ratio e/h = 0.125, the failure mode was similar to that in the case of concentrically loaded columns. This is because of the linear grading of compressive stress that covered the whole section due to the small value of eccentricity ratio. In the case of eccentrically loaded columns with eccentricity ratio 0.25, the cross-sectional stress distribution changed and the stress at the column side far from the load became tensile one but with a small value. At the point when the lateral stress in the wrapping material reached a value equals to its ultimate tensile strength, a simultaneous rupture was observed in both the CFRP lateral wrapping sheets and also in the longitudinal CFRP strengthening sheet attached to the column side far from the load. The rupture of CFRP sheets was accompanied by concrete crushing at the column side near the load but was less explosive than that in the case of eccentricity ratio e/h = 0.125.

In the case of eccentrically loaded columns with large eccentricity ratio e/h = 0.5, the tensile stress at the column side far from the load became larger which resulted in a dramatic reduction in the confinement induced by wrapping and led to a quick early rupture of CFRP sheets. However, the failure in this case was not explosive.

4. Theoretical study

The objective of the theoretical study was to develop a reliable simplified method for predicting the ultimate load carrying capacity of reinforced concrete columns wrapped with CFRP sheets and subjected to concentric loads. The ultimate load capacity for any reinforced concrete column subjected to concentric load according to the definitions of the stress-strain curves of both concrete and steel, given by the Egyptian code of practice [17], can be expressed in the form of;

$$P_u = 0.67 f_{cu} A_c + A_s f_y , \tag{1}$$

where:

P_u is the ultimate load capacity of the column;

f_{cu} is the characteristic concrete cube compressive strength;

f_y is the yield strength of longitudinal steel reinforcement:

A_c is the cross-sectional area of column; and

A_s is the area of steel reinforcement.

The presence of stirrups in the column increases the ultimate load capacity of the column due to the confinement provided by the stirrups to the concrete core. The degree of confinement provided depends on the volumetric ratio of stirrups [16]. Introducing the effect of confinement provided by the stirrups, eq. (1) can be rewritten in the form of;

$$P_u = 0.67(f_{cu} + f_{cst}) A_c + A_s f_y , \tag{2}$$

where:

f_{cst} is the the increase in the concrete strength induced by the confinement provided by the stirrups. Such stress increase can be expressed in the following form;

$$f_{cst} = \frac{\rho_{st} f_{yst} A_{co}}{A_c} , \tag{3}$$

where:

ρ_{st} is the volumetric ratio of stirrups and can be defined as the ratio between the volume of stirrups to the volume of concrete;

f_{yst} is the yield strength of steel reinforcement used for the stirrups; and

A_{co} is the area of concrete core located within the stirrups.

In the case of wrapped columns, the confinement provided by the wrapping material results in an increase in the ultimate load capacity of the column. In this case the effect of internal stirrups becomes marginal and can be ignored. The ultimate load capacity of the column can be written in this case in the form of;

$$P_u = 0.67(f_{cu} + f_{cf}) A_c + A_s f_y , \tag{4}$$

where:
f_{cf} is the increase in the concrete strength induced by the confinement provided by the wrapping material. Such increase in the concrete strength is proposed herein to be expressed in the following form;

$$f_{cf} = \alpha \, \rho_f \, f_{tf} , \qquad (5)$$

where:
ρ_f is the volumetric ratio of wrapping material which can be defined as the ratio between the volume of wrapping material to the volume of concrete;
f_{tf} is the ultimate tensile strength of wrapping material; and α = column cross-sectional shape factor;

Using test results from the experimental program conducted in this paper it was found that shape factor α can be taken equals to 2.0 in the case of any column with a circular cross-section. Also, the shape factor α can be taken equals to 1.0 in the case of any column having a square or rectangular cross-section.

Table 3 shows a comparison of the ultimate load capacity obtained from the current test program for wrapped reinforced concrete columns and those obtained theoretically using the proposed eq. (4). Excellent agreement can be observed between the experimental and theoretical results with an error not exceeding 5%.

The proposed simplified theoretical method developed is reliable since it takes into account all the important parameters affecting the ultimate load capacity of wrapped reinforced concrete columns. These parameters are: (i) the concrete cube compressive strength; (ii) the effect of longitudinal steel reinforcement; (iii) the volumetric ratio of wrapping material ρ_f; and (iv) the column cross-sectional shape in terms of a proposed shape factor α. Furthermore, since the proposed method is in terms of the volumetric ratio of wrapping material, therefore it can be applied whether the wrapping material covers the whole column height or it is applied on the form of separate strips. Also, the method can be applied for any wrapping material since it takes into account the tensile strength of such material.

Results not shown herein for brevity revealed that the theoretical predictions for the ultimate load capacity of wrapped reinforced concrete columns obtained using the proposed method are also in good agreement with test results from several experimental studies found in the literature. The proposed method was examined for wrapped columns having different slenderness ratios, and the results showed the reliability of such method in predicting the ultimate load capacity of any column as long as it considered to be a short one.

5. Summary and conclusions

Experimental and theoretical studeis were conducted in this paper. The experimental program included testing twenty two columns in order to investigate the effect of column cross-sectional shape and rectangularity ratio on the effeciency of CFRP wrapping in enhancing reinforced concrete columns behavior. Also, the behavior of CFRP wrapped reinforced concrete columns subjected to eccentric loads was investigated. In the theoretical study a simplified method was proposed which permits predicting the ultimate load capacity of wrapped reinforced concrete columns with any shape. Based on the results presented in this paper, the following conclusions can be drawn:

1-Generally, the use of CFRP sheets in wrapping reinforced concrete columns significantly enhances the column behavior since it increases the ultimate load capacity and also increases the strain at ultimate load which reflects ductility enhancement.

2-The effeciency of using CFRP sheets in enhancing column bahavior was greater in the case of circular columns than that in the case of square or rectangular columns. This can be attributed to the uniform distribution of the confining pressure around the perimeter of the circular column. In the case of square or rectangular column a variation in the confining pressure distribution is found having a maximum value at the corners and a minimum value between edges.

Table 3
Comparison between experimental ultimate load capacity of wrapped columns and theoretical ones from the proposed method

Column	Experimental ultimate load capacity, $(P_u)_{exp}$ (kN)	Theoretical ultimate load capacity*, $(P_u)_{the}$ (kN)	Error** (%)
WC	480	490	-2
WS	460	437	5
WR1.5	610	610	0.0
WR2.0	800	782	2
WR2.5	950	955	-0.01

* theoretical values were obtained using proposed eq.(4)
** Error = $[(P_u)_{exp}-(P_u)_{the}] \,/\, (P_u)_{exp}$

3- In the case of rectangular columns both the enhancement in the ultimate load capacity and the increase in the strain at ultimate load as a result of CFRP wrapping decreases significantly with an increase in the column rectangularity ratio.

4- For both circular and square columns, the efficiency of CFRP wrapping in enhancing column behavior decreases with the increase in the eccentricity ratio. This can be explained by the fact that in the case of eccentric load the compressive strain at the column side far from the applied load decreases and as the eccentricity ratio increases such strain becomes a tensile one. The presence of tensile strain decreases the effect of confinement. Therefore, CFRP wrapping can be used in the case of eccentric loads provided that the section is completely under compressive strain.

5- The proposed simplified theoretical method developed is reliable since it takes into account all the important parameters affecting the ultimate load capacity of wrapped columns. The method can be applied whether the wrapping material covers the whole column height or it is applied as separate strips. Also, the method can be applied for any wrapping material since it takes into account the tensile strength of such material.

6- The proposed method is reliable in predicting the ultimate load capacity of a wrapped column having any slenderness ratio as long as it can be considered to be a short column.

Acknowledgements

The test program in this paper was carried out during 2001 at the Reinforced Concrete Research Laboratory, Alexandria University. The authors would like to thank all the technicians of the laboratory for their helpful assistance in the preparation and testing the columns.

References

[1] U. Erosy, A. T. Tankut, and R. Suleiman "Behavior of Jacketed Columns", ACI Structural Journal, Vol. 90 (3), pp.288-293 (1993).

[2] M. Demers and K.W. Neale, "Confinement of Reinforced Concrete Columns with Fiber-Reinforced Composite Sheets-an Experimental Study" Canadian Journal of Civil Engineering, Vol. 26, pp. 226-241 (1999).

[3] B.K. Purba and A.A. Mufti, "Investigation of the Behaviour of Circular Concrete Columns Reinforced with Carbon Fiber Reinforced Polymer (CFRP) Jackets", Canadian Journal of Civil Engineering, Vol. 26, pp. 590-596 (1999).

[4] P. Rochette and P. Labossiere, "Axial Testing of Rectangular Column Models Confined with Composites ", Journal of Composite for Construction, ASCE, Vol. 4 (3), pp. 129-136 (2000).

[5] S Pessiki, K. A. Harries, J. T. Kestner, R. Sause, and J. M. Ricles, "Axial

Behaviour of Reinforced Concrete Columns Confined With FRP jackets", Journal of Composite for Construction, ASCE, Vol. 5 (4), pp.237-245 (2001).

[6] A. Parvin and W. Wang, "Behaviour of FRP Jacketed Concrete Columns Under Eccentric Loading", Journal of Composite for Construction, ASCE, Vol 5 (3), pp.146-152 (2001).

[7] A. Mirmiran and M. Shahawy, "Behaviour of Concrete Columns Confined by Fiber Composites", Journal of Structural Engineering, ASCE, Vol. 123 (5), pp. 583-590 (1997).

[8] A. Mirmiran, M. Shahawy, M Samaan, H. El Echary, J. C. Mastrapa, and O. Pico "Effect of Column Parameters on FRP-Confined Concrete", Journal of Composite for Construction, ASCE, Vol. 2 (4), pp. 175-185 (1998).

[9] H Saadatmanesh, M. R. Ehsani, and M. W. Li, "Strength and Ductility of Concrete Columns Externally Reinforced with Fiber Composite Straps", ACI Structural Journal Vol. 91 (4), pp. 434-447 (1994).

[10] H.A. Toutanji "Stress-Strain Characteristics of Concrete Columns Externally Confined with Advanced Fiber Composite Sheets" ACI Structural Journal Vol. 96 (3), pp. 397-404 (1999).

[11] M. Saafi, H.A. Toutanji, and Z. Li "Behaviour of Concrete Columns Confined with Fiber Reinforced Polymer Tubes" ACI Structural Journal Vol. 96 (4), pp. 500-509 (1999).

[12] M.R. Spoelstra and G. Monti "FRP-Confined Concrete Model" Journal of Composite for Construction, ASCE, Vol 3 (3), pp. 143-150 (1999).

[13] A.Z. Fam and S.H. Rizkalla, "Confinement Model for Axially Loaded Concrete Confined by Circular Fiber-Reinforced Polymer Tubes" ACI Structural Journal Vol. 98 (4), pp. 451-461 (2001).

[14] Y.C. Wang and J.I. Restrepo, "Investigation of Concentrically Loaded Reinforced Concrete Columns Confined with Glass Fiber-Reinforced Polymer Jackets", ACI Structural Journal Vol. 98 (3), pp. 377-385 (2001).

[15] S. Parent and P. Labossiere, "Finite Element Analysis of Reinforced Concrete Columns Confined with Composite Materials" Canadian Journal of Civil Engineering, Vol. 27, pp. 400-411 (2000).

[16] J. Hoshikuma, K. Kawashima, K. Nagaya, and A. W. Taylor, "Stress-Strain Model for Confined Reinforced Concrete in Bridge Piers" Journal of Structural Engineering, ASCE, Vol. 123 (5), pp. 624-633 (1997)

[17] Ministry of Housing, "Building Code Requirements of Reinforced Concrete Structures ECP", Cairo, Egypt (2000).

Received May 7, 2002
Accepted June 30, 2002