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EXPERIMENTAL STUDY OF HOLLOW SLENDER REINFORCED CONCRETE COLUMNS SUBJECTED TO ECCENTRIC LOADS

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Abstract

This paper was focused on the investigating on the behavior of hollow slender reinforced concrete columns subjected to the axial loads. A total of seven specimens were designed as slender reinforced columns and these were divided into two groups. Each column is symmetrical and had a rectangular cross section of 140 × 80 mm and 2000 mm in length. The column was reinforced by 6Ø6mm for longitudinal reinforcement and Ø6@6 mm bars were used for transverse reinforcement ties. The effect of strengthening by CFRP sheet on the buckling of column, eccentricity 20, 40 and 120 mm and opening shape were studied. The results showed that the strengthened columns by CFRP caused an in the ultimate load CFRP were 26.3 % and 76.3 % for strengthened lengths of *L*/4 and *L* respectively compared with the un-strengthened column. The ultimate load of columns is reduced with existing the load eccentricity and amount of losses in strength increased with increasing the eccentricity. Also, it was found the hollow columns having circular holes had better performance compared to hollow columns having rectangular hole

Keywords:

Hollow slender column opening;
Shape eccentricity;
CFRP.

1 Introduction

To maximize structural efficiency in term of strength ratios and to reduce contribution of the column to seismic response and high carrying demand on foundation, it is desirable to use hollow cross section for columns [1]. It could be economical to use hollow reinforced concrete columns if the cost of concrete is comparatively high or if the weight of the concrete members is to be kept to a minimum [2, 3]. The hollow columns have been preferred to solid columns to reduce the cost of the structures, and to decrease the self-weight of the structures where it is technically necessary. Few experimental works have been done on the presence of longitudinal openings in slender reinforced concrete columns, the present work is devoted to study experimentally the hollow slender reinforced concrete columns under axial loading and eccentric loading. Also, the effect of CFRP on the strengthening of hollow slender concrete column had been studied. Many previous studied for the experimental works on slender reinforced concrete columns and short hollow reinforced concrete columns. Notable investigations can be summed up briefly as follows:

Elimihilmy [4], tests were carried out to investigate the behavior of slender columns subjected to pure axial loads or to axial loads with small eccentricity. Seventeen square slender reinforced concrete columns with different slenderness ratios were tested under axial load and flexure. The research program studied slenderness ratio, lateral and vertical steel reinforcement ratios, tie and spacing eccentricity of the axial load. The results are summarized that columns with closely spaced transverse reinforcement showed more ductile behavior at higher ultimate loads. The test results indicated that tie arrangement effects on both peak loads and ductility. The vertical reinforcement ratio alters both the ultimate loads and lateral deflections. It was noticed that the recorded lateral deflection increased by the amount of the initial applied eccentricity. Bakhteri and Iskandar [5], carried out tests to investigate

the effect of embedding rain water pipes inside reinforced concrete short columns in multistory buildings. Fourteen short columns in seven sets, having different sizes and reinforcement, with a PVC drain pipe positioned at the center of the cross section of each column have been tested. The test result showed that the positioning of a drain pipe PVC inside the column significantly reduces the load carrying capacity and the effective cross-sectional area of the specimens. Son et al. [6], experimental tests were conducted on nine concrete columns with different ones transvers opening. Eight concrete columns with various transverse openings and one column without a hole were cast to evaluate the effect of section loss on the compressive resistance capacity. For every type of column, two samples were cast. The parameters investigated experimentally were the diameter, relative position and number of holes. The results showed that the presence of column holes caused a loss of approximately 9 to 21 % of the bearing capacity of the column load, and their analysis deduced that this loss is directly proportional to the loss of area. Lignola et al. [7], experimental tests were carried out on seven short columns of square hollow reinforced concrete confined to CFRP. To study the behavior of the hollow members, three eccentricities of 50, 200, and 300 mm were selected. The results show that the improvement in strength was more significant in the case of specimens loaded with lower eccentricity, while the improvement in ductility was more important in the case of higher eccentricity. Yazici and Hadi [8], a series of tests on hollow core reinforced concrete circular short columns wrapped with CFRP were carried out. Eight circular short columns were divided into two groups in this study, four columns denoted by C letter for externally unconfined and L letter for externally confined by wrapping three layers of lateral CFRP sheets in the direction of the hoop. They summarize that CFRP wrapping has shown that the ductility and strength of the axial load carrying capacity are more efficient, by increasing axial and lateral deformation capacities. When the load is concentric, the axial load carrying capacity of the FRP wrapped sample was increased by 50.91 % and the axial deflection corresponding to the maximum load Δ was increased by 178.67 % compared to the unwrapped sample. Waleed A. et al. [9], RC columns reinforced with CFRP according to different parameters such as layer thickness CFRP and eccentricity were experimentally studied. The study results showed that the carrying capacity of the reinforced columns has increased relative to normal columns. Gajdosova and Bilcik [10], the effects of slender rectangular reinforced concrete columns reinforced by CFRP through two techniques were shown. Furthermore, they showed that the effects of CFRP were comparatively greater in terms of increasing column strength than for short RC columns subjected to compression. Further, the research showed that longitudinal fibers in the form of CFRP strips affixed to the grooves in the cover of concrete were of greater influence in increasing the flexural load capacity of slender reinforced concrete column SRCC. Youcef et al. [11] investigated the effectiveness of strengthening by CFRP on behavior of four very slender reinforced concrete columns, subjected to monotonic eccentrically axial load. Four columns with cross section 200x200 mm and length 1600 mm were used to study the effect of strengthening, one control column, and three columns, differently strengthened with a composite of CFRP. The control column without strengthening, the second strengthening with composed of 2 CFRP layers, the third column strengthening with consists of a layer of CFRP which the fibers are disposed longitudinally to the column axis and fourth column strengthening consists in two layers, one the same as that of third column, on this is added another CFRP layer, such as the fibers are arranged perpendicularly to the column axis. The results of this study showed the three types of strengthening used in this research have relatively increased resistance significantly. Nadeem et al. [12] investigated of slender circular RC columns strengthened with FRP composites. A total of 12 small-scale circular RC columns of 150 mm diameter were cast in three groups, each group containing four columns of the same height. The strengthened columns were prepared using three different strengthening schemes, the first strengthening scheme, the columns were wrapped using a single layer of hoop CFRP sheet, whereas other strengthening schemes employed two and four longitudinal CFRP sheets in addition to one layer of hoop CFRP wrap. CFRP-strengthening improves the strength and ductility of slender RC columns substantially. The results of this study showed the percent increase in load carrying capacity due to FRP strengthening the increase in load carrying capacity for strengthening scheme varies from 34 % to 73 % which is mainly due to the increase in the confining strength of concrete. The effect of hoop wraps on the strength of columns is more significant for short columns 73 % than slender columns 61 % for 900 mm and 34 % for 1200 mm columns. Al-Zubadi [13], the behavior of slender reinforced concrete columns with a longitudinal hole under axial compression load and uniaxial bending has been studied. The research program examined the hole size, eccentricity, vertical hole locations, tie spacing and column height. Test results indicate that the effect of hollowing ratio on load capacity is insignificant when the holes were located at the center of the column cross-section and the column

was loaded with high load eccentricity, The effect of the hollow ratio on columns loaded with low eccentricity is greater than that of the hollow ratio on columns loaded with high eccentricity, which reduces the loading capacity of the columns. Hadi et al. [14]. The behavior of columns confined to a circular Carbon-Fibre-Reinforced Polymer CFRP tube of hollow core reactive powder concrete HCRPC has been studied. Sixteen circular hollow core specimens 206 mm in diameter, 800 mm in height and a 90 mm circular hole were made of 105 MPa compressive strength Reactive Powder Concrete RPC. These specimens have been categorized into four groups. The control group, consisting of four unconfined HCRPC specimens reinforced with conventional longitudinal steel bars and steel helices, was the first group. The second group of specimens had the same configuration as the first group, except that they were externally confined to the CFRP tube. The third group specimens were externally confined with a tube of CFRP and internally confined with a tube of Polyvinyl chloride PVC. Finally, there was no steel reinforcement in the specimens of the fourth group and they were only made with an external CFRP tube and an internal steel tube. The results showed that the strength of the HCRPC columns was slightly increased by the CFRP tube confinement, while ductility was significantly enhanced.

2 Experimental program

2.1 Material

2.1.1 Concrete

Normal strength concrete used in casting of all specimens and the compressive strength was 35 MPa. The mix design listed in Table 1.

Table 1: Mix proportion.

Cement [kg/m^3]	Water [kg/m^3]	W/C ratio	Sand [kg/m^3]	Gravel [kg/m^3]
531.7	217.9	0.41	655.32	890

2.1.2 Steel reinforcement

Deformed steel bars with diameter of 6 mm were used for both lateral and longitudinal reinforcement in all columns, while deformed steel bars were used in this study with nominal diameter of 12 mm and 8 mm for corbel reinforcement in columns. Were tested at the laboratory to determine the yield stress f_y and the ultimate strength f_u. The test was conducted according to ASTM A615 [15]. The properties of the tested bars is presented in Table 2.

Table 2: Properties of reinforcing bars.

Bar diameter [mm]	Actual diameter [mm]	Area [mm^2]	Yield stress f_y [N/mm^2]	Tensile strength f_u [N/mm^2]	Elongation [%]
6	5.9	27.3	378.58	424.5	11.8
8	7.82	48.03	432	540	25
12	12	113	562	665	15

2.1.3 Carbon fiber reinforced polymer (CFRP)

SikaWrap®-300 C/60 carbon fiber was used in this study to externally strengthen the reinforced concrete columns. The thickness of CFRP is 0.127 mm, and is laminated with epoxy resin adhesive (Sikadur-330) to form a carbon fibre-reinforced polymer laminate CFRP. CFRP and epoxy properties are as shown in Table 3 [16].

Table 3: CFRP sheet and epoxy properties.

Properties	CFRP sheet	Epoxy
Tensile strength [MPa]	3,900	30
E modulus [MPa]	230,000	4,500

2.2 Specimens details

Ten concrete columns that were casted and tested. Two specimens tested under axial loads and the other specimens that were designed with a corbel at the ends of the column, for testing under eccentric load. Corbels have been added to the columns that are applied an eccentricity loads for two main reasons: the first reason was to prevent a failure near the ends of the columns due to the occurrence of shear stress in the area opposite to the direction of the eccentric distance because of its small area. The second reason was that the load can be applied with an eccentric distance outside the column, so the presence of the corbel is to provide a support for the purpose of applying the load according to the required distance. The details of columns with corbels are observed in Fig. 1. All columns are symmetrical in this study, with a cross section of 140×80 mm and 2000 mm in length. The slenderness ratio $\lambda = kl/r$ of this study was 80·5 and this ratio was successfully according to the American code ACI 318-19 [17] and British standard BS-8110 [18]. Each column was reinforced by 6Ø6 mm for longitudinal reinforcement and Ø6 mm bars were used for transverse reinforcement ties. Three experimental factors were studied for the columns specimens. The factors were strengthening by carbon fiber polymer CFRP sheet, opening shape and eccentric load. The ten columns were divided into seven groups as illustrated in the Table 4.

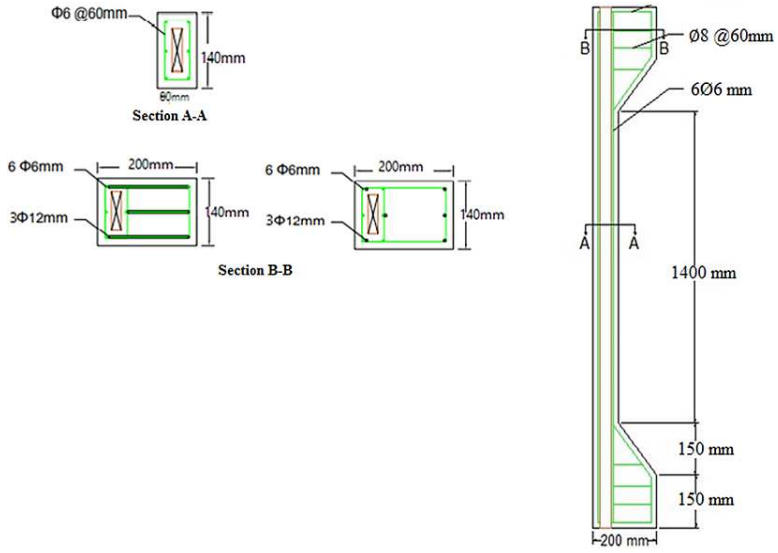


Fig. 1: Details of column.

Table 4: Details of groups.

No. of groups	Column ID	Distance of strengthening by CFRP from the inner end of corbels [mm]	Shape of opening	Eccentricity [mm]
First group	C1	-	Rectangular	0
	C2	-	Rectangular	20
	C3	-	Rectangular	40
Second group	C2	-	Rectangular	20
	C4	-	Circular	20
Third group	C3	-	Rectangular	40
	C5	-	Circular	40
Fourth group	C6	500	Rectangular	0
	C7	200	Rectangular	40
Fifth group	C7	200	Rectangular	40
	C8	200	Circular	40
Sixth group	C9	1400	Rectangular	120
Seventh group	C5	-	Circular	40
	C8	200	Circular	40
	C10	1400	Circular	40

2.2.1 First group

Through this group the effect of the eccentricity on slender columns was studied. Where, C2 column was tested by subjecting it on the load with an eccentric distance perpendicular to the width of the column, equivalent to one fourth of the column thickness, which was 20 mm. Also, C3 column was tested with an eccentric distance equal to half of the column thickness, which was 40 mm. Both columns were compared with the reference column C3, which was tested under axial load. The opening in all the columns in this group was rectangular. The details are shown in Fig. 2.

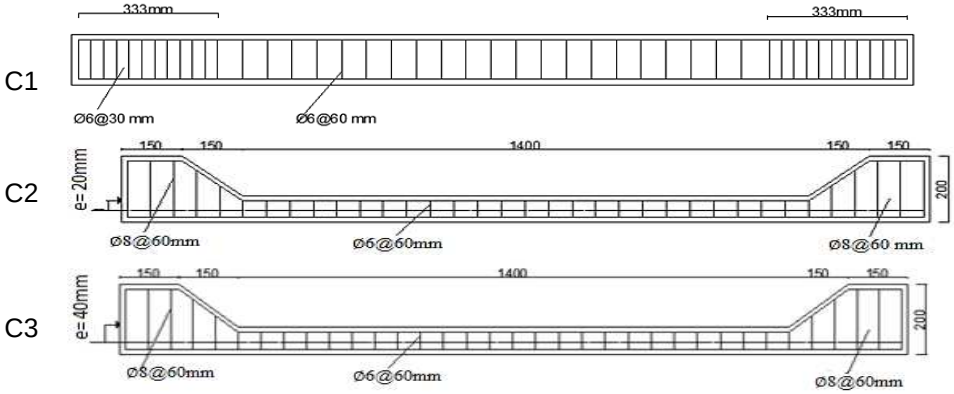


Fig. 2: First group details.

2.2.2 Second group

This group included two columns. The columns have eccentricity equal to 20 mm with opening of different shape. The objective of the study was to understand the effect of the eccentricity on the hollow slender columns with openings of different shapes. A circular hole inside the column with a diameter of 45 mm with an area roughly equivalent to the area of the rectangular hole. The details are shown in Fig. 3.

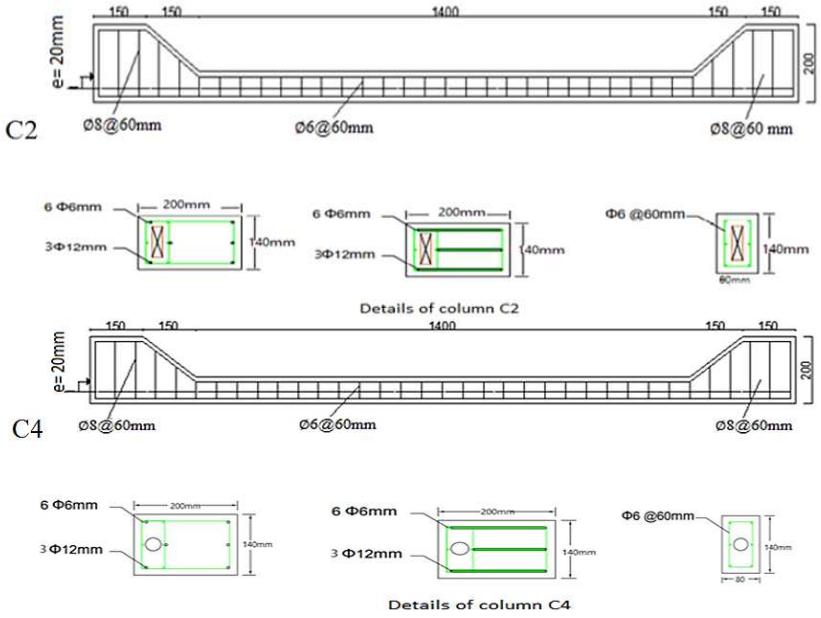


Fig. 3: Second group details.

2.2.3 Third group

This group included two columns, C3 and C5. The columns C3 and C5 have eccentricity equal to 40 mm with opening of different shape. The objective of the study was to understand the effect of the eccentricity on the hollow slender columns with openings of different shapes. Details in Fig. 4.

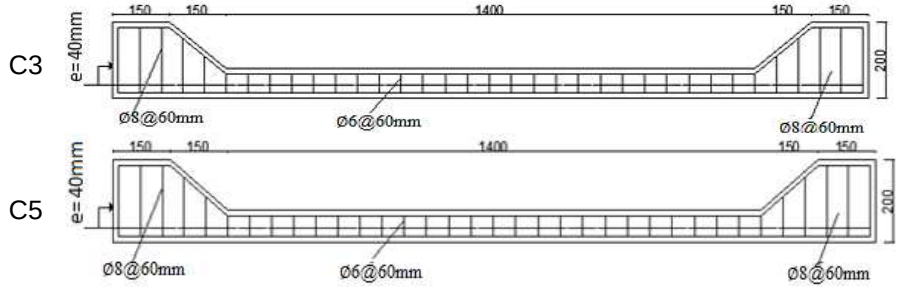


Fig. 4: Third group details.

2.2.4 Fourth group

The effect of eccentricity on strengthened columns with CFRP was studied. Where, C6 column was tested by subjecting an axial load and strengthened with CFRP at distance of 500 mm. While, C7 was tested with an eccentric equal to 40 mm and strengthened with CFRP at distance of 200 mm from both internal corbels. Actually, the choice of the above strengthening distance is not arbitrary, but rather for the purpose of strengthening the column for a distance equivalent to a quarter of the length of column from each end. But the presence of the corbels at a distance of 300 mm from each end denied the need to strengthen this area with CFRP and remaining distance of 200 mm was strengthened. The details are shown in Fig. 5. The shape of the opening is a rectangular of all the columns.

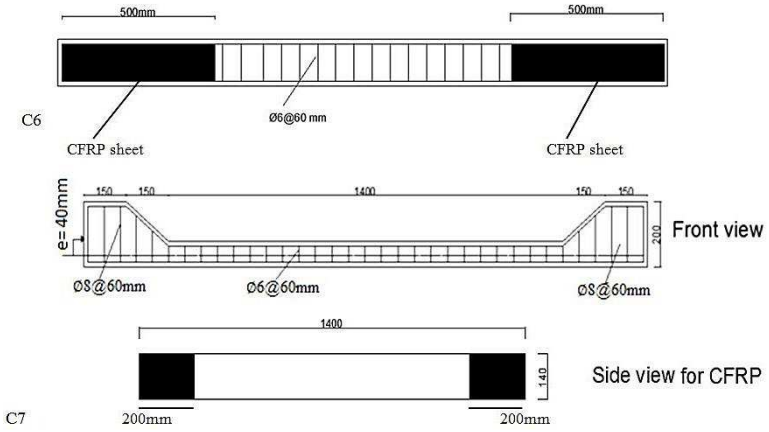
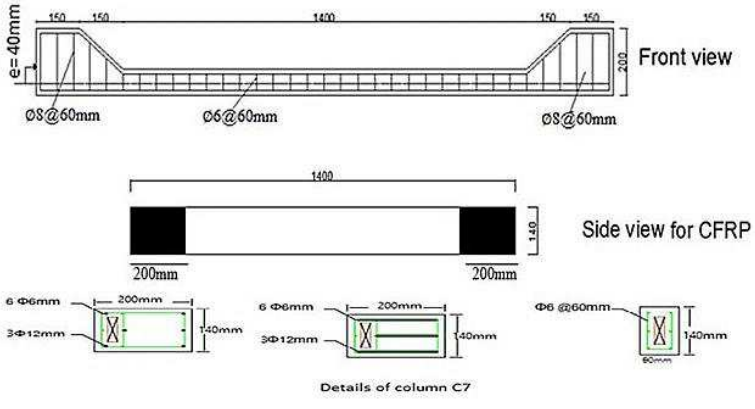


Fig. 5: Fourth group details.

2.2.5 Fifth group

In this group there were two columns C7 and C8. The columns having the same eccentricity and strengthened with opening of different shapes. The purpose of this group was to study the effect of eccentricity with different hollow and strengthened by CFRP sheet with the same length. Details are shown in Fig. 6.



C7

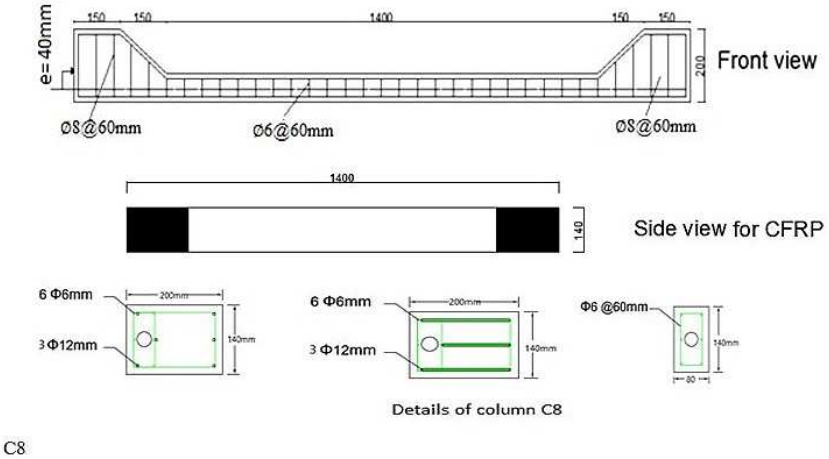


Fig. 6: The details of fifth group.

2.2.6 Sixth group

This column was selected for the purpose of applying an eccentric load at a distance of one and half times of the thickness of column and was 120 mm. The purpose of choosing this distance is to test a column that the load is applied on it at a distance outside the boundaried of the column dimensions to know how this column behaves. It is expected that there will be a high moment due to the large eccentric distance, so a fully strengthened column was chosen C9. No previous studies have studied the existence of eccentricity outside the boundaried of the dimensions of the column, so this specimen was studied in a group alone. The details are shown in Fig. 7.

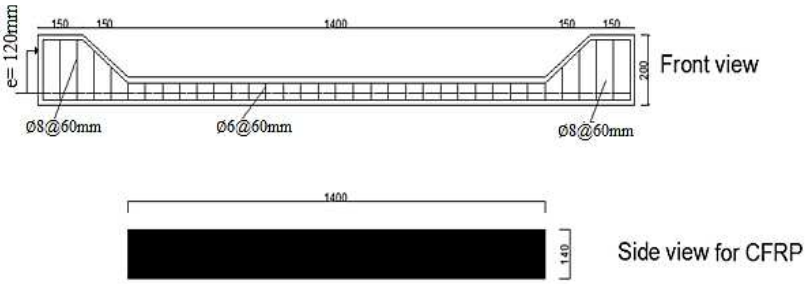
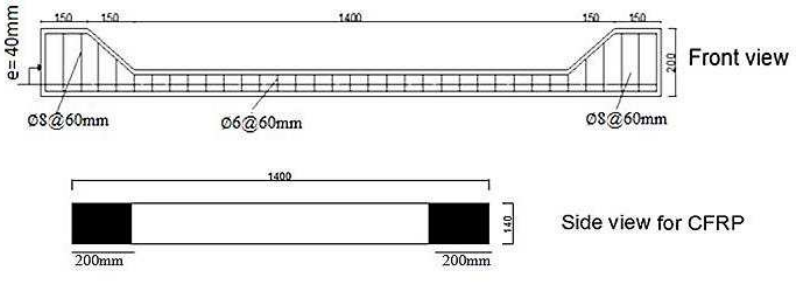


Fig. 7: Details of C9.

2.2.7 Seven group

This group included three columns. The objective of this group to study the effect of eccentricity on the column having a circular hollow and strengthened by CFRP sheet in different lengths. The C5 was kept without strengthened. While C8 and C10 were strengthened using CFRP sheet in 200 mm and 1400 mm respectively at opposite sides of the width of the column. Details are shown in Fig. 8.



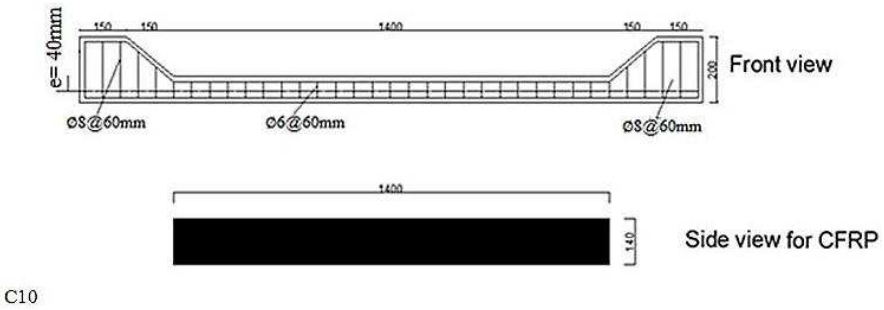


Fig. 8: Details of ninth group.

2.3 Preparation of samples for strengthening

All samples were cast in a horizontal arrangement. To apply CFRP, the following steps were followed: It should be removed a layer of concrete surface of 0.5 – 1.0 mm. Coarse aggregate using grinding tool as shown in Fig. 9. Further, any materials and dust should be removed using water and brush. The adhesive of epoxy Sikadur-330 was applied on CFRP and column surface. After that, applying epoxy on CFRP sheet and columns surface on the coated region and pressure applying by a rubber roller to seat the sheet by that cause epoxy forced out from both sides of the sheet. Finally the columns be ready to test after curing for some days.



Fig. 9: Preparing and setting the CFRP sheet.

2.4 Testing machine and test setup

Steel rig had been fabricated and assembled at the Reinforced Concrete Laboratory of the Technical Institute of Amara, Iraq, in order to facilitate the execution of the experimental work program. Steel caps with dimension 200 × 50 × 8 mm is provided at both ends to facilitate the application of eccentric loading. A 20 mm rod was used in the plate and device to restrict the horizontal and vertical movements of the specimens, as shown in Fig. 10. While the column was loaded using compression test machine of 600 kN capacity. The load was applied on the top end of the column. The columns are placed under the test frame socket and adjusted so that the midline. Before the test, to adjust the supports and loading system a small load was applied, and then the initial readings were taken. Order scale readings were taken at each step of the download. It took some time for this conduct to occur until the failure.



Fig. 10: Column cap for eccentric load.

2.5 Result and discussion

The main structural characteristics observed and recorded during the test of each column specimen and at each loading stage are used to evaluate the structural behavior of the tested column specimens.

Table 5: Experimental test results of column specimens.

Column ID	Ultimate load Pu [kN]	Lateral displacement Δ [mm]	Ductility index [μΔ]	Energy absorption [kN·mm]	Moment *M-P* × e [kN·mm]
C1	195	3.7	4.11	612.638	0.7215
C2	175	4.3	3.11	584.579	4.24
C3	160	3	2.5	320.792	6.88
C4	200	6.5	4.33	1074.47	5.3
C5	190	5.75	4.1	870.954	8.69
C6	400	17.8	10	6298.875	7.12
C7	200	6.75	4.22	1121.825	9.82
C8	240	7.5	4.4	1431.214	11.4
C9	100	2.5	2.5	195.85	12.25
C10	335	11	6.11	2948.085	17.1

2.5.1 Results of first group

Eccentricity of load was one of the important factors on load carrying capacity of columns especially slender columns. The behavior was affected by the eccentricity. It can be observed that increasing the eccentricity of the applied load caused an increasing in the lateral displacement at the same load level. Increasing of the eccentricity from 0 to 20 and to 40 mm caused an increasing in the lateral displacement by 110.5 % and 215.8 % respectively at a level of load equal to 160 kN, the minimum ultimate load in this group, as shown in Fig. 11. Two eccentricity values 20 mm and 40 mm caused decreasing in the load carrying capacity of columns by 10.26 % and 17.95 % for columns C2 and C3 respectively compared with the column C1. Also, when the eccentric load on the column is further increased, it will tend to increase the applied moment. So the moment increased by 487.42 % and 853.172 % in column C8 and C9 respectively compared with the column C3. The eccentricity led to decrease in the ductility index and energy absorption by 24.33 % and 39.17 % and 4.58 % and 47.63 % for columns C2 and C3 respectively compared with the column C1. Figs. 12 and 13 showed the effect of eccentricity on ductility and energy absorption.

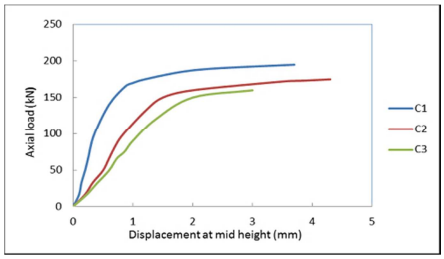


Fig. 11: Load-displacement curves for first group

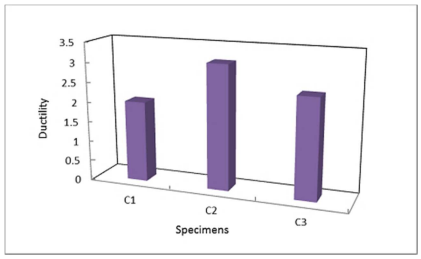


Fig. 12: Effect of eccentricity on ductility.

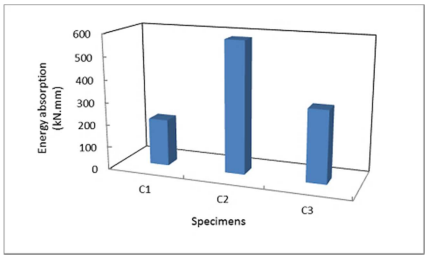


Fig. 13: Effect of eccentricity on energy absorption.

2.5.2 Result of second group

The test results proved that the columns with circular hole have a good performance compared to the columns have rectangular hole in terms of ultimate load. The increased in ultimate load and deflection were 14.29 % and 51.2 % respectively in column C10 compared with the column C8. Fig. 4.17 represented the effect of opening shape under the same eccentricity *e* = 20 mm on load-displacement curve. From the result above the increase in maximum lateral displacement and ultimate

load in column C10 due to the use of a circular hole instead of a rectangular hole in column C8. This is due to the fact that the distribution of the load was more uniform in the circular opening shape because there is no weak point at the corners as in the rectangular section. The moment also increased by 24.7 % in column C4 compared with the column C2. It's noticed that column C4 with circular openings has ductility and energy absorption greater than C2 by 39.23 % and 83.8 % respectively. Fig. 14 represent to load-displacement curve. From the result above the increase in lateral displacement, ultimate load, moment, ductility index, and energy absorption in column C4, due to the use of a circular hole instead of a rectangular hole in column C2 for area roughly equivalent to the area of the rectangular hole. This is due to the fact that the distribution of the load was more uniform in the circular opening shape because there is no weak point at the corners as in the rectangular section. Figs. 15 and 16 showed the effect shape opening under the same eccentricity *e* = 20 mm on ductility and energy absorption.

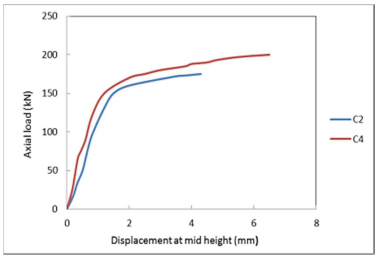


Fig. 14: Load-displacement curve for second group.

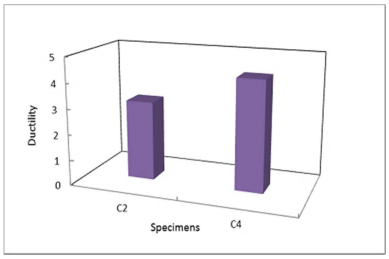


Fig. 15: Effect of shape opening on ductility, *e* = 20 mm.

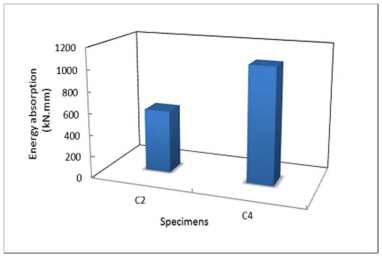


Fig. 16: Effect of shape opening on energy absorption, *e* = 20 mm.

2.5.3 Result of third group

The shape opening under eccentric load *e* = 40 mm played a remarkable role on the ultimate load, max displacement, ductility and energy absorption. The ultimate load and deflection of column C5 increased by an average of 18.75 % and 91.7 % respectively compared with the column C3. The effect of eccentricity on displacement at mid height of columns is shown in Fig. 17. When the value of lateral displacement increased from 3 mm to 5.75 mm under the same eccentricity the moment also, increased by 26.3 in column C5 compared with the column C3. The ductility and energy absorption increased by 64 % and 171.5 % respectively in column C5 compared with the column C3. Figs. 18 and 19 showed the effect shape opening under the same eccentricity *e* = 40 mm on ductility and energy absorption respectively. It is clear that increase the ultimate load and maximum displacement of the hollow circular column exceeds that of hollow rectangular column for the same cross sectional area, possibly due to the distribution of the load being more regular in the columns having circular hole due to the absence of corners.

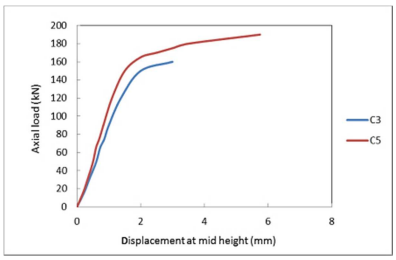


Fig. 17: Load-displacement curve for third group.

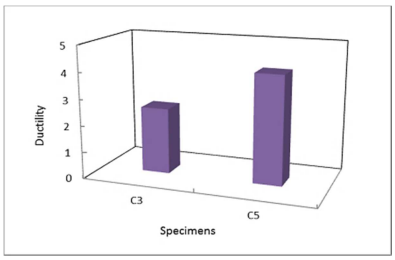


Fig. 18: Effect of shape opening on ductility, *e* = 40 mm.

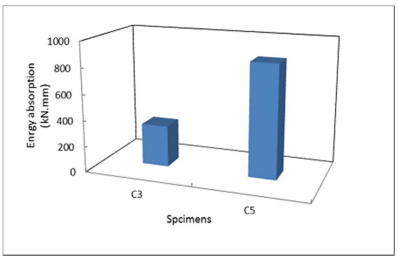


Fig. 19: Effect of shape opening on energy absorption, *e* = 40 mm.

2.5.4 Result of fourth group

The test results for two columns showed that the ultimate load and max lateral displacement decreased by 47.5 % and 61.8 % respectively when the eccentricity increased from 0 to 40 mm in column C7 compared with the column C6 as shown in Fig. 20. Increasing eccentric load from zero to 40 mm with strengthening by CFRP in the column C12 means that the moment is greater than in column C7 by 37.9 %. The presence of eccentricity caused an increase in ultimate moment on the columns, causing buckling and early failure. The ductility and energy absorption decreasing by 52.5 % and 82.2 % respectively for column C7 compared with the column C6. Figs. 21 and 22 show the effect of using CFRP under eccentric loading on ductility and energy absorption.

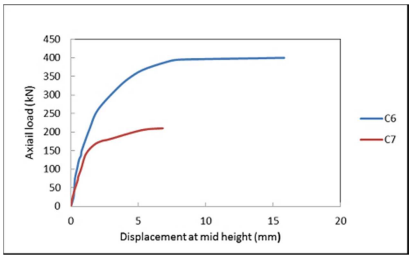


Fig. 20: Load-displacement curve for fourth group.

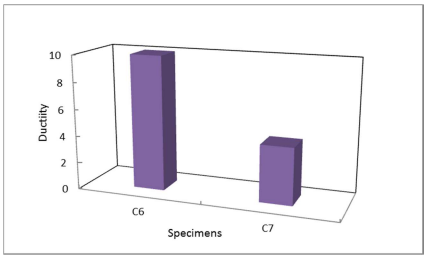


Fig. 21: Ductility index.

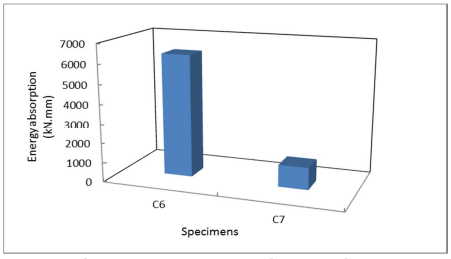


Fig. 22: Energy absorption.

2.5.5 Result of fifth group

The hollow reinforced concrete column had circular hole C8 carry higher ultimate load and displacement, compared to column had rectangular hole C7. The increased in ultimate load and maximum displacement by 14.3 % and 10.3 %, respectively as shown in Fig. 23. It can be seen that strengthening the columns using CFRP at the same length with circular hole led to a higher ultimate moment than rectangular hole. It was found that the increasing in moment was 16.1 % in column C8 compared with the column C7. The increased in ductility and energy absorption in the column C8 were 4.27 % and 27.5 % respectively compared with the column C7. The gain in the capacity for RC columns increases with the change the type of opening shape from rectangular hole to circular hole and the use of carbon fiber led to increased confinement in the columns and thus increased the strength in columns as illustrated in Figs. 24 and 25.

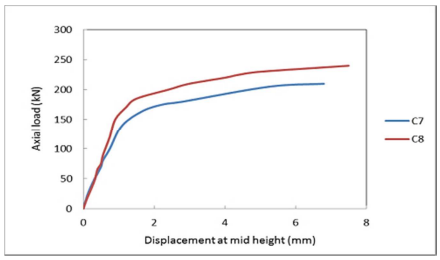


Fig. 23: Load-displacement curve for fifth group.

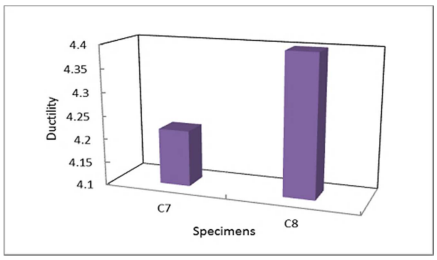


Fig. 24: Effect of CFRP with different opening on ductility.

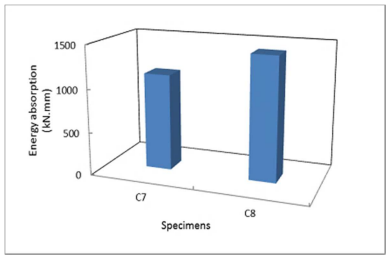


Fig. 25: Effect of CFRP with different opening on energy absorption.

2.5.6 Result of sixth group

C14 column was strengthened at a distance of 1400 mm between both internal ends of the corbels. The ultimate load and max lateral displacement record 100 kN and 2.5 mm, respectively. It was also noted that these values are few compared to the others column due to the presence of high eccentricity. The ultimate moment equal to 12.25 kNm. The ductility and energy absorption were 4.1 and 195.85 respectively. Fig. 26 showed mensuration of load-displacement relation result for C3 tested under high eccentricity e = 120 mm.

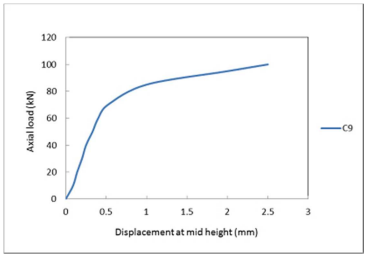


Fig. 26: Load-displacement curve for C3.

2.5.7 Result of seventh group

This case included three specimens C5, C8 and C10 tested under the same eccentricity 40 mm and circular hollow with different CFRP sheet lengths. Max lateral displacement increased in C8 and C10 by 26.1 % and 91.3 % respectively compared with column C5. When the CFRP sheet is fixed along the width of column, the ultimate load in the column C10 was increased by 76.3 %. Also column C18 gave a good result when fixed CFRP sheet on the quarter of length. Where the increase in C13 was 26.3 % when compared to the non-strengthened column C5. Fig. 27 showed the load-displacement result for seventh group. The increase in ultimate load due to used CFRP in different lengths because the use of CFRP has properties such as: high strength to weight ratio; corrosion resistance; ease and speed of application; minimal change of cross-sections; possibility of installation without interruption of structure functions. For these reasons, CFRP has been widely used in the retrofitting and strengthening of reinforced concrete structures, especially in regions under high seismic risk [19]. The moment increased by 31.2 % and 96.8 % for C8 and C10 respectively compared with the column C5. Also the ductility enhancement by 7.32 % and 49.02 % respectively in C8 and 10 when compared to the non-strengthened column C5 as shown in Fig. 28. Energy absorption ranged between 870.954-2948.085 kNm. Fig. 29 showed the effect of eccentricity on the column having a circular hollow and strengthened by CFRP sheet in different lengths on energy absorption.

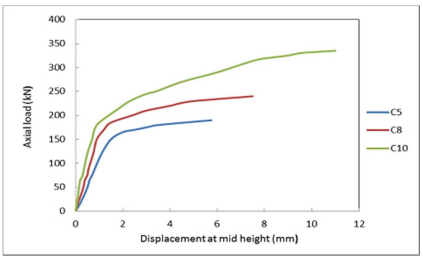


Fig. 27: Load-displacement curve for seventh group.

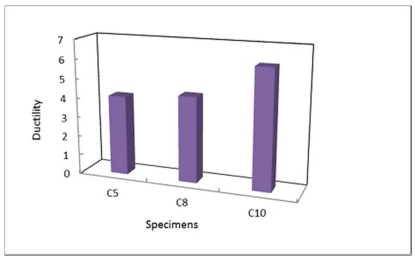


Fig. 28: Effect of CFRP with circular hole on ductility.

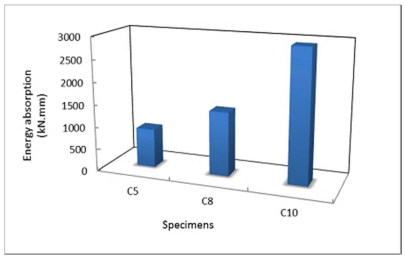


Fig. 29: Effect of CFRP with circular hole on energy absorption.

3 Mode failure

When the columns are exposed to loads, they start to buckle without obvious cracks in the areas of tension and compression of the column and then the column suddenly fails in the form of an explosion. The failure mode of column C1 was local buckling but the failure happened at distance 340 mm from the top of column. Column C2 failed due to local buckling at a distance of 500 mm from the top end of this failure occurred due to change the eccentricity from 0 to 20 mm without obvious cracks. In column C3, the mode failure was local buckling but at a distance of 340 mm with eccentricity equal to 40 mm and this failure was accompanied with buckling of longitudinal reinforcement. When changing the opening type to circular opening and under eccentricity 20 mm, the column C4 failed due to buckling at distance 840 mm, the failure did not occur exactly at the mid-height but still in the test region. Also, the failure mode in column C5 was buckling at a distance of 800 mm with circular opening and under eccentricity 40 mm. In the column C6 failed due to buckling in mid-point because used CFRP sheet at a distance of 500 mm from both ends of column, strengthening with CFRP sheet up to 50 %, so the stresses from the stronger region CFRP to the weaker region have been transferred at the ends of the CFRP material itself. Whilst, the mode failure in C7 strengthening with CFRP at a distance of 200 mm was buckling in the mid-height of the column and this failure accompanied with buckling in longitudinal reinforcement, meanwhile, C8 also strengthening in the same way as C7 with different opening shape circular opening, the failure occurred suddenly in the last third of the length column at end of CFRP sheet. C9 column failed early and the failure occurred from the top at the end distance of the corbel because the stresses were concentrated in the upper third of the column under the corbel area due to the high eccentricity. In column C10, the failure occurred in the last third of the length column accompanied by a rupture in CFRP sheet, a ripple in CFRP, and buckling in longitudinal reinforcement. All concrete removed from the failed columns was loose and able to be removed easily by hand. Fig. 30 represented the mode failure of hollow slender reinforced concrete columns C1-C10.



Fig. 30: Mode failure for specimens C2-C10.

4 Conclusion

1) Effect of increasing the eccentricity values of reinforced concrete slender columns led to reduce ultimate load capacity by 10.26 % and 17.95 % for *e* = 20 mm and *e* = 40 mm respectively. The ductility index decreased by 24.33 % and 39.17 % when the value of *e* is increased from 0 to 20 mm and 40 mm respectively. Also when the values of *e* increased from 0 to 20 mm and 40 mm, the energy absorption decreased by 4.58 % and 47.63 % respectively.

2) For 20 mm load eccentricity, it was found that the column having circular opening shape caused an increase in the load capacity, ultimate moment, ductility and energy absorption than column having rectangular by 14.29 %, 24.7 %, 39.23 % and 83.8 % respectively.

3) For column strengthened by CFRP at distance of 200 mm from both internal corbels and having a rectangular opening shape under eccentricity of 40 mm led to decease in the ultimate load, ductility and energy absorption by 47.5 %, 52.5 % and 82.2 % respectively. But, the ultimate moment increased by 37.9 %.

4) In case of columns strengthened by CFRP, whole the column, and having rectangular opening with eccentricity equal to 120 mm the results showed decrease in ultimate load, ductility and energy absorption compared to other columns. it can be advise don't take a high eccentricity, and take a value of eccentricity with a distance equal to quarter or half of the column thickness, which were 20 mm and 40 mm to avoid early failure.

5) Strengthening the column length by CFRP caused an increase in resistance to buckling.

6) For columns tested under the same eccentricity of 40 mm and circular hollow with different CFRP sheet lengths, it was found the column strengthened by CFRP sheet along the width of column from both internal corbels. The ultimate load, ultimate moment, ductility and energy absorption increased in this column 76.3 %, 96.8 %, 49.02 % and 238.5 % respectively compared with un-strengthened column. Also when fixed CFRP sheet on the quarter of length from both internal corbels column gave a better performance in terms of ultimate load, ultimate moment, maximum lateral displacement, ductility and energy absorption compared with un-strengthened column

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