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# Behaviour Assessment of Reinforced Concrete Columns Externally Rehabilitated with Carbon Fiber-Reinforced Polymers (CFRPs) Subjected to Eccentric Loadings

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## ABSTRACT

Rehabilitating of concrete columns with Carbon Fiber-Reinforced Polymer (CFRP) under axial load has been extensively covered in the past and has proven to be an effective method of enhancing the strength and the ductility of reinforced concrete columns. The main objective of this investigation is to assess the effectiveness of utilizing CFRP in short reinforced concrete columns subjected to eccentric loadings. An experimental study using twelve 150 mm x 150 mm x 900 mm short reinforced concrete columns, consisting of six control specimens and six CFRP-rehabilitated specimens, was carried out using eccentricities of 15 mm, 30 mm and 45 mm on the subject columns. The columns were designed using the ACI 318-14 building code. Rehabilitation and wrapping were carried out using the provisions of ACI 546, ACI 503 and ACI 440, where the columns were strengthened using a single-layer wrap of carbon fiber composites. Testing was carried out under a uni-axial eccentric compressive loading servo machine up to failure, where the P-Delta relationship was recorded *via* a data acquisition system. The results showed an improved load-carrying capacity and a significant improvement in ductility when compared to the control specimens. Based on the test results, load-carrying capacity was observed to increase by 22.5% to 37.2% when the eccentricity increased from 15 mm to 45 mm, respectively. On the other hand, maximum deflection (i.e., Delta) increased by 24% to 15% for eccentricities respectively ranging between 15 mm and 45 mm. Generally speaking, the load–deflection curves of the rehabilitated columns showed a stiffening trend and ductility reduction when the eccentricity was increased.

**KEYWORDS:** RC columns, CFRP, Rehabilitation, Eccentricity, Uniaxial bending, Strength.

## INTRODUCTION

Columns are considered vital structural elements that transmit loads from the superstructure to the soil through the foundations. As such, it would seem counterintuitive that such elements must be carefully detailed and designed in order to preserve the structural integrity of the underlying sub-structure, while maintaining safety and soundness of the superstructure being carried. It is important that when such elements show any deterioration or loss in their load-carrying capacity, they should be rehabilitated in a manner that preserves their original integrity, ductility and strength capacities and even increases their load-carrying capacity in line with the original design intent for a fit-for-purpose functional structure. Such increase was found to be achieved by improving the bond strength between concrete and CFRP wrapping.

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Several previous studies aimed at understanding the behavior and effect of using CFRP to rehabilitate and strengthen sound or damaged columns. The objective was to increase the load-carrying capacity of sound columns and to rehabilitate damaged ones to their original design capacities in an effort to maintain their integrity and safety.

Chikh et al. (2012) carried out an experimental study to investigate the effect of using CFRP sheets on short and slender high-strength concrete columns subjected to concentric loadings. Forty-eight specimens were tested up to failure in axial compression. Test results showed that CFRP wrapping enhanced both strength (i.e., an increase was observed from 17% to 24%) as well as ductility (which was shown to increase from 11% to 19%).

Zadeh and Eshghi (2018) studied the efficiency of GFRP wraps to strengthen slender RC columns with structural deficiency subjected to axial compression. They tested twelve RC columns with a square cross-section of 150×150 mm and 800 mm height. To simulate the deficiencies in the column, they reduced the number of stirrups at parts of the columns. They concluded that externally bonded GFRP wraps can enhance axial, shear and flexural strengths of slender RC columns. Moreover, GFRP wraps helped in altering the failure mode from brittle shear to ductile flexural failure at the deficient zones.

Parretti and Nanni (2005) conducted an experimental investigation to study the effect of CFRP confinement on both strength and ductility of concentrically-loaded concrete columns. The authors used carbon fibers with varying fiber orientations within the range of ±45 degrees. Results showed that the capacity of columns having ±45-degree orientation was decreased by 28% when compared to columns strengthened with horizontally-oriented (i.e., zero degree) fibers. It was further observed that columns strengthened using ±45-degree sheets exhibited a 21% increase in ductility when compared to those strengthened with horizontal sheets (i.e., zero degree).

Obaidat (2018) investigated the debonding between CFRP wraps and RC structural elements. In this study, the effects of several design parameters on CFRP debonding were tested. The studied parameters were: steel reinforcement, concrete cover and element width. It was concluded that these parameters have significant effects on the load capacity and ultimate strain of the strengthened elements.

Chastre and Silva (2010) tested twenty-five CFRP-confined concrete columns under concentric loading with the objective to study the stress-strain behavior throughout the range of loading up to failure. Test results showed a 26% improvement in the load-carrying capacity of CFRP-confined circular columns when compared to the control specimens.

Wu and Wei (2010) studied the effect of CFRP on short rectangular concrete columns using forty-five specimens under concentric loading. It was shown that the strength of confined concrete columns when compared to that of their unconfined counterparts increased by 10% for rectangular sections having an aspect ratio (i.e., length-to-width ratio of the cross-section) of 2, to 17% for columns having square cross-section (i.e., those with an aspect ratio equal to 1).

Belouar et al. (2013) carried out an experimental study on forty-eight square specimens with high and normal concrete strengths to study the variation of CFRP performance at different compressive strengths. The specimens were loaded up to failure under concentric loading. Test results showed that the use of CFRP to enhance normal-strength concrete columns effectively increased both strength by 32% and ductility by 15% when compared to their high-strength concrete column counterparts.

Wei et al. (2009) carried out an experimental investigation on ten concrete columns subjected to concentric loading. Each specimen had two different strength portions: an upper sound segment and a lower segment that was characterized as being both low-strength and deteriorated. The lower portion of the specimens was wrapped with different layers of CFRP sheets in an effort to investigate the advantages of using partial confinement. Experimental results showed that both ductility and strength of the deteriorated lower portions of the columns were increased by 22% and 28%, respectively. It was subsequently concluded that partial confinement showed significant improvement of load-carrying capacity as well as ductility of the partially damaged concrete columns.

Widiarsa and Hadi (2013) studied the effect of CFRP wraps on twelve (12) reinforced concrete square columns subjected to eccentric loading. Test parameters consisted of varying both eccentricity and number of CFRP layers. Test results showed a remarkable enhancement in load-carrying capacity and ductility of square reinforced concrete columns when using CFRP wrapping on specimens subjected to eccentric loading. The authors observed that load-carrying capacity was increased from 1% for specimens having zero eccentricity, to 6.2% for those with a 25 mm eccentricity. Specimens having a 50 mm eccentricity showed a 17.2% increase in load-carrying capacity. On the other hand, ductility merely increased by 0.7%, 15.6% and 20.4% for specimens with zero, 25 mm and 50 mm eccentricities, respectively.

Al-Ameeri et al. (2013) carried out an experimental investigation on six (6) reinforced concrete columns subjected to biaxial eccentricities and rehabilitated using epoxy and Sika repair. After preloading, loose concrete material was taken out from the columns' damaged corners and either epoxy or Sika was used as a filler. The first material used was SikaRepair-640, while the second one was Sikadur-330 (epoxy). It was concluded that both repairing methods enhanced the behavior of the repaired RC columns, where the ultimate load-carrying capacity and ductility increments, respectively, reached 22.7% and 10.8%. It was also further shown that the use of epoxy for repair enhanced the behavior of damaged columns when compared to using the Sika product.

As shown from the review of previous literature, it has been observed that the majority of past studies which focused on the behavior of CFRP-confined RC columns were carried out using concentrically-loaded columns, while relatively fewer studies addressed the effect of eccentricity using the CFRP rehabilitation technique. This experimental investigation aims to examine the effect of using CFRP on eccentrically-loaded columns.

## Experimental Program

### RC Column Design

Twelve columns of 900 mm height were designed using a concrete compressive strength of 18 MPa provided with an adequate amount of longitudinal ($f_y$ = 420 MPa) and transverse ($f_v$ = 280 MPa) reinforcements, as shown in Fig. 1. Their design was carried out using ACI 318-14.

The specimens were cast using formwork having fair face panels of size 0.15 m x 0.9 m x 20 mm, as shown in Fig. 2. Concrete segregation was prevented by a careful concrete placement and proper vibration throughout the pouring process. The specimens were then cured for seven (7) days using damped sackcloth along the exposed face of the specimen.

## Material Properties

### Specimen Setup

Fig. 3 depicts a schematic representation of the test setup used in this experimental investigation, where the test specimens were subjected to uniaxial eccentric loading and were further pinned at both ends. The deflection (i.e., Delta) was measured at the column mid height using a horizontally placed LVDT.

In order to simulate uniaxial eccentric loading on the tested specimens, a small piece of steel was used to transmit the load from the hydraulic jack to the column top surface (Fig. 3). The point of application of the load being transmitted through the steel metal piece was at a distance equal to "*e*" from the column centerline. The pin end boundary conditions were modeled through the placement of loading caps at both ends. Lateral movement was restricted using small wooden blocks at both ends.

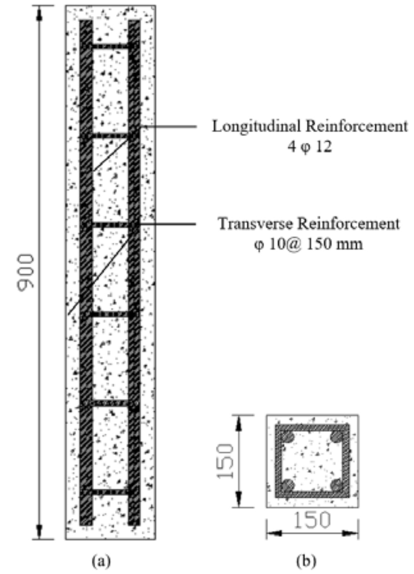


Figure (1): Reinforcement details for all specimens (a) profile and (b) cross-section

Figure (2): Formwork of columns with fair face panels

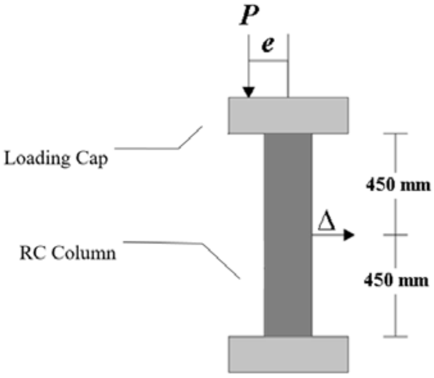


Figure (3): Specimen setup

### CFRP Sheets

Commercially available CFRP sheets used in this study consisted of MBrace (Master Brace) FIB CF 230/4900.300g having mechanical properties as shown in Table 1. MBrace FIB consists of unidirectional fabric sheets made out of carbon which is regarded as the main strengthening system in addition to the epoxy resin. Fig. 4 shows a typical CFRP roll used to wrap the tested columns in the present investigation.

**Table 1. Mechanical properties of CFRP (BASF Master Builders Solutions, 2013)**

| **Product** | **MBrace FIB CF 230/4900.300g** |
|---|---|
| Description | High-strength carbon UD fabric |
| Fiber Areal Weight | 300 g/m$^2$ |
| Fabric Design Thickness | 0.166 mm |
| Fiber Tensile Strength | 4.900 MPa |
| Fiber Tensile E-modulus | 230 GPa |
| Elongation at Break | 2.1% |
| Fabric Length / Roll | 100 m |
| Fabric Width | 50 cm |
| Self-Life | Unlimited (product warranty) |
| Package | 25 m$^2$/roll |

**Figure (4): Carbon fiber-reinforced polymer roll**

### CFRP Wrapping

Six reinforced concrete columns were prepared in a laboratory environment and preloaded up to their average cracking load. Prior to wrapping, the surfaces of all specimens were thoroughly roughened using sand paper and then cleaned *via* a wire brush to remove the accumulating dust. Epoxy adhesive resins were then properly mixed and applied to the column surfaces, followed by the application of two CFRP wraps around the columns using two unidirectional (CFRP) sheets. The two sheets were wrapped such that a 100 mm overlap in the horizontal direction was created between the first and second sheets.

The rehabilitation technique used was carried out in accordance with (ACI Committee 546 2001), (ACI Committee 503 1998) and by following the general guidelines of (ACI Committee 440 2008) and O-BASF guidelines (BASF Master Builders Solutions, 2013). Fig. 5 depicts these steps.

(a) (b) (c)

**Figure (5): (a) Surface roughening with sand paper, (b) CFRP sheet wrapping around the column and (c) concrete column after CFRP rehabilitation**

### Test Setup

A hydraulic jack of a compression load capacity up to 4000 kN (DARTEC-Universal Testing Machine) was used as depicted in Fig. 6a. A data acquisition system was connected to the load cell which measured the load increment throughout the loading stage, as shown in Fig. 6b. Load *vs*. Delta (i.e., the deflection at the middle of the column height) at a 25 kN load increment was recorded up to failure.


(a) (b)

**Figure (6): Testing machine (a) hydraulic jack and (b) data acquisition system**

The twelve specimens were divided into two groups: group A which represented the control group and group B which included the CFRP-rehabilitated specimens, as shown in Table 2. The six control specimens were further divided into three sub-groups; where each included two columns tested under a varying load eccentricity of 15 mm, 30 mm and 45 mm. The same grouping was applied to the remaining six CFRP-rehabilitated specimens. All specimens were tested throughout their loading up to failure after being subjected to the varying eccentricities, as shown in Fig.7.

Group A was loaded until visual observation of the cracking load was recorded. Group B was loaded up to the same cracking load as group A for each eccentricity value. Then, group B samples were wrapped with CFRP and then subsequently tested until failure. The testing procedure is summarized *via* a simplified flow chart, as per Fig. 7.

**Table 2. Details for the column specimen groups and sub-groups**

| Group Label | Details | Subgroup |
|---|---|---|
| Group A<br>(Control Group)<br>(C1, C2, C3, C4, C5 and C6) | Undamaged short reinforced concrete columns subjected to eccentric loading.<br>(6 control specimens) | A15<br>Load eccentricity e = 15 mm<br>(C1 and C2) |
| | | A30<br>Load eccentricity e = 30 mm<br>(C3 and C4) |
| | | A45<br>Load eccentricity e = 45 mm<br>(C5 and C6) |
| Group B<br>(CFRP-rehabilitated Group)<br>(C7, C8, C9, C10, C11 and C12) | Damaged short reinforced concrete columns rehabilitated and restored using carbon fiber-reinforced polymer (CFRP) subjected to eccentric loading.<br>(6 rehabilitated specimens) | B15<br>Load eccentricity e = 15 mm<br>(C7 and C8) |
| | | B30<br>Load eccentricity e = 30 mm<br>(C9 and C10) |
| | | B45<br>Load eccentricity e = 45 mm<br>(C11 and C12) |

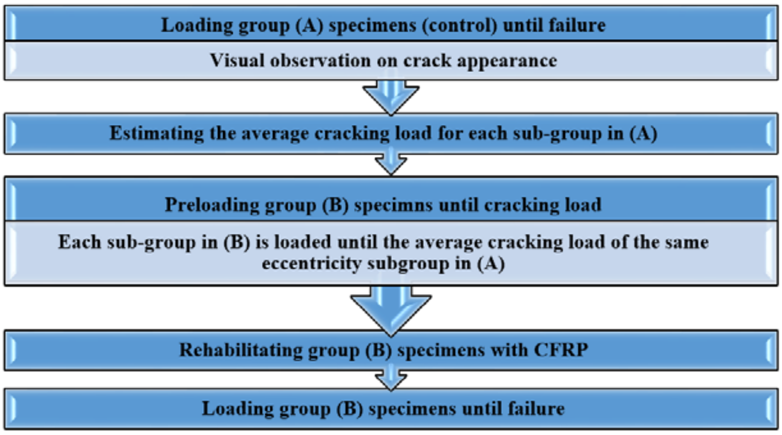


**Figure (7): Test description process**

## Test Results and Discussion

Analysis of the results was conducted by comparing the ultimate load capacities of the control *vs*. the rehabilitated columns. Load-deflection curves for each test sample were established and a comparison was carried out between the control and the rehabilitated specimens. Failure modes were investigated and a summary was prepared, as shown in the sub-sections below.

### Ultimate Load-Carrying Capacity

The failure load for each sub-group in groups A and B was calculated by taking the average failure loads of the two samples within each sub-group, as depicted in Fig. 8 that shows the average failure load for each sub-group. When compared with the control specimens, the CFRP-rehabilitated specimens exhibited an increase in the ultimate load-carrying capacity by 22.5%, 27.7% and 37.2% for, respectively, the 15 mm, 30 mm and 45 mm load eccentricity sub-groups. The increase was a direct result of the lateral confinement provided by the CFRP wraps. It is obvious that as the load eccentricity increases, the confining pressure increases due to the presence of a higher flexural moment, leading to a beneficial usage of CFRP wraps in rehabilitating the RC columns. This trend has been also witnessed by Widiarsa and Hadi (2013). In their experimental study, they observed that load-carrying capacity was increased from 1% for specimens having zero eccentricity, to 17.2% for specimens tested under 50 mm eccentricity. This finding should be studied extensively to enhance the understanding of rehabilitation of beam-column members and to set up an optimization scheme for a better utilization of CFRP wraps depending on the intended load-moment capacity.

When comparing the ultimate load-carrying capacity of the CFRP-rehabilitated specimens with varying eccentricity, it was observed that the ultimate load decreased as the eccentricity increased. The decrease in ultimate load was observed to be equal to 16.7% and 27.6% when the load eccentricity increased from 15 mm to 30 mm and 45 mm, respectively. The decrease in load-capacity was a direct result of the increase in eccentricity and was mainly attributed to the stiffening behavior in the load - deflection curves. This behavior was manifested by the increase in confining pressure as the CFRP wrap reached its limited elongation caused by the increase in eccentricity, and subsequently, moment. Al-Ameeri et al. (2013) proposed to increase the number of wraps to increase the confining pressue and elongation.

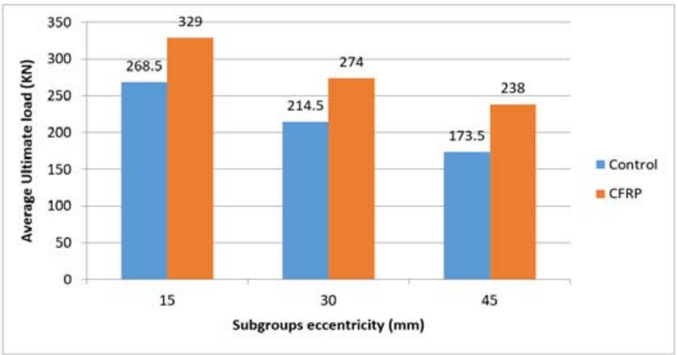
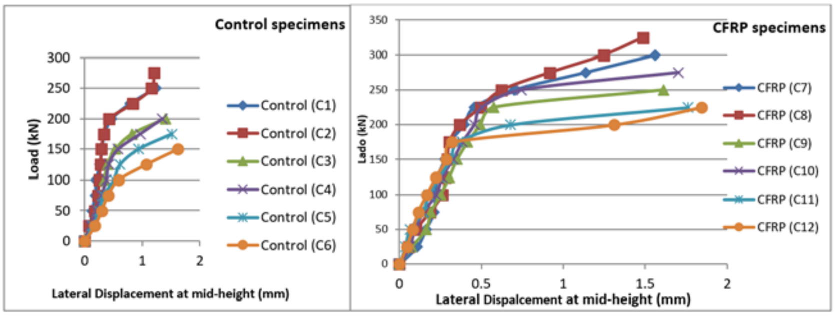


**Figure (8): Ultimate failure load for columns**

**Deflection**

The CFRP-rehabilitated specimens showed an enhanced confinement and ductility behavior as evident by the increased area under the load-deflection curve, which is considered as a measure for the amount of ductility that a member possesses (see Fig. 9). It was further observed that ductility of control specimens was much less than that of rehabilitated specimens. When compared with control specimens, CFRP-rehabilitated specimens showed an increase in the maximum deflection by 24%, 20% and 15% for, respectively, the 15 mm, 30 mm and 45 mm load eccentricity sub-groups. This increase in the maximum deflection was referred to the confinement effect of the CFRP wraps, which increased the absorbed energy. This conclusion agreed with Widiarsa and Hadi (2013) experimental study, which reported that ductility increased by 15.6% and 20.4% for specimens with 25 mm and 50 mm eccentricities, respectively. When comparing the maximum deflection of CFRP-rehabilitated specimens with varying eccentricity, it was found that maximum deflection and eccentricity were directly proportional, where both were found to have increased. Maximum deflection increased by 8.8% and 18.3% when load eccentricity increased from 15 mm to 30 mm and 45 mm, respectively. When increasing load eccentricity, the increase in maximum deflection was observed to decrease due -in part- to the stiffening behavior in the load - deflection curves. This behavior was referred to limited elongation and reduced deformation in the CFRP wrap as confinement increases with load eccentricity increase. In other words, the increase of confining pressure as maximum elongation is reached restrained the circumferential movement of the rehabilitated columns.



(a) (b)

**Figure (9): Load – deflection curves for: (a) control columns and (b) CFRP-rehabilitated columns**

## Elastic and Post-cracking (Plastic) Stiffness

To clearly understand the effect of CFRP rehabilitation on RC columns, the stiffening behaviour witnessed in the rehabilitated columns, due to the confining effect, should be discussed. Each of the CFRP-rehabilitated columns will be compared with the corresponding control column to investigate the effect of CFRP rehabilitation on the stiffness of the load-deflection curves in the elastic and plastic (post-cracking) regions.

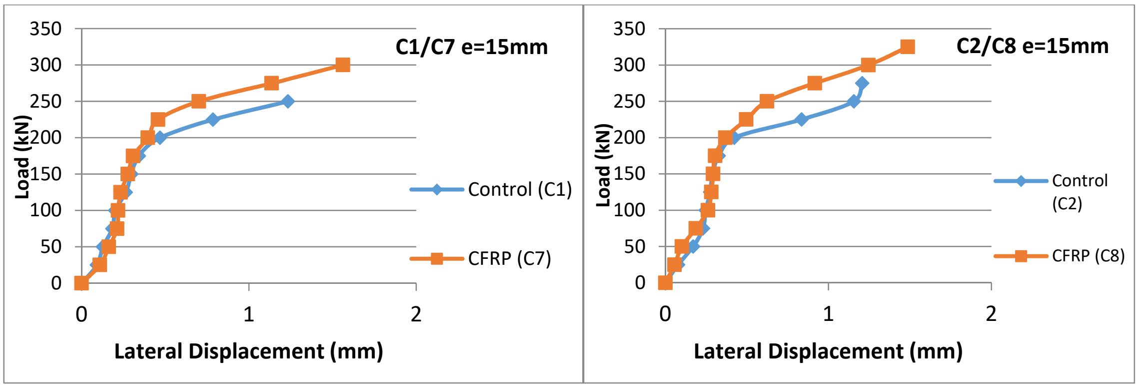


**Figure (10): Load – deflection curves for: (a) C1 and C7 columns and (b) C2 and C8 columns**

It can be noticed from Fig. 10 that using CFRP wraps increased load capacity and ductility (maximum deflection) under 15 mm eccentric loading. Nevertheless, the stiffness in the elastic and the post-cracking regions was not affected by CFRP wrapping at this loading eccentricity. This trend was changed when the load eccentricity increased from 15 mm to 30 mm, as shown in Fig 11. The elastic stiffness increased by 13.3%, while the post-cracking stiffness decreased by 4.3%. Moreover, the elastic stiffness increased by 21.1% and the post-cracking stiffness decreased by 6.5% when load eccentricity increased to 45 mm, as shown in Fig. 12. This increase in elastic stiffness was referred to the confinement that the column is getting in addition to its own stiffness. Conversely, the decrease in post-cracking stiffness was referred to the damage that occurred in the column at this region.

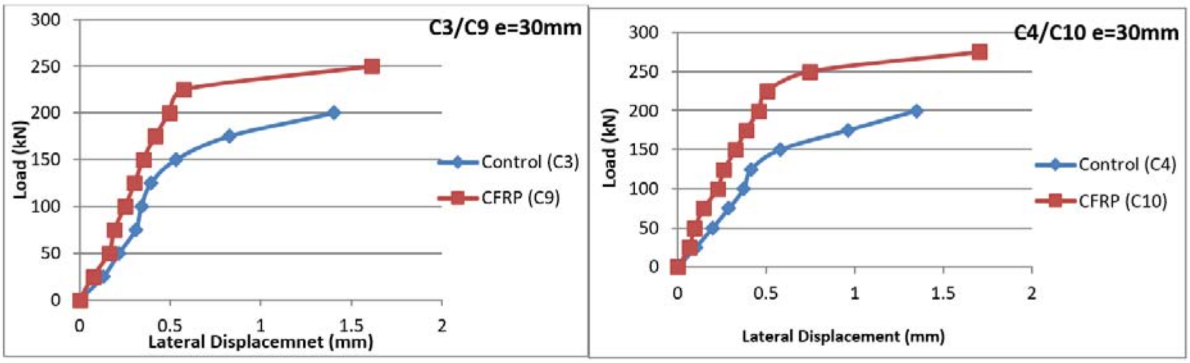


**Figure (11): Load – deflection curves for: (a) C3 and C9 columns and (b) C4 and C10 columns**

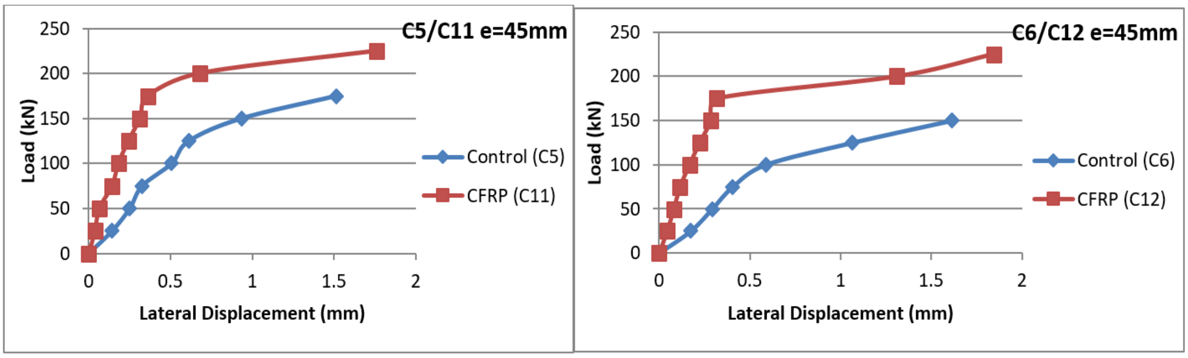


Figure (12): Load – deflection curves for: (a) C5 and C11 columns and (b) C6 and C12 columns

### Energy Absorption

When comparing the area under load-deflection curves of rehabilitated with control columns, it is clear that the increase in energy absorption (toughness) of the columns was enhanced when rehabilitating them by CFRP wraps. The stiffening behaviour due to CFRP wrap confinement was interpreted by a larger area (energy absorption) under load-deflection curves for both elastic and post-cracking regions, as shown in Figs. 10,11 and 12.

After comparing that area for control and rehabilitated columns, an increase of 9%, 19.4% and 28.2% was found for, respectively, the 15 mm, 30 mm and 45 mm load eccentricity sub-groups. When studying the effect of load eccentricity on energy absorption of rehabilitated columns, it was found that increasing the load eccentricity resulted in a higher energy absorption in both of elastic and post-cracking regions. It was estimated that the energy absorption increased by 14.2% and 20.7% when increasing load eccentricity from 15 mm to 30 mm and from 30 mm to 45 mm, respectively. The slight reduction in energy absorption increase when increasing load eccentricity was referred to the wrap reaching its limited elongation due to increase in the flexural moment.

### Failure Modes and Crack Patterns

The specimens of the control group displayed brittle failure due to introduction of eccentric loading. Compression failure was observed to start on the compression side, where crack formation was observed and eventful concrete crushing of the column was noted. It was observed that the concrete strain has reached its ultimate theoretical value prior to the yielding of the rebar, as depicted in Fig 13. It was further observed that the control specimens displayed brittle failure that was characterized by a sharp face cut at the line of loading along the steel plate face and crushing beneath it. Immediately after the ultimate load was reached, the specimens collapsed in a sudden manner by noticing concrete spalling and crushing.

Figure (13): Failure modes for control specimens

On the other hand, the rehabilitated specimens failed in a relatively ductile manner due to the confinement of CFRP wraps which prevented concrete from spalling, as shown in Fig. 14. Compression failure was observed to initiate on the compression side and progressed towards the tension side involving the contraction of CFRP wraps and concrete crushing at the compression side and tearing of CFRP wraps at the tension side due to excessive tensile stresses.

**Figure (14): Failure modes for rehabilitated specimens**

## CONCLUSIONS

An experimental investigation was carried out to study the behavior of CFRP-rehabilitated concrete columns under eccentric loading in comparison with control specimens that remained unwrapped. The program included twelve square columns, where six were used as control specimens, while the remaining six were pre-loaded up to cracking load and then rehabilitated and subsequently tested up to failure. Based on the results obtained from the study, the following conclusions can be drawn:

1. In general, it can be concluded that using CFRP wraps proved to be efficient and effective in increasing load capacity and ductility of rehabilitated short reinforced concrete columns under eccentric loading. Compared to control specimens, CFRP-rehabilitated specimens exhibited an increase in the ultimate load by 22.5%, 27.7% and 37.2% for 15 mm, 30 mm and 45 mm load eccentricity. Regarding ductility, CFRP-rehabilitated specimens showed an increase in maximum deflection by 24%, 20% and 15%, respectively, for 15 mm, 30 mm and 45 mm load eccentricity when compared to control specimens. Also, CFRP wraps provided a more ductile failure mode by confining the concrete from spalling.
2. When comparing ultimate load of CFRP-rehabilitated specimens with varying eccentricity, it was found that ultimate load decreases while increasing load eccentricity. Ultimate load decreased by 16.7% and 27.6% when load eccentricity

increased from 15 mm to 30 mm and 45 mm, respectively.

3. When comparing maximum deflection of CFRP-rehabilitated specimens with varying eccentricity, it was found that the maximum deflection increases while increasing load eccentricity. Maximum deflection increased by 8.8% and 18.3% when load eccentricity increased from 15 mm to 30 mm and 45 mm, respectively.
4. While increasing load eccentricity on CFRP-rehabilitated columns, the decrease in ultimate load capacity shows a reduction and the increase in ductility shows a reduction; this reduction can be related to the stiffening behavior in the load - deflection curves. This behavior was referred to the increase in confining pressure as the CFRP wrap reaches its limited elongation due to the increasing moment caused by the increase in eccentricity.

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**Nomenclature**

$f_c'$: Average uniaxial concrete compressive strength of standard cylinder at 28 days (MPa).
$f_y$ : Yield strength of steel reinforcement (MPa).
$f_v$: Shear strength of steel reinforcement (MPa).
$e$: Uniaxial load eccentricity from center of column cross-section (mm).
$\Delta$: Maximum deflection at the center of the short column (mm).
$P$: Maximum eccentric load applied (kN).

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