Rehabilitation of eccentrically loaded reinforced concrete columns using CFRP Products

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Abstract. This study covered the impact of CFRP wrap on pre-damaged reinforced concrete (RC) columns. A total of Ten reinforced concrete columns were made of normal strength concrete, and eight of them were strengthened with CFRP, and all these specimens tested under eccentric loading with two ratios of eccentricity (e/h=0.5 and e/h=0.8). The main parameters in this study included strengthening scheme, pre damaged condition, and the ratio of eccentricity. The failure modes, applied load-displacement curves, ductility index, and the stiffness were analysed. The results showed that the ultimate load capacity and ductility of specimens were improved and increased by using CFRP wrap around the specimens. In addition, the best strengthening scheme has been suggested.

Keywords: CFRP Composite; RC Columns; Repairing; Strengthening; Eccentric loading.

1. Introduction
Reinforced concrete (RC) columns are one of the most important structural element in building, which carry the loads and transfer them to the foundations. Because it has many characteristics like excellent strength, rigidity, and capability. There are many factors that directly effect on the safety and bearing capacity of columns, includes overloads, cracks, and peeling of concrete, etc. All these can cause the column to fail, which could cause a great danger to the building leading to building collapse [1]. When a compressive strength works eccentrically, the RC column has extra bending strength applied on it. For this reason, it is necessary for these columns give a resistance under axial load and bending moment. The eccentric load produces an axial load and bending strength in two perpendicular directions. The importance of this resistance in the column in fact that the weak compressed structure must acclimate to the abnormal loads. In recent years, using fiber-reinforced polymer (FRP composites) has gained great interest in many areas, included in strengthening and rehabilitation of concrete structures, in particular RC columns. CFRP jacketing is effective with observance to strength, less rigid and weight against steel, resistance to erosion, high flexibility and lower cost of installation and maintenance. In this respect FRP jacketing gained a great attention in the field of civil engineering to notably increase the compressive strength and ductility of RC columns [2]. It should be noted that this technique can be applied in different forms like external wrapping, sheets, fabric, or spray. CFRP sheets has been, exceedingly and successfully used to promote and support damaged RC columns, in particular, slender reinforced concrete columns. The strengthening technique by wrapping the CFRP sheets requires
心里 forbidding stress concentricity in a specified position on the laminates as it leads to their failure. Due to this it is better to round the corners of rectangular and square columns to avert the stress concentricity in these positions [3]. Some literature has been reviewed about strengthening columns by using CFRP sheets. Widiarsa & Hadi [4] studied the performance and bearing capacity of square reinforced concrete columns (RC) enveloped with CFRP laminates under eccentric loads. The effect of two variables was studied which include the number of CFRP layers and the proportion of eccentricity. The compression test was performed on twelve short square reinforced concrete (RC) columns enveloped with CFRP composites. The columns dimensions were 200 mm × 200 mm × 800 mm and a circular corner with a radius of 34 mm. The results of the RC columns compression test are shown that wrapping columns with CFRP laminate increased the bearing capacity of the columns. One of the most important advantages has been achieved that CFRP wrapping increased the performance of the RC columns by put off the rupture of the reinforcement and concrete, and improved the ductility effect. Chotickai et al [5] have investigated on the structural performance of corroded RC columns strengthened with CFRP sheets under eccentric loading. The influence of the ratio of volumetric the confinement on the performance of RC columns after rehabilitation with the different corrosion levels under eccentric loading were investigated by using and testing 12 specimens of square RC columns. The results showed that CFRP jacket had a lower confinement impact in RC columns with corrosion before the CFRP utilization. The effectiveness of the reinforcement system is highly dependent on the volumetric CFRP rate. Also, the ductility and ultimate load of the RC columns under eccentric loading were greatly improved. Yang et al [6] studied the behavior of rectangular high-strength RC columns enhanced with CFRP wrap under eccentric compression loading. They used 16 rectangular RC columns and all specimens were tested under eccentric loading with eccentricity domain from 50 mm up to 100 mm. The variables in this research included CFRP layout, pre-damaged condition and the number of CFRP sheets. The results of this study; showed several things; energy absorption and factor of ductility of the CFRP reinforced RC columns were improved compared with the control specimens which showed significant levels of brittleness under both eccentricities of 50 mm and 100 mm. Hadi & Widiarsa [7] presented an experimental study on the performance of CFRP enveloped square RC columns under eccentric loading. The impact of the number of CFRP layers, the eccentricity magnitude for sixteen specimens of RC columns strengthened with CFRP were tested. The results showed that CFRP wrapping had more important influence on the maximum loads of eccentrically loaded RC columns than concentrically loaded RC columns. Quiertant & Clement [8] have researched and investigated the performance of eccentrically loaded RC columns reinforced with various CFRP systems. Ten specimens were made from ordinary-strength concrete with low-grade reinforcement specifics, designed to represent structural RC columns of old buildings. The results shown that, when the transverse wrapping is sufficiently strong, makes the axial hardness better and strengthening the compressive capacity of the concrete. In addition, it is clear that the lateral compression applied by the straps also allows additional support in the face of buckling of longitudinal rebar. Al-jelawy et al [9] studied the bending behaviour of the reinforced concrete enhanced with PU carbon fiber–resin strips by using a specimens of small scale wrap shear, large scale RC girders, and unenhanced specimens. The experimental results showed an increase in strength for specimens strengthened with polyurethane (PU), because of its ability to redistribute the loads inside the bond line.

The aim of this research is to study the structural behaviour of pre-damaged RC columns enhanced with CFRP wrap under eccentric loading.

2. Experimental Program
Ten specimens were casted of normal strength concrete and tested in this study. All RC specimens were included of a test zone in the center of columns with a rectangular cross section of 120 mm 120 mm and corbel end at both end of the RC columns and each corbels have the same dimensions with 240 mm 120 mm with 800 mm total height. Two different diameters of steel reinforcement were used in these specimens. Ø8 mm rebars were used for primary reinforcement and Ø6 mm rebars were used for stirrups. The RC columns used in this study were designed according to the ACI 318-2014 [10]. The details of
RC columns, are seen in Figure 1. Two ratios of eccentricity were used e/h = 0.50 and e/h = 0.80 which is it 60 mm and 96 mm. The specimens were divided into two groups according to the ratio of eccentricity, each group has one control column without strengthening and four columns strengthened with CFRP according to the strengthening scheme for each column. The details of RC columns, the ratio of eccentricity, as well as the strengthening scheme are shown in Table 1 and Figure 2 for strengthening scheme.

**Table 1.** The details of columns.

| Group No. | No. | Specimen | Eccentricity (mm) | Strengthening scheme |
|-----------|-----|----------|-------------------|----------------------|
| 1         | 1   | CC50     | 60                | Three horizontal CFRP strips of 100 mm width and spacing @ 100 mm |
|           | 2   | C50S     | 60                | full horizontal reinforcement with CFRP wrapping of 500 mm width |
|           | 3   | C50F     | 60                | longitudinal CFRP sheet wrapped in the tensile area + two horizontal CFRP strips of 100 mm width and spacing @ 300 mm |
|           | 4   | C50R     | 60                | longitudinal CFRP sheet wrapped in the tensile area + three horizontal CFRP strips of 100 mm width and spacing @ 100 mm |
|           | 5   | C50RS    | 60                | /                     |
| 2         | 6   | CC80     | 96                | Three horizontal CFRP strips of 100 mm width and spacing @ 100 mm |
|           | 7   | C80S     | 96                | full horizontal reinforcement with CFRP wrapping of 500 mm width |
|           | 8   | C80F     | 96                | longitudinal CFRP sheet wrapped in the tensile area + two horizontal CFRP strips of 100 mm width and spacing @ 300 mm |
|           | 9   | C80R     | 96                | longitudinal CFRP sheet wrapped in the tensile area + three horizontal CFRP strips of 100 mm width and spacing @ 100 mm |
|           | 10  | C80RS    | 96                | /                     |

![Figure 1](image.png)

**Figure 1.** The details of columns: (A) side view, (B) cross-section.
2.1. Material Properties
A concrete mix with normal strength has been designed. At 28-day, the average compressive strength test was (35 MPa). All mixture details are shown in Table 2. It was observed that the mixture that used in the specimens gave a good workability and symmetrical mixing of concrete without isolation.

Table 2. Concrete mixture details.

| Material      | Unite | NSC Mix |
|---------------|-------|---------|
| Cement        | Kg/m³ | 400     |
| Sand          | Kg/m³ | 880     |
| Aggregate     | Kg/m³ | 1030    |
| Water         | l/m³  | 170     |
| Visocrete-5930| l/m³  | 4.5     |
| W/C           | %     | 0.425   |

The materials used in this mixer were ordinary cement (Portland, type 1), natural sand with a maximum size level of 4.5 mm, and black crushed gravel with size range 5-12 mm. Two kinds of steel reinforcement diameters were used in this columns. Ø8 mm of deformed steel bars were used for longitudinal reinforcement (primary reinforcement) and Ø6 mm of deformed steel bars were used for transverse reinforcement (for stirrups). A tensile tests were performed for the steel reinforcement by using three specimens with a 390 mm of length for each diameter of the steel reinforcement, to find out the tensile properties of steel reinforcement according to ASTM A615 [11]. The main properties of the steel reinforcement (steel bars) are given in Table 3.

Table 3. The test results of steel rebar.

| Nominal Diameter (mm) | Yield Stress, \( f_y \) (MPa) | Ultimate Strength, \( f_u \) (MPa) | Elongation Ratio (%) |
|-----------------------|-------------------------------|-----------------------------------|----------------------|
| 8                     | 460.5                         | 614.6                             | 13.8                 |
| 6                     | 453.2                         | 480.3                             | 5.6                  |
Carbon fiber reinforced polymer (Sika Wrap®-300c) with nominal thickness 0.167 mm and tensile strength 4000 MPa (average is 3500 MPa) was used to strengthen and improve the RC columns damaged by partial loading. Sikadur®-330 (epoxy) was used in the process of installing CFRP sheets on the surface of RC columns.

2.2. CFRP Installation Procedure

The surface of specimen was polished and cleaned, by using a special electrical hand device to remove the paint layer and any hindrance materials separating the surface of concrete and the epoxy resin. The corners of RC columns have been rounded before the installation of CFRP wrap to avert stress concentration on the CFRP strip from the sharp corners of column and to improve the efficacy of the CFRP confinement. After that, the epoxy resin (sikadur-330) was mixed in a ratio of 1:4 hardeners, epoxy, respectively by an electrical mixer for three minutes. Then, the mixed epoxy resin was applied in generously quantities on the required areas by using a special brush roller. Then, CFRP fabrics were cut down according to the prepared strengthening scheme for each column. Then, CFRP wrap was placed over the resin layer and making sure that CFRP wrap was pulled in tension position. Then, the CFRP wrap was massaged by a plastic blade to ensure a good bonding with the resin. Then, a second resin layer was added and applied over the CFRP strips which in turn will provide an additional bonding layer as well as provide a good confinement of CFRP strips. Finally, the specimens were left for a week for curing process. Specimen after strengthening are shown in Figure 3.

![Figure 3. Specimens after strengthening.](image)

2.3. The Test Setup and Loading

Hydraulic testing machine was used to transfer and apply the axial load to the RC columns with maximum capacity of 2000 KN. The RC column has been placed on the test machine, the lower end of RC column was attached to the machine, while the upper end of RC column was supported on the high strength steel cap. The upper and lower ends supports were designed as roller connections with pre-specified eccentricity ratio by using the loading caps. A total of two linear variable displacement transformers (LVDT) were used to measure the displacement of reinforced concrete (RC) columns. The first LVDT was linked directly to the hydraulic testing machine to take the measurements of the axial displacement of the RC specimen during the experimental test, and the second LVDT was placed in horizontal way at the centre of the column height from the back side (tension zone), it was also used for eccentric load to take the measurements of the lateral deflection (δ) of the RC column. All data reads by the LVDTs have been recorded at the same time as load data were recorded by the hydraulic testing machine. These data were collected by a computer which connected to the LVDTs and the test machine. The experimental tests were stopped when the CFRP failed on the tension zone or the concrete crushed on the compression zone. All tests were conducted in the civil engineering laboratory at the University of Kerbala. The test machine and setup are shown in Figure 4.
2.4. Loading cap
A new loading cap has been made with high-strength steel plate. The loading caps were placed at both ends of the RC column. The loading cap consists of a rectangular steel plate with dimensions of (250 mm × 130 mm) and thickness of 20 mm, in addition to four steel plates with thickness of 6 mm around the main plate to prevent the RC column from sliding. Four steel poles of 10 mm diameter were installed over the steel plate to ensure that eccentric loading is applied (60 mm and 96 mm from the centre). The eccentric load generated by the hydraulic testing machine, was transferred and applied on the loading cap by using a roller of 30 mm diameter. Then, the main plate applies the load to the RC column, as seen in Figure 5.

3. Experimental Results and Discussion
The control column was tested for each group until failure to find out the maximum load capacity of the control specimens. Then, the RC columns in-group one were partially loaded under eccentric load (50% eccentricity, which it 60 mm) roughly to a quarter of their ultimate load capacity. The first cracks were appeared at the range of loading 30-40 KN on the RC columns. While the RC columns in-group two were partially loaded under eccentric load (80% eccentricity, which it 96 mm) almost to a quarter of their ultimate strength. The initial cracks have been observed at the range of loading from 15 KN up to 20 KN on the RC columns. Then, the partially loaded specimens were repaired by using CFRP wrap according to the strengthening scheme for each column. Then, the strengthened specimens were tested until failure to find out the structural behaviour of columns after enhancement.

3.1. Failure Modes
The failure pattern of RC column related with ratio of eccentricity. For the control columns (without strengthening), when the eccentricity equal to 60 mm, the specimen CC50 showed a small change of the column before loading peak and the mid-span deformation was developed slowly. The RC column tested under the eccentric compression showed many cracks on the tension zone, those cracks mainly began at the tension zone along the RC column length and the failure was started by crushing of the concrete in
the compression zone in mid-height of specimen. When the eccentricity equal to 96 mm, the specimen CC80 showed plenty cracks on the tension zone along the RC column length. and the width of these cracks range from 1 mm to 6 mm. Mainly, the failure was started by crushing of the concrete in the compression zone like CC50 at above the middle of specimen height near to the corbel, which can be seen in Figure 6.

![Figure 6. The failure modes of control columns.](image)

As for specimens that strengthened with CFRP and tested under eccentric load with 60 mm eccentricity, it can be said that the failure mode was similar to the control column but the difference here was that the number of cracks less and the area of concrete crushing which was smaller than CC50 specimen. With the increase of applied load and the continuation of the loading process especially when the load is nearing to the peak, the CFRP strips were started to stretch a bit with intermittent popping sounds and that indicates that the CFRP strips are effective. Moreover, the deflection of reinforced concrete column increased widely at the same time. The failure mode of specimen C50S was described by a crushing of concrete in the compression area and it was happened at the top part of the RC column. While the mode of failure in specimen C50F was described by a crushing of concrete in the compression area at the top side of column inside the CFRP, which leads to rupture of CFRP wrap, plus to deep cracks in the top of tension area also lead to transvers rupture on the CFRP. As for the specimens C50R and C50RS, the failure patterns were slightly similar and they were started by crushing of concrete at the mid-height of the specimens in the compression area. But in specimen C50RS, the failure was not limited to the crash of concrete only but it was accompanied by a severe rupture in the longitudinal CFRP wrap at the tension zone near the mid height of the specimen. The failure modes and load-displacement carves are shown in Figures 7 and 8 respectively. For the specimens that enhanced with CFRP and tested under eccentric load with 96 mm eccentricity, the following findings were observed. For specimen C80S, the failure pattern was identical to CC80 and C50S with crushing of concrete in the compression area. On the other hand, the failure pattern in specimen C80F was also similar to C50F. While the specimen C80R, the failure mode was started by sudden crushing and spalling of the concrete in the compression zone at the mid height of column plus to a rupture in the longitudinal CFRP wrap at the tension zone near the mid height of the specimen. The pattern of failure in specimen C80RS was different from all other columns, which yielded many deep cracks on the head of column on the corbel plus to the de-bonding of longitudinal CFRP wrap from the top part of specimen, without any noticeable damage in the mid height of the column. The failure modes and load-displacement carves are shown in Figures 9 and 10 respectively. Generally, the mechanical behaviour, particularly for ductility, and energy absorption were improved and increased due to a magnificent confinement effect of CFRP wrap. Table 4 are shown the ratio of increase in ultimate load capacity and failure pattern of specimens.
Figure 7. The failure modes of specimens with 60 mm eccentricity.

(a) Vertical (b) Lateral (60 mm eccentricity)

Figure 8. Load-displacement curves (a) Vertical, (b) Lateral. (60 mm eccentricity)

Figure 9. The failure modes of specimens with 96 mm eccentricity.
Figure 10. Load-displacement curves (a) Vertical, (b) Lateral. (96 mm eccentricity)

Table 4. Increase ratio of ultimate load and failure pattern of specimens.

| Group No. | No. | Specimens | Ultimate load (KN) | Increase ratio (%) | Failure pattern |
|-----------|-----|-----------|--------------------|--------------------|----------------|
| 1         | 1   | CC50      | 171.9              | /                  | Crushing       |
|           | 2   | C50S      | 162.1              | -5.70              | Crushing       |
|           | 3   | C50F      | 202.3              | 17.68              | Crushing + Rupture of CFRP |
|           | 4   | C50R      | 201.0              | 16.92              | Crushing       |
|           | 5   | C50RS     | 222.4              | 29.37              | Crushing + Rupture |
| 2         | 6   | CC80      | 70.5               | /                  | Crushing       |
|           | 7   | C80S      | 77.4               | 9.78               | Crushing       |
|           | 8   | C80F      | 85.4               | 21.13              | Crushing + Rupture of CFRP |
|           | 9   | C80R      | 123.3              | 74.89              | Crushing + Rupture of CFRP |
|           | 10  | C80RS     | 130.9              | 85.67              | Cracks + De-bonding of CFRP |

3.2. Ductility and Stiffness

Ductility index can be described as the ratio of the ultimate displacement to the yielding displacement (displacement at 80% of maximum applied load) [12]. Whereas, the initial stiffness can be defined as the ratio of 70% of the ultimate load capacity to the displacement at the same load ratio [13]. The stiffness and ductility index were calculated for all columns, and they are listed in Table 5.

Table 5. Ductility and stiffness for specimens.

| Group No. | No. | Specimen | Ultimate load (KN) | Stiffness at service load $Fs=0.7 Fu$  | Ultimate displacement $\Delta u$, (mm) | Yielding strength $f_y=0.8f_u$ (KN) | Yielding displacement $\Delta y$, (mm) | Ductility index $DI=\Delta u/\Delta y$ |
|-----------|-----|----------|--------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| 1         | 1   | CC50     | 171.9              | 32.78                                  | 5.198                                  | 137.5                                  | 4.10                                   | 1.26                                   |
|           | 2   | C50S     | 162.1              | 26.12                                  | 5.781                                  | 129.6                                  | 4.81                                   | 1.20                                   |
|           | 3   | C50F     | 202.3              | 48.32                                  | 4.638                                  | 161.8                                  | 3.40                                   | 1.36                                   |
|           | 4   | C50R     | 201.0              | 56.73                                  | 4.359                                  | 160.8                                  | 2.84                                   | 1.53                                   |
|           | 5   | C50RS    | 222.4              | 47.4                                   | 5.153                                  | 177.9                                  | 3.72                                   | 1.38                                   |
| 2         | 6   | CC80     | 70.5               | 15.55                                  | 4.281                                  | 56.4                                   | 3.61                                   | 1.18                                   |
|           | 7   | C80S     | 77.4               | 14.62                                  | 5.372                                  | 61.4                                   | 4.27                                   | 1.25                                   |
|           | 8   | C80F     | 85.4               | 25.77                                  | 4.660                                  | 68.3                                   | 2.75                                   | 1.69                                   |
|           | 9   | C80R     | 123.3              | 23.97                                  | 6.645                                  | 98.4                                   | 4.26                                   | 1.55                                   |
|           | 10  | C80RS    | 130.9              | 17.41                                  | 7.997                                  | 104.7                                  | 6.12                                   | 1.30                                   |
4. Conclusion
The control specimens showed considerable brittleness under the both ratios of eccentricity of 60 mm and 96 mm, which is similar with the traditional failure patterns of RC columns. Nevertheless, the mechanical behaviour, particularly for ductility, stiffness, and ultimate load capacity was improved and increased due to the enhancement with CFRP wrap. The strengthening scheme used in C50S and C80S did not provide an adequate improvement comparing with control columns regardless of the ratio of the eccentricity because the CFRP strips have not covered all the cracks caused by the initial loading process. While, the other strengthening schemes provide a good improvement in ultimate load capacity, stiffness, and ductility impact. Depending on the experimental results, it is suggested to adopt the strengthening schemes used in the specimens C50RS, and C80RS because it gives better improvement in terms of ultimate load capacity of columns.

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