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Behavior of Eccentrically Loaded R.C. Columns Confined with CFRP Composites

Mahmoud Elsayed[1], Mohamed Elassaly[2], and Wafaa Esmail[3]

[1]*Assistant Professor, Dep. of Civil Engineering, Faculty of Engineering, Fayoum University, Fayoum, Egypt*
[2] *Professor of structural Eng., Dep. of Civil Engineering, Faculty of Engineering, Fayoum University, Fayoum, Egypt*
[3] *Post-graduate student, Dep. of Civil Engineering, Faculty of Engineering, Fayoum University, Fayoum, Egypt*

Abstract - The scope of this research is to study experimentally the behavior of reinforced concrete slender columns strengthened with carbon fiber-reinforced polymer (CFRP) under the effects of eccentric loadings. A total of twelve R.C. rectangular columns were cast and tested experimentally. Eight columns have a dimension of 100*150 *1700 mm whereas the other four specimens have 100*150*1900 mm. Among the tested samples, three unwrapped columns were chosen as reference specimens, while the other nine columns were wrapped by CFRP composites. The columns were tested under the effects of concentrated load accompanied with eccentricity. The investigated variables in this experimental program, include different wrapping schemes, the thickness of the CFRP layer, column slenderness, and load eccentricity. The experimental results show a significant enhancement on the performance of wrapped columns by CFRP sheets compared to unwrapped columns. The load carrying capacity and the ductility of columns were visibly improved by wrapping CFRP sheets around the columns. It was found that the partial and full CFRP jacket can significantly improve the ultimate load capacity by 55%–75% respectively.

Key Words: R.C. Slender Columns, Retrofitted, CFRP, Eccentric Loading

1. INTRODUCTION

In recent years, fiber reinforced polymer (FRP) composite jackets have been used to strengthen R.C. compression members. Strengthening and repair of R.C. elements using Fiber Reinforced Polymers (FRP) are gaining a wide popularity and acceptance due to its well-established and promising performance. In this regard, FRP confinement obtained a major step in the field of strengthening and repairing R.C. columns to significantly improve the capacity and ductility of RC columns [1–3]. The researchers [4-7] studied experimentally the behavior of CFRP strengthened circular RC columns under eccentric loadings. The effect of strengthening scheme and slenderness ratio, eccentric ratio, and concrete strength was suggested. It was observed that CFRP-wrapping enhances the ultimate loads and ductility of slender RC columns considerably. The behavior of FRP wrapped fiber steel R.C circular columns under eccentric loading was experimentally studied by Hadi [16]. Widiarsa [8] and Lie [9], investigated the performance of RC short columns wrapped by FRP and subjected to eccentric loadings. Three main variables were studied; eccentricity ratio, the compressive strength of concrete, and the number of FRP layers. Hassan et al [10] and Hadi [11] and [12] carried out an experimental program to evaluate the influence of FRP confinement columns of normal and high strength concrete under different loads eccentricity. The effect of CFRP and GFRP jackets were studded. The columns were tested under three eccentricities of 0, 25 mm, and 50 mm. The results indicated that the load carrying capacity and ductility was improved with using CFRP-strengthening. Rahai and Akbarpour [13] performed a laboratory test to improve the efficiency of using CFRP composites for rehabilitation rectangular R.C. columns under axial load and biaxial bending moment. Csuka and Kollar [14] proposed an analytical model to evaluate the efficiency of using FRP in strengthening circular and rectangular columns under eccentric loading. Quiertant and Clement [15] investigated the behavior of eccentrically loaded columns confined with various CFRP techniques. Experimental results show that the increase in ultimate load and ductility of the columns depend on the wrapping schemes. Hadi [17] carried out an experimental study to investigate the effectiveness of FRP confined R.C. columns. The specimens were tested under three eccentricities conditions (0, 25 mm, and 50 mm). It was observed that increasing the eccentric load led to reducing the failure load of strengthened columns. Minafò et al [18] suggested a non-linear finite element method to calculate the buckling curves in masonry members confined by FRP wraps. The influence of the cross-sectional shape under different loading cases on the behavior of R.C columns strengthened with CFRP was investigated by El Maaddawy [19] and Pham, et al [20]. The results indicated that the performance of the eccentrically loaded columns had enhanced with the CFRP- retrofitting and the shape of the cross section had a slight influence on the ductility. Yang [21] carried out an experimental program to study the structural performance of eccentrically loaded high strength high-strength concrete columns strengthened with CFRP laminates. The influence of eccentricity ratio, wrapping scheme, the number of CFRP layers, and pre-damaged condition was investigated. The test results indicated that wrapping CFRP sheets around the columns led to increasing the ductility and ultimate capacity of columns.

2. Research Significance

The main goal of this study is to investigate experimentally the effect of external CFRP laminates on the behavior of RC slender columns under eccentric loadings. Four main parameters which were; two different eccentricities of 25 mm and 50 mm, two column clear height of 1300 mm and 1500 mm, two number of CFRP layers (single and double layers), and strengthening schemes were introduced to achieve a maximum efficiency of CFRP wrapping. In order to achieve this objective, a total of twelve R.C. columns were cast and tested.

3. Experimental work

3.1 Material properties

All columns were cast in a horizontal position using wood plates as formwork. The columns were constructed from the same batch of concrete to preserve the same concrete strength. The average cube strength of concrete was 26 MPa at the time of testing. Two different types of reinforcing steel bars were used in reinforcement the columns Ø 8mm as stirrups and Φ12 as longitudinal steel reinforcements. The yield strength of transverse and main reinforcement was 290 Mpa and 420 MPa, respectively. The CFRP composites used were (BASF MBRACE FIBER). The ultimate tensile strength, elastic modulus, ultimate elongation and thickness of composite is 3800MPa, 240GPa, 1.55%, and 1.20 mm respectively. The fabric was glued to the specimens with an epoxy resin (Master Brace ADH 4000), the two-component epoxy adhesive having the tensile strength of 32 Mpa and modulus of elasticity of 10 GPa.

3.2 Test specimens

The experimental program of this study involved testing of twelve rectangular slender columns, three columns were kept as reference specimens without CFRP confinement, whereas the other nine were wrapped by CFRP composites. All columns have a rectangular cross-section of 100*150 * 1700 mm and 1900 mm in over height, including corbel heads, the dimensions of top and bottom corbels were 100*200*250 mm and 100*200*300 respectively. In all columns, Ø 8mm smooth bar was used as a transverse reinforcement spaced at 180 mm in the middle region and at 100 mm to the ends of the columns, the columns were reinforced with 4 Φ12 as main longitudinal reinforcement. The concrete cover was maintained at 25 mm thick on the surface and 20 mm thickness at top and bottom. **Fig -1** shows the columns geometry and reinforcement details. The specimens were divided into main three groups [A], [B], and [C]. Each group containing four columns of the same height and the same load eccentricity. The Specimens of groups [A] and [B] belonged of 1300 mm clear height, whereas the specimens of group [C] have 1500 mm clear height. The columns of groups [A] and [C] were tested under eccentricity of 25 mm of (e/t = 0.17), while the specimens of group [B] were subjected to eccentricity loading of 50 mm of (e/t = 0.34). Each group consisted of control unstrengthened specimen, two fully wrapped columns with single or double layers in the transverse direction of the column, and one strengthened column with partial wrapping with single straight longitudinal CFRP laminate glued along the tension side of the specimen hence wrapped by transverse confining partially applied single layered CFRP wraps spaced 200 mm center to center. The CFRP layer had an overlap of 100 mm in the hoop/transverse direction of the specimen. The description and strengthening schemes of the test specimens are shown in **Table 1** and **Fig- 2** respectively.

Strengthening of the test specimens

Before applying the CFRP, the columns were rounded 20 mm in the corners and cleaned the surface of the specimens from dust and rough surfaces. The CFRP sheets were cut according to the size required, and then CFRP was glued to the concrete columns. The epoxy was mixed according to the specifications from the manufacturer. After wrapping CFRP, one more layer of epoxy was applied on the surface of CFRP. Finally, the confinement columns were kept in the laboratory under the air condition environment for one week to ensure that the epoxy was effective.

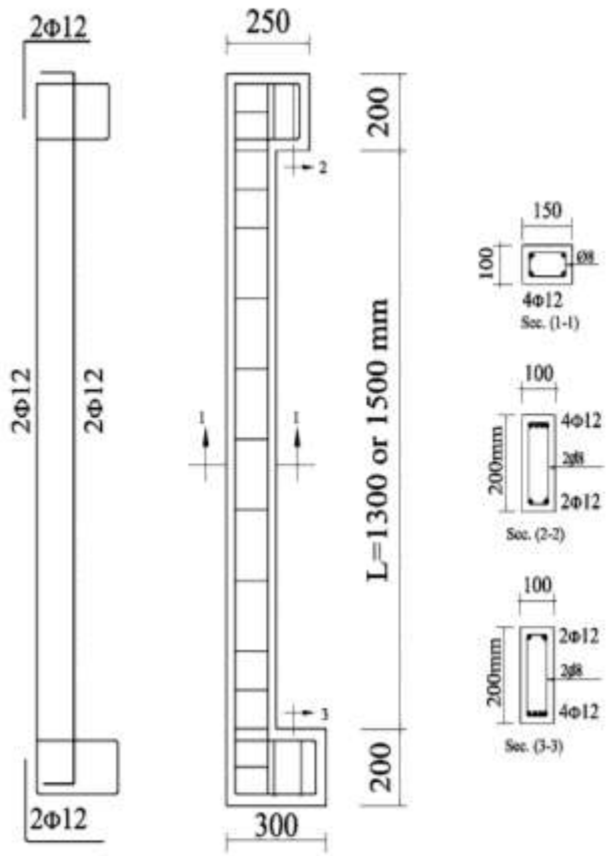


Fig -1: Dimensions and Reinforcement Details of column

3.3 Test Setup

All columns were tested using a 1000 kN capacity compression hydraulic actuator. The specimens were tested under two eccentric compression loads with an eccentricity of 25 mm and 50 mm. The columns subjected to a monotonic concentrated load until failure. The load eccentricity was achieved using bearing plates of 100*100 mm having a bearing area of 10000 mm2. Two linear variable differential transformers (LVDT) were used in this study, one LVDT was located at mid-height of the specimen to measure the lateral displacement and the other LVDT was placed on a corner of the column to measure the axial deflection. Each specimen was instrumented with two electrical strain gauges placed at mid-height of the column, one strain gauge (SG1) is installed at the compression side and while the other one (SG2) is installed at tension side. **Fig -3** shows the experimental test setup.

TABLE -1: Sample Test specimens Configurations

Group	Specimen ID	Clear height of column (mm)	CFRP Wraps	Long. FRP Scheme	Trans. Wrap. Scheme	Eccentricity (mm)	Eccentricity ratio (e/t)
[A]	C01	1300	No-CFRP	No-CFRP	No-CFRP	25	0.17
	C02	1300	1	No-CFRP	Full	25	0.17
	C03	1300	2	No-CFRP	Full	25	0.17
	C04	1300	1	1 Layer tension side	1 Partial	25	0.17
[B]	C05	1300	No-CFRP	No-CFRP	No-CFRP	50	0.34
	C06	1300	1	No-CFRP	Full	50	0.34
	C07	1300	2	No-CFRP	Full	50	0.34
	C08	1300	1	1 Layer tension side	1 Partial	50	0.34
[C]	C09	1500	No-CFRP	No-CFRP	No-CFRP	25	0.17
	C10	1500	1	No-CFRP	Full	25	0.17
	C11	1500	2	No-CFRP	Full	25	0.17
	C12	1500	1	1 Layer tension side	1 Partial	25	0.17

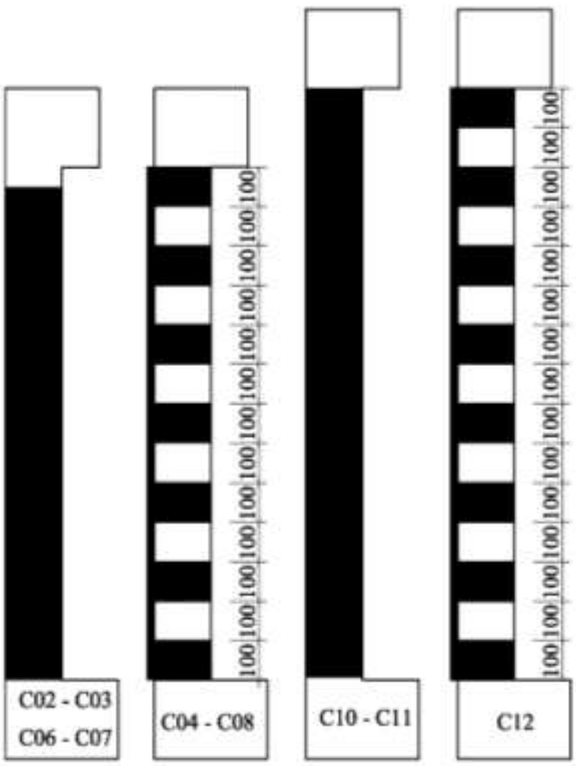


Fig -2: Strengthening schemes of wrapped specimens

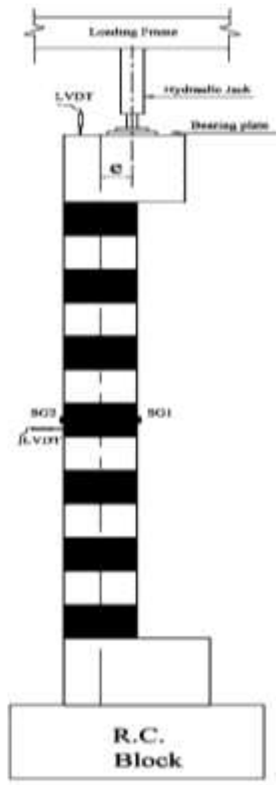


Fig -3: Experimental Test Setup

4. Experimental Results and Discussion

The test results of confined and unconfined specimens are discussed in the following sections. The ultimate load, ultimate deflection, ultimate moment, crack pattern and failure mode, ductility ratio, and energy absorbation were compared to evaluate the efficiency of strengthening of those columns.

4.1 Cracking Pattern and Mode of Failure

Fig -4 shows the cracking patterns and failure region of the test specimens after the completion of the test. It can be observed that the failure of unwrapped specimens was occurred at compression side accompanied by crushing of large portions of the concrete cover and no signs were observed before failure. The damaged of the columns C1 and C5 appeared near the ends. The locations of plastic hinge region were at the first and last third of the column for specimens C1 and C5 respectively, whereas the position of crushing was represented at mid-height of the column C9 accompanied by buckling of compressive longitudinal bars. The type of failure modes of reference specimens is still crushing failure, however, changing the eccentricity ratio and column slenderness. For confined columns, it can be detected that the damage patterns are affected by strengthening schemes and the number of CFRP layers. The rupture of CFRP sheets was almost started at the wrapped columns mid-height. Specimens of partial wrapping with single straight longitudinal CFRP laminate the crushing of concrete in compression zone accompanied by rupture of longitudinal CFRP strip at the tension side and buckling of longitudinal bars in compression zone were observed. For full wrapped columns, the failure was occurred by rupture of the transverse wrapping CFRP mid height layer at compression face. The retrofitted specimens C10 and C11 the CFRP layers were cut out accompanied by buckling out of plan due to the weakness of column slenderness in the perpendicular direction. The failure of specimen C12 was occurred due to crushing accompanied by rupture of transverse CRFP layer in compression face at the zone under the upper corbel.

4.2 Load - Displacement Relationship

Figs -5 to 7 show the axial and lateral displacement versus the applied load curves for groups [A], [B], and [C] respectively. The three strengthening schemes proved their effectiveness in improving the load-carrying capacity and deformability of eccentrically-loaded columns. The overall behavior was the same for all the CFRP wrapped specimens. The ultimate load of all CFRP wrapped columns was significantly improved. It was observed that CFRP strengthening RC columns with full wrapping with CFRP is more effective in increasing the column strength than the use of longitudinal tension side CFRP laminates overlaid by transverse partially applied ones for small eccentricity loaded specimens (e/t=0.17). Confinement columns with one or two layers of CFRP laminates led to gain in the strength of the columns up to 51% and 75% over the control specimen, respectively. The effectiveness of applying CFRP sheets in the tension side only was increased with increasing the eccentricity ratio as the ultimate load was increased by 55%. The gain in ultimate load capacity of the strengthened columns was significantly reduced with increasing the eccentricity and column slenderness. The experimental results indicated that the productive wrapping effects of each of the three CFRP strengthening schemes are more marked for the shorter columns. It was indicated that the initial stiffness of retrofitted columns was slightly increased. It was observed that the deflections corresponding to the peak load of the confined columns were enhanced significantly compared to that of control specimens. The restraint effect of full wrapping strengthening technique was the most superior scheme with increasing the number of CFRP layers.

4.3 Ultimate Load Capacity

The ultimate carrying capacity and the increment in the ultimate load of the test specimens are listed in **Table -2**. The failure loads of confined columns were closely related to the CFRP strengthening schemes and CFRP layers. The two layers CFRP confinement scheme brought significant enhancements in peak load up to 75%, 62% and 65% for the groups [A], [B], and [C], respectively. Increasing no of CFRP layers from single to double layers led to increasing the failure load from 41% to 65%. The use of strengthening technique of applying of two layers of CFRP laminates in full wrapping resulted in markedly higher ductility than that obtained from flat laminate in tension side. The results indicated that the load capacity of specimens of group [A] (e=25 mm) C02, C03, and C04 was 51%, 75%, and 21% greater than that of control specimen C01 respectively The increment in failure load of specimens C03 (e=25 mm) and C08 (e=50 mm) was found 21% and 55 % higher than that of the control specimens C01 and C04 respectively. The gain in ultimate load capacity of wrapped specimens (c10, C11, and C12) of the group [C] was 35%, 65%, and 13% larger than that of unwrapped specimen C09 respectively. It was demonstrated that the failure load decreased and the corresponding axial deflection increased when the eccentricity changed from 25 mm to 50 mm.

4.4 Moment-Curvature Behavior

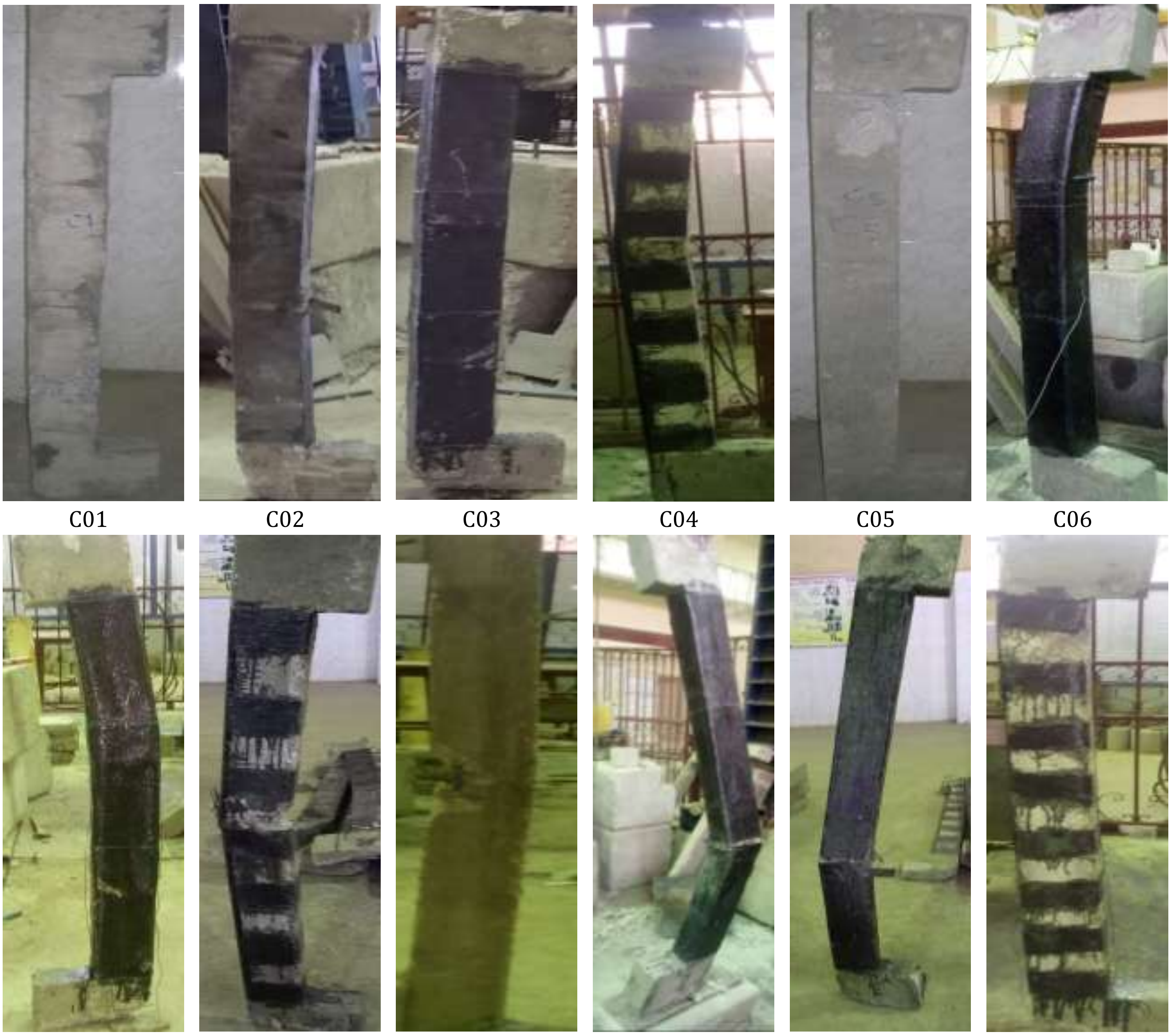
The test specimens were tested under eccentric loading creating eccentric bending. The bending moment was determined by multiplying the axial load by the effective eccentricity as shown in Eq. (1). The effective eccentricity was calculated at each load step by predefined eccentricity e plus lateral displacement mid height ULat at the previous load step. The curvature φ was calculated using the longitudinal strain on the tension and compression sides of the mid-height section as shown in Eq. (2).

$$M = P(e + ULat) \qquad \text{Eq.(1)}$$

$$\varphi = \frac{\varepsilon L,top - \varepsilon L,bot.}{h} \qquad \text{Eq.(2)}$$

TABLE -2: Summary of the test results

Group	Specimen	Ultimate Load (kN)	Displacement at ultimate load (mm)		Pu/Pc	Ductility ratio	Energy absorption (kN.mm)	Ultimate Moment (Mu) (kN.m)	Mu/Mc
			Axial	Lateral					
[A]	C01	248	7.00	13.50	1.00	2.32	2730	9.55	1.00
	C02	375	7.25	9.75	1.51	3.29	3653	13.03	1.36
	C03	434	8.25	10.50	1.75	3.89	4242	15.41	1.61
	C04	297	8.00	13.00	1.21	2.93	3870	11.29	1.18
[B]	C05	183	7.50	8.00	1.00	2.38	2115	10.61	1.00
	C06	258	8.25	9.50	1.41	2.56	2453	15.35	1.45
	C07	296	10.25	8.25	1.62	3.88	3255	17.24	1.63
	C08	284	8.00	7.00	1.55	4.17	2811	16.14	1.53
[C]	C09	203	8.75	11.50	1.00	2.57	1734	7.41	1.00
	C10	275	12.00	13.00	1.35	3.37	2473	10.45	1.41
	C11	335	7.50	13.25	1.65	3.92	3734	12.81	1.73
	C12	230	7.25	9.00	1.13	4.11	1973	7.82	1.06



C01 C02 C03 C04 C05 C06

C07 C08 C09 C10 C11 C12

Fig -4: Failure modes and cracking pattern of the test specimens

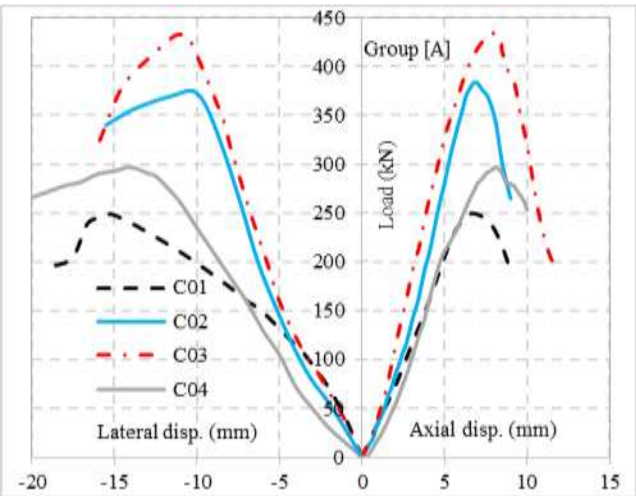


Fig -5: Load –Displacement Curves for group [A]

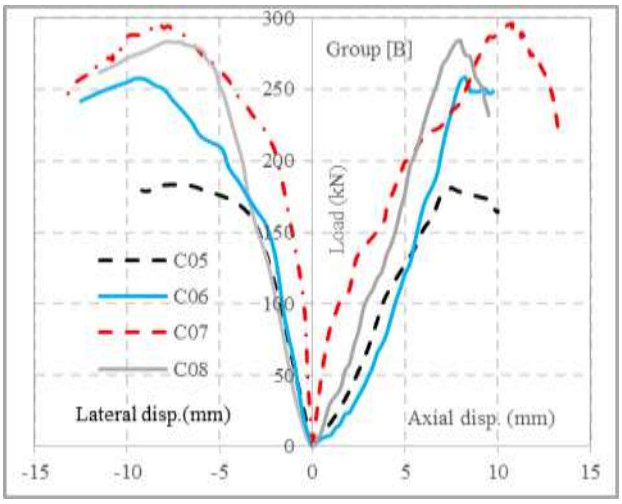


Fig -6: Load –Displacement Curves for group [B]

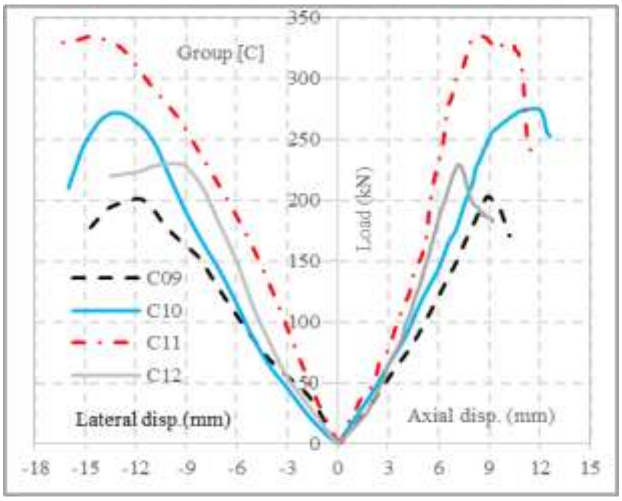


Fig -7: Load –Displacement Curves for group [C]

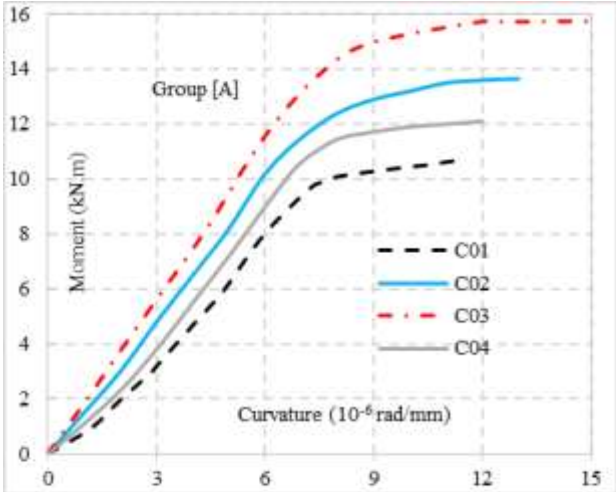


Fig -8: Moment-Curvature Curves for group [A]

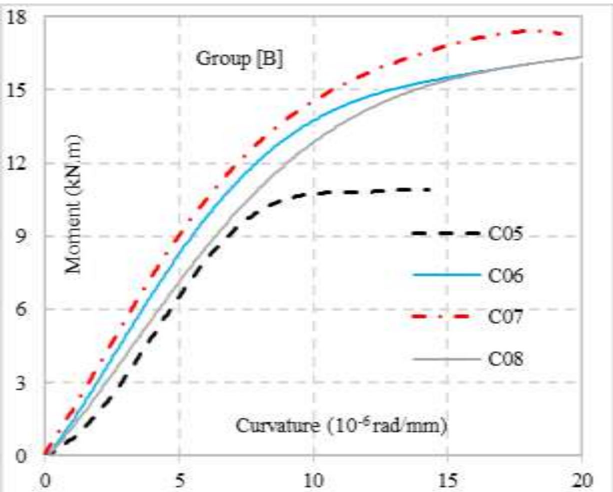


Fig -9: Moment-Curvature Curves for group [B]

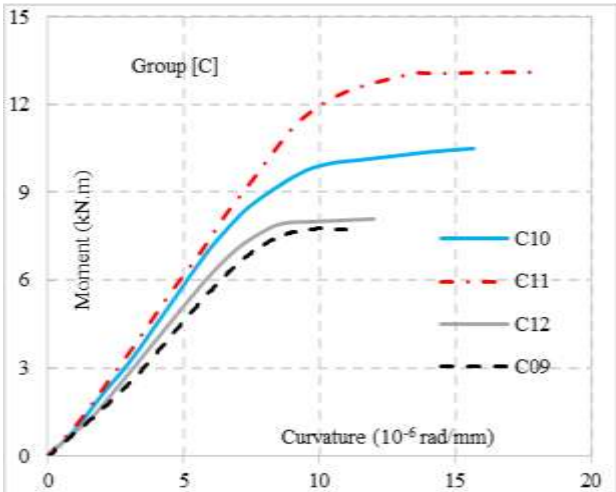


Fig -10: Moment-Curvature Curves for group [C]

Where; ε L,top is the longitudinal strain of the tension side; ε L,,bot. is the longitudinal strain of the compression face; and h is the height of the cross-section = 150 mm. The moment-curvature behavior of the test specimens was investigated around the major axis of the cross-section. **Figs -8** to **10** show the moment-curvature for groups [A], [B], and [C] respectively. The ultimate moment was determined and listed in **Table -2**. It was observed that the ultimate moment and moment stiffness of CFRP wrapped columns were enhanced. Full wrapping strengthening technique with double layers achieved better improvements in moment capacity and bending stiffness. Compared to the unconfined columns, the double layers CFRP wrapping scheme brought significant improvements in moment capacity amounting up to 61% and 63%, and 73 % for the columns C03, C07, and C11 respectively. The use of vertical tension side CFRP sheets overlaid by transverse partially applied ones leads to slightly significant improvements in the flexural capacities under the eccentricity of 25 mm. The ultimate moment of retrofitted columns C04 and C12 was increased by 18% and 6% higher than that of the control specimens respectively. The results indicated that the curvature capacities are not enhanced significantly.

4.5 Ductility and Energy absorption

The structural behavior of a retrofitted column is not only measured by its load carrying capacity but with its capability to absorb external energy through its deformational capacity also, so the ductility and energy absorption can directly reflect the plastic deformation capacity of the specimens. From the load-displacement curves ductility and energy absorbation were calculated and tabulated in **Table -2**. The ductility index was calculated as the ratio of area under the load-lateral displacement curve to the area under the curve up to the 80% of the maximum load Wang and Wu [22]. The Energy absorption was calculated as the area under load–mid-height lateral displacement which was calculated by numerical integration. From Table 2, it was observed that the ductility ratio and energy absorption of the wrapped specimens was higher than that of the unwrapped column. The increasing no of CFRP sheets causes an increase in ductility index and energy dissipation. The results indicated that the energy absorption of full wrapping CFRP sheets was higher than that of partial wrapping with longitudinal CFRP layer in tension side. The energy absorption was reduced with increasing load eccentricity and column slenderness.

5. CONCLUSIONS

This study presents an experimental investigation on the structural performance of R.C. rectangular columns wrapped with CFRP jacket under eccentric loading, the following conclusion can be summarized.

1. The CFRP jackets provide an effective technique in retrofitting R.C. columns under eccentric loadings.
2. All strengthened columns showed a significant improvement in the ultimate capacity over the unwrapped specimens which supports the hypothesis that the CFRP is very effective in terms of load carrying capacity of the test specimen by increasing the overall load capacity with 67% in average.
3. The effect of CFRP strengthening technique is slightly reduced with increasing column slenderness and load eccentricity.
4. The load carrying and ultimate moment capacities of confined columns were significantly enhanced with increasing the number of CRFP layers, as its enhancement ratio was about 75% and 73% respectively.
5. The pronounced improvements of wrapped R.C. columns under eccentric loadings in mechanical characteristics ensure the effectiveness of the strengthening techniques. It was observed that the average increment in ductility ratio and energy absorption was measured as 49 % and 45% respectively, compared to that of the unwrapped specimens.
6. The number of CFRP layers is major parameters, which has a significant influence on the strength, ductility, and energy absorbation of confined specimens. The ultimate strength of confined columns with double layers is 21% higher than that of a single layer.
7. Full wrapping with double layers of CFRP sheets is the most convenient method for the strength of eccentricity loaded columns as its average improvement ratio was about 75%.
8. The strengthening technique of longitudinal tension face CFRP laminates overlaid by transverse partially applied ones becomes a suitable method with increasing load eccentricity. The load and flexural capacities of CFRP- confinement were enhanced up to about 55% and 52% respectively.

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