Effect of slenderness ratio of RC columns strength with CFRP in both directions under uniaxial moment

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Abstract. The present study investigates the effect of slenderness ratio of circular reinforcement concrete (RC) columns strengthened with carbon fiber-reinforced polymer (CFRP) sheets. Twelve RC columns made of normal concrete were casted and tested, these specimens subjected to eccentric loading. The influence of three parameters that including the slenderness ratio, distribution, and direction of CFRP strips were studied. These results appear high improvement in the load capacity of columns for both stages of cracking load and ultimate load for all groups of columns.

1. Introduction
Column as Compression elements potentially support a variety of structures, for example floor slabs and bridge decks, and can act as piers or piles. Columns vary in cross section shape depending on their application within a situation, although typically they are either circular or rectangular for ease of construction. The notion of the ideal column projected as a purely compression member is generally false, as eccentricities commonly exist in situ. Once a compressive force acts non-concentrically the element has additional bending forces applied to it. Therefore, it is vital that RC columns form resistance under axial loadings and biaxial bending. Eccentric load creates an axial compression load and bending forces in two orthogonal directions. The significance of such resistance in a column is that a weakened compressed structure should adapt to abnormal loads and before full redundancy, redistribute bending moments to other element. Fiber-reinforced polymer (FRP) composites have found wide applications and uses in the civil engineering structures due to ease of application and their high corrosion resistance. The most important application of FRP is as confinement of the concrete columns to enhance the strength and ductility. Such confinement can be used for increased service load when the strength of concrete structure should be improved. In literature there many research studies have been reported, about strengthened columns tested under concentric loads. However, in a practical sense there is no column that is under perfect concentric loading. Due to many circumstances such as loads from adjoining members and columns being out of plumb, most columns are placed under some amount of eccentric loading. In a study performed by Parvin [1] and Wang tested several short square concrete wrapped with varying layers of CFRP with the loading under different eccentricities. The results from the study showed in each strengthened group, the increase in eccentricity resulted in a decrease in strength capacity of the column. It was also noted from the results that even under eccentric loading, the use of external reinforcement increases the load capacity of the column, with further increases in the load capacity achieved when the number of layers of external reinforcement is increased. Fam et al [2] tested several FRP tubes filled with concrete and subjected to
different loading configurations including combined axial and bending loads with eccentricities ranging between 10 mm and 300 mm. Three of the beam-column specimens had a height of 1.8 m and were made of a 326 mm tube and the remaining five beam-column specimens had a height of 1.7 m and 320 mm diameter. The compressive strength of the concrete in the first three columns was 60 MPa and for the remaining five columns was 67 MPa. Based on their experimental results, Fam et al. constructed interaction diagrams for axial load–bending moment for FRP filled concrete beam-columns. Hadi et al. [3-13] have published several studies on the behavior of eccentrically-loaded FRP confined with different wrapping materials. The concrete had different strengths. This the results of this studies concluding that the improvement of ductility was more obvious than the improvement in strength. Application of multiple layers of FRP increases the stiffness of the external confinement and enhances the efficiency of the confining system. The increase of eccentricity has a direct impact on the maximum load capacity, while for the lateral deflection there is no influence with the eccentricities. Carbon fibres (CFRP) embedded in a polymeric matrix provided the highest amount of confinement compared to other types of fibres or steel reinforcement. Fitzwilliam & Bisby [14] investigated the effect of slenderness and eccentricity on the behavior of FRP confined circular RC columns tested under eccentric compression loading with various eccentricities. These studies highlighted that increasing of load eccentricity and slenderness is producing a reduction of confinement efficiency, also used of longitudinal CFRP wraps reduced lateral deflections and allow slender columns to achieve higher strengths. different CFRP external strengthened methods was studied by Quiertant & Clement [15] combining longitudinal flexural reinforcement and lateral confinement. Various arrangements of plates, unidirectional and bi-directional composite fabrics were investigated. Depending on the CFRP strengthening system, significant deformation capacity and ductility improvement was achieved for columns subjected to eccentric compression. However, for the tested strengthening configuration the contribution of flexural reinforcement to strength enhancement was not clearly established.

2. Experimental Program

Twelve circular columns were cast with cube ends to fixed in loading cap and tested at the laboratories of the faculty of Engineering, Al-Mustansiriyyah University, Iraq. All columns were made of normal concrete strength and reinforced with minimum ratio of steel reinforcement using deformed bars of 6 mm. The twelve columns were subdivided into three groups GA, GB and GC with four columns in each group depended on the slenderness ratio. Three slenderness ratio were tested (19.6, 29.4 and 37.8) for groups GA, GB and GC respectively to covered a wide range of column slenderness ratios. The specimens of first group CA had 150 mm diameter, 1200 mm overall height and 900 mm height, each cube ends had a cross section of 150x150 mm and a length of 150 mm. the specimens of second CB and third group CC had 100 mm diameter, 1200,1500 mm overall height and 900,1200mm height respectively, each cube ends had a cross section of 100x100 mm and a length of 150 mm. The first specimen of each group (CA-0, CB-0 and CC-0) tested as control columns, other specimens strengthened with CFRP in three manners (5strip with 50mm width, full wrapping, 5strip&longitudinal strip with perimeter/3 width). All columns were tested with eccentricity to diameter ratio (e/h) equal to 0.5. table 1 shows a compendium of the tested specimens.

| Group name | Column Symbol | Dimensions (mm) | Overall height (mm) | Reinforcement ratio % | No. of CFRP strip | Width of CFRP strip (mm) |
|------------|---------------|----------------|--------------------|----------------------|-------------------|------------------------|
| CA-0       |               | 150            | 900                |                      |                   |                        |
|            |               |                |                    | 1200                 |                   |                        |
|            |               |                |                    | $\rho_{min} = 0.0112$ | $7φ6$             |                        |

Table 1. Experimental column configurations.
2.1. Material Properties

Testing specimens has an average 28-days compressive strength of 34 MPa which was determined by conducting tests on six cylinders and six cubes. Normal strength concrete mix was used to make the test specimens. As shown in table 2.

| Mix No. | W/C Ratio | Mix Proportions (kg/m³) | Compressive Strength fₐ (MPa) at 28 days |
|---------|-----------|-------------------------|----------------------------------------|
| 1       | 0.42      | W: 170  C: 400  S: 600  G: 1200 | 34                                      |

The materials used through this study were ordinary Portland cement OPC (type 1), Normal weight natural sand with 4.75mm maximum size and Crushed gravel with maximum size of 12mm.

The types of steel reinforcements were used deformed steel bars Ø6 for longitudinal reinforcement, also; used deformed steel bars Ø6 for transversal reinforcement at bottom and top only. The tensile strength of used reinforcement bars was conducted as shown in table 3.

| Nominal Diameter (mm) | Yield stress fₛ (MPa) | Ultimate Stress fᵤ (MPa) | Elongation at ultimate stress (%) |
|-----------------------|-----------------------|--------------------------|----------------------------------|
| 6                     | 449.54                | 510.72                   | 2.04                             |

The fiber composite used for wrapping the column specimens was CFRP SikaWrap-301C product with fabric design thickness 0.167 mm and tensile strength 4900 MPa. The epoxy resin Sikadur-330 was used to bond the carbon fabrics over the columns.
2.2 Strengthening Procedure
After the preparing of the columns surfaces and making clean and dry; The two parts of epoxy resin (gray and white) mixed together according to the manufacturer recommendations, then applied on the Specific place of RC column. After that, CFRP was applied and handled carefully on the Specific place with a 30 mm overlap. Once the relevant layer of fabric was wrapped, another coat of the epoxy resin was applied. After the application process had been finished. The columns remained in its place for seven days before being tested. After completing the CFRP installation, and before the testing date, all concrete surface columns were painted white to distinguish the crack propagation easily.

2.3 Details of Columns Reinforcement
In this study all specimens reinforced with minimum ratio of steel reinforcement used deformed steel bars Ø6mm. All columns have the same diameter 100 mm were reinforced with minimum steel ratio ($\rho=0.0108$) which are equivalent (3Ø6mm) longitudinal steel bars to indicate the real effect of CFRP sheets, while the other columns have the diameter 150 mm were reinforced with minimum steel ratio ($\rho=0.0112$) which are equivalent (7Ø6mm) longitudinal steel bars in order to compared its results. As for the transverse steel reinforcement (ties) were used Ø6 mm deformed bars for all columns at bottom and top only. figure.1 show reinforcement details of the specimens. And CFRP distribution is shown in figure.2.

2.4 Test Setup
Twelve columns were tested under uniaxial compression loading up to failure with eccentricity equal to (0.5 diameter) of each group of specimens. According to the circumstances of this test, the upper part is supported to be pin and lower part is supported to be fixed. One dial gauge position was marked at the middle of length of each column specimen, to measure the mid-height lateral displacement (deflection) of columns as shown in figure.3 The resultant was taken from the direction of displacement.

2.5 Loading cap
For testing of specimens under eccentric load the researcher was designed and manufactured a special loading head system made of high strength steel which were fixed on column cube ends, it consists of
two main parts: a 30-mm thick steel couple plate can be moved and fixed on another by bolts sitting on column cube ends, and a circular steel roller as a knife load with 40 mm diameter. It can be moved and fixed along the axis of the plate to achieve the required eccentricity at a set distance from the center of the cross section of the column as it can be seen in figure 4.

![Image of test set-up and loading caps](image)

**Figure 3.** Test set-up of column specimen. 
**Figure 4.** Loading caps.

### 3. Test Results and Discussion

All specimens were tested using an 8551MFL SYSTEM of hydraulic universal testing machine type EPP300, in the laboratories of the faculty of Engineering, Al-Mustansiriya University, Iraq. The ultimate loads and the corresponding lateral displacements of RC columns were recorded during the uniaxial compression loading applied which based on the slenderness ratio with CFRP distribution. The test results for all specimens are given in table 4. After every (5 second) load increasing of the RC columns was checked for cracks and any probable failure marks.

| Group name | Column symbol | Ultimate load Pu (kn) | Crack Load Pcr (kn) | Displacement at mid-height mm | % increasing in Pu |
|------------|---------------|-----------------------|---------------------|------------------------------|-------------------|
| Group (A)  | CA-0          | 370                   | 40                  | 8.7                          | Reference column  |
|            | CA-5S         | 435                   | 57.5                | 9.4                          | 17.56             |
|            | CA-FULL       | 570                   | 65                  | 12                           | 54                |
|            | CA-5S&Longit. | 690                   | 140                 | 1                            | 86.5              |
| Group (B)  | CB-0          | 97.5                  | 17                  | 9.35                         | Reference column  |
|            | CB-5S         | 137                   | 25                  | 11.52                        | 40.5              |
|            | CB-FULL       | 162.5                 | 25.5                | 12.82                        | 66.67             |
|            | CB-5S&Longit. | 193                   | 30                  | 13                           | 97.94             |
| Group (C)  | CC-0          | 80                    | 17.5                | 11                           | Reference column  |
|            | CC-5S         | 121                   | 22.5                | 14.7                         | 51.25             |
|            | CC-FULL       | 140                   | 22.5                | 13.1                         | 75                |
|            | CC-5S&Longit. | 175                   | 23                  | 15.2                         | 118.75            |

*Table 4. Test Results and Details of columns up to failure*
From below figures, curves and bar charts show failure modes of tested columns and testing results, there are found that the confined of columns by using the carbon fiber reinforced polymer (CFRP) cause increasing in the load capacity of columns, such that when used five strip confined of CFRP with width 5 cm for each strip distributed symmetrically along column give more strength of column with respect to reference column and this increasing approximately about 21%. But for columns with full CFRP confined the increasing of load capacity of columns becomes approximately about 55% with respect to reference column, in addition to improve the ductility of columns with respect to reference column and the improvement becomes about 30%.

In the other hand, the confined with five stripe in the circumferential direction of columns and one strip in the longitudinal direction of columns at tension face increased the load capacity of columns with rate higher than the two previous type of confined and the increasing rate becomes about 85% with respect to reference column, and the ductility increased about 40% with respect to reference column.

Final, from economic side the direction of CFRP in the strategy of columns strengthen is very adequate to use lowest area of CFRP in the strengthening of columns as shown in the figures (10) and (11). The use of CFRP in the strengthening of columns must be according to the structural behavior of columns to satisfy the economic condition.

In the other hand, the effect of slenderness ratio gave the logical results, such that, when the slenderness ratio increased the load capacity of columns becomes decreasing for all groups, and these results still show the confined of columns with CFRP were improving the results with high value with the same above rate for all slenderness ratio.

![Figure 5. Failure modes and Comparison between Load Buckling curves of Group A (GA) Columns.](image)
Figure 6. Failure modes and Comparison between Load Buckling curves of Group B (GB) Columns.

Figure 7. Failure modes and Comparison between Load Buckling curves of Group C (GC) Columns. It is obvious that slenderness ratio had clear effect on crack load and ultimate load as shown in follow charts:
Figure 8. Relationship between slenderness ratio and crack load and ultimate load of several Columns.

Effect of carbon FRP area ratio on crack load and ultimate load for columns under eccentric loading the direction of carbon fibres have clear effect on load capacity of columns. That is clear when columns strengthening with longitudinal strip and five circumferential strips cause increasing in the load capacity of columns more than strengthening with full CFRP wrapping as shown in charts below:

Figure 9. Relationship between CFRP area ratio and crack load and ultimate load of several Columns.

In order to show the effective of CFRP wrapping directions on crack load and load capacity below bar charts plotted. Crack load and load capacity increased when strengthened with longitudinal strip on tensile face as shown below:
4. Conclusion
From this research, the following pointes could have been concluded: The confined of columns with CFRP increasing the load capacity of columns with rate reach to 85%. The direction of confined with CFRP is very affected on the load capacity of columns and the increasing due to direction reach to 40%. The direction of confined with CFRP is very affected on the cost conjugate with CFRP. The load capacity of columns decreasing with increase slenderness ratio but stilled show the confined of

Figure 10. Bar chart of effect of CFRP direction on crack load of several columns at crack stage.

Figure 11. Bar chart of effect of CFRP direction on the load capacity of several columns at ultimate stage.
columns with CFRP were improving the results with high value. The ductility of columns confined with CFRP increasing with rate reach to 40% with respect to reference column.

5. References

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