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Experimental Study for Strengthening of RC Rectangular Columns with Anchored CFRP Sheets

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Abstract— Debonding between CFRP sheets and concrete surface is one of the most important modes of failure. The common solution to prevent this mode of failure is to extend the CFRP sheets by enough length to avoid debonding. A more advanced technique is to anchor the CFRP sheets to the concrete element using either steel or CFRP anchors. The aim of this research is to study the effect of using CFRP anchors on the capacity of concentric and eccentric RC columns. In order to achieve that goal, ten specimens of RC columns divided into two sets were tested. The first set was tested under concentric load, while the other set was tested under eccentric load. Each set had one control sample, while the other four samples were wrapped with CFRP bands. Two of the wrapped samples were anchored and the others were not. The spacing between CFRP wraps was varied between 80 and 200 mm. The results showed that the concentric and eccentric capacity of the sample increased with decreasing the spacing between CFRP bands as long as the eccentricity is small enough to cause compression failure mode. But for samples with tension failure caused by large eccentricity, the CFRP bands have no effect on the capacity. It was also noted that anchors have no significant effect on the axial capacity of the samples.

Index Terms— Strengthening, RC Column, Eccentric Load, CFRP Sheets, CFRP Anchors.

1 Introduction

Strengthening of existing structures is required for many reasons such as increasing ultimate load capacity, changing the activity of the structures, updates in design codes and overcoming of construction mistakes [1]. In most cases, strengthening presents more economical alternative than demolition and re-construction [2]. Because vertical elements in multi-story buildings are the most affected elements due to increasing gravity or lateral loads, many earlier researches were carried out to present different techniques to strengthen them [3] [4]. One of the most recent techniques is to wrap the RC columns with CFRP sheets. The advantages of CFRP wrap are easy installation, corrosion resistance, short construction period, no maintenance required, light weight and low cost. CFRP sheets have been applied to increase the concrete confinement and loading resistance of reinforced concrete columns. Increasing the capacity of reinforced concrete columns by CFRP sheets depends on different variables, steel reinforcement, number of layers of CFRP sheets and loading conditions. Although it is simple technique, earlier researches show a great success for this technique in increasing the ultimate capacity of the RC columns [5]. Debonding is one of the main failure modes that were observed in earlier researches on CFRP wrapped columns. It simply occurs by separating the CFRP sheets from the RC column surface. This phenomenon most likely happens when the cross section of the column has large aspect ratio and it happens on the long side of column section [6]. To overcome this phenomenon, many anchorage systems were proposed to ensure the bond between the CFRP sheets and RC column surface. CFRP anchors are one of the most recently proposed techniques to eliminate debonding failure and improve the efficiency, reliability and safety of CFRP strengthening. It is more effective than steel anchors due to its non-corrosive nature and it can be applied to a wide variety of structural elements [7].

The Aim of this research is to investigate the effect using CFRP anchors on the structural behavior of the CFRP wrapped RC columns subjected to axially and eccentric loads.

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2 Experimental Work

2.1 Research program

The research program comprised testing ten RC Rectangular concrete columns up to failure. All samples had a cross section of 120×300mm and total height of the sample is 1600mm, 1000mm clear height and two hammer heads 300mm height each as shown in Figure (1-a), and reinforced vertically by 6 deformed bars 10mm diameter and laterally with 13 smooth stirrups 8mm diameter at the clear height of the column and 4 stirrups 8mm diameter at each column head as shown in Figure (1-a).

Samples C1 and C6 were control samples without CFRP sheets while samples C2, C3, C7 and C10 were partially wrapped using 4 CFRP bands with 200mm clear spacing between bands, Samples C4, C5, C8 and C9 were partially wrapped using 6 CFRP bands with 80mm clear spacing between bands. Samples C3, C5, C9 and C10 had CFRP anchors at the mid height of each CFRP band on each long side of the column. Samples were divided into two groups; the first group (form C1 to C5) was subjected to axial loads while the second group (from C6 to C10) was subjected to eccentric loads. Samples C6 and C7 were loaded under eccentricity of 80mm to test the tension failure mode, while samples C8, C9 and C10 were loaded under eccentricity of 20mm to test the compression failure mode. The research test matrix is summarized in table (1).

All samples were provided with two internal strain gauges. The two internal strain gauges were attached to reinforcement bars; one of them was attached on the middle vertical bar on the 300mm side at mid height, while the other was attached to the stirrup at the same location. All columns loaded with axial load were provided with one external strain gauge. This strain gauge was attached to the critical CFRP sheet (the sheet which near to the mid height of the column) at the half of long length in the column. All columns loaded with eccentric load were provided with two external strain gauge. One strain gauge was attached to concrete surface at the mid height of the sample on the middle of the 300mm face, while the other gauge was attached to the critical CFRP band (the sheet which near to the top third height of the column).

The lateral deformation in all columns was measured by LVDT in three positions of column, (a) the first position at distance 50mm from the top in the clear height of the column, (b) the second position at distance 500mm from the top in the clear height of the column and (c) the third position at distance 800mm from the top in the clear height of the Column. The results of the lateral deformation in the second deformation were the most accurate, so it was listed at table (3).

All columns were installed in the testing machine as fixed at the bottom and hinged at the top and loaded vertically using load step of 2 ton up to failure. A special steel jacket was installed around the hammer head to prevent any local failure mode within the head. Loading on the top of the column was carried out through cylindrical steel roller to ensure that the load is vertical and accurately positioned at the required eccentricity as shown in Figure (1-b).

2.2 Materials

The material properties used to produce the samples are as follows:

Concrete: All columns were casted using concrete mix consist of 450kg ordinary Portland cement, 600 kg siliceous sand, 1115 kg coarse aggregate of crushed dolomite with 10-mm maximum nominal size and 200 liter of portable water. Six cubes were prepared and tested. The average 28-days cube compressive strength was 45.0 MPa.

Steel Reinforcement: Smooth mild steel 8mm diameter bars of grade 24/37 with minimum yield stress of 240 MPa were used for stirrups; while 10mm diameter deformed steel bars of grade 40/60 with minimum yield stress of 400 MPa were used for vertical reinforcement.

CFRP sheets, Epoxy resin & CFRP Anchors: SikaWrap-230C sheets were used to wrap the samples using Sikadur-330 as epoxy resin to bond the sheets to the concrete surface. SikaWarp FX-50C anchors were fixed using Sikadur-330 in the long side of the columns to ensure full bond between the sheets and the concrete. The properties of SikaWrap-230C and FX-50C listed in Table (2).

TABLE (1): SUMMARY OF THE RESEARCH PROGRAM

Sample	Eccentricity (mm)	No. of CFRP bands	Spacing bet. bands (mm)	CFRP Anchors	Notes
C1	0	-	-	-	Control, Axial
C2	0	4	200	-	Axial
C3	0	4	200	Used	Axial
C4	0	6	80	-	Axial
C5	0	6	80	Used	Axial
C6	80	-	-	-	Control, Tension failure
C7	80	4	200	-	Tension failure
C8	20	6	80	-	Comp. failure
C9	20	6	80	Used	Comp. failure
C10	20	4	200	Used	Comp. failure

TABLE (2): THE PROPERTIES OF SIKAWRAP-230C AND FX-50C

Fiber Properties	SikaWrap-230C	FX-50C
Tensile Modulus	238 GPa	230 GPa
Tensile Strength	4.3 GPa	2.1 GPa
Elongation at break	1.8% (nominal)	>1.6% (nominal)

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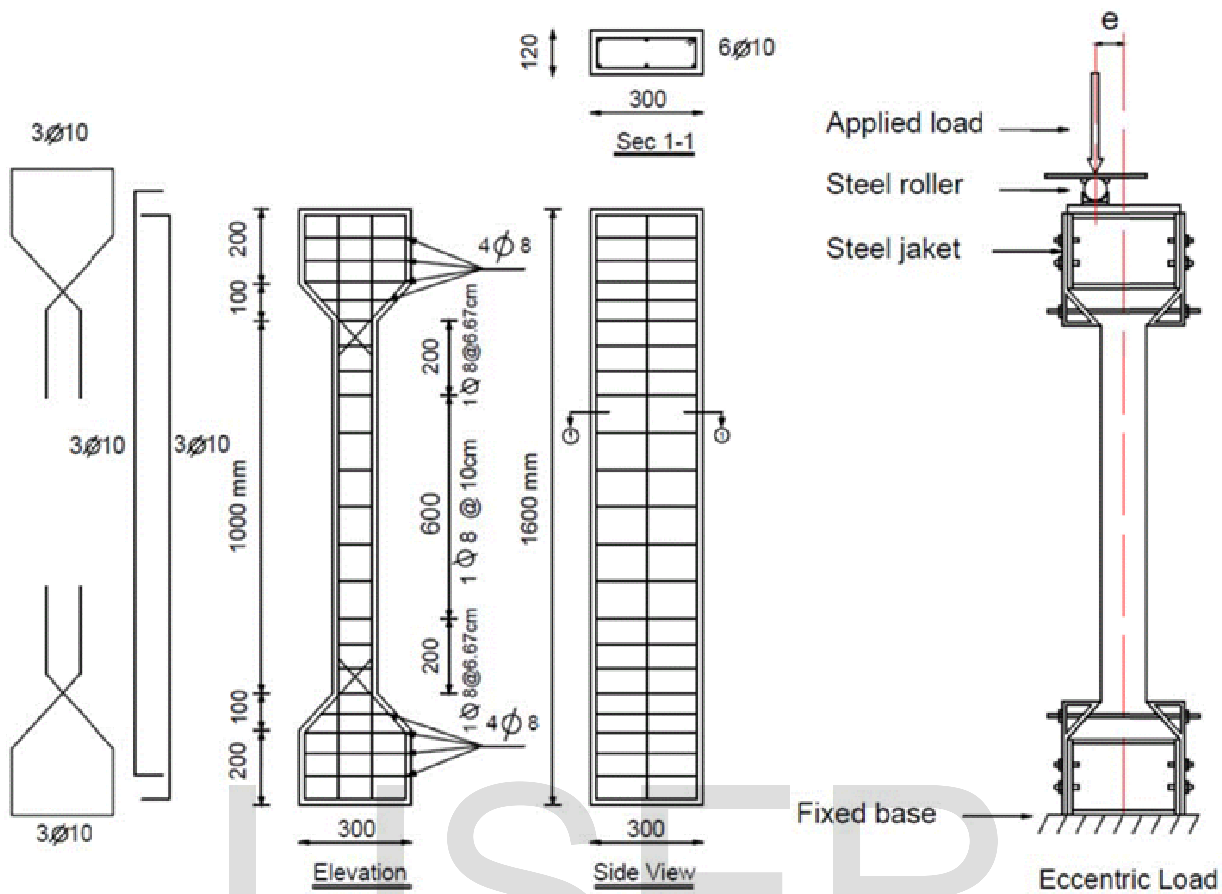


(a) (b)

Figure (1): a) Concrete Dimensions and reinforcement for all samples, b) Test setup

3 Experimental Results

3.1 Modes of failure

The axially loaded samples (from C1 to C5) were failed in compression at the mid height of the column causing rupture in CFRP bands in this zone. Large eccentrically loaded samples (C6 and C7) were failed in tension at the top third of the column without any failure in the CFRP bands, while the small eccentrically loaded samples (C8 to C10) were failed in compression at the top third of the column causing rupture in the adjacent CFRP bands. Figure (2) shows failure mode of each sample.

3.2 Discussion

Table (3) summarizes the measured results of all samples. Figure (3) presents the measured strains from axially loaded samples (from C1 to C5), while Figure (4) present the measured strains from eccentrically loaded samples (from C6 to C10). The theoretical yield strains for main steel, stirrups and CFRP sheets are 2000, 1200 and 1500 □-strain respectively. Comparing the theoretical yield strain values with those shown in figure (3) shows the following:

- Load-main steel strain chart of (C1) shows linear relation up to strain of 1100μ-strain, after that, the nonlinear behavior occurs due to cracking.
- Load-main steel strain chart of (C2 to C5) shows linear relation up to strain of 2200 μ-strain, which matched the theoretical value. Strain in both stirrups & CFRP sheets starts linearly with load up to 200 μ-strain which is the cracking strain of the concrete and then losses stiffness gradually up to yield at strain of 1200, 1500 □-strain for stirrups and CFRP sheets respectively which matches the theoretical values.

Listed values in Table (3) indicate the following:

- Using 4 CFRP bands without CFRP anchors increases the sample capacity to 119%, while using the anchors increases the capacity to 110%.
- Using 6 CFRP bands without CFRP anchors increases the sample capacity to 122%, while using the anchors increases the capacity to 118%.
- The strengthened columns by Anchored CFRP sheets were not optimized than the columns strengthened by CFRP sheets without anchors that can be attributed to CFRP sheets were not debonding from concrete surface, so the anchors did not make any improvements.
- The capacity of column C2 (with 4 CFRP bands) was 97.5% than the capacity of column C4 (with 6 CFRP bands).
- The lateral Deformation for C2 is 91% from the lateral deformation in C1, the lateral Deformation for C3 is 84% from the lateral deformation in C1.
- The lateral Deformation for C4 is 75% from the lateral deformation in C1, the lateral Deformation for C5 is 74% from the lateral deformation in C1.

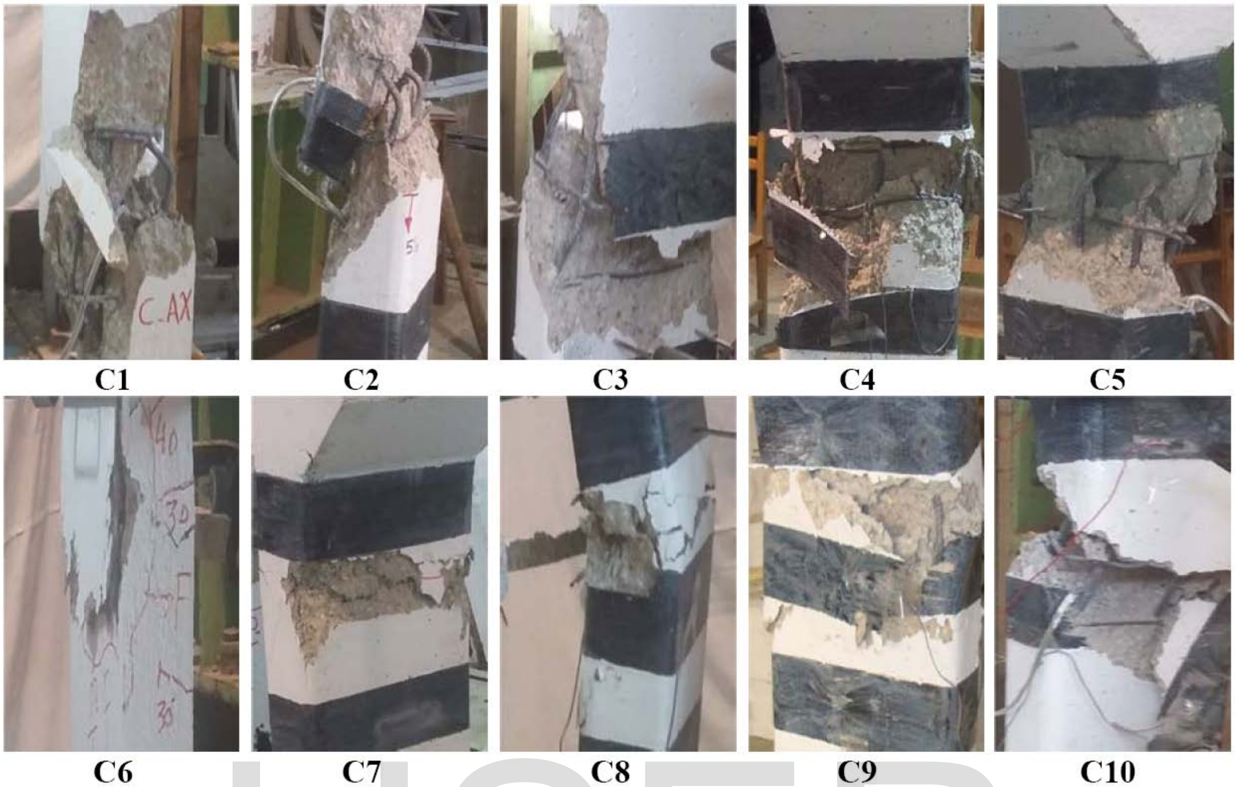


Figure (2): Failure modes of the tested samples

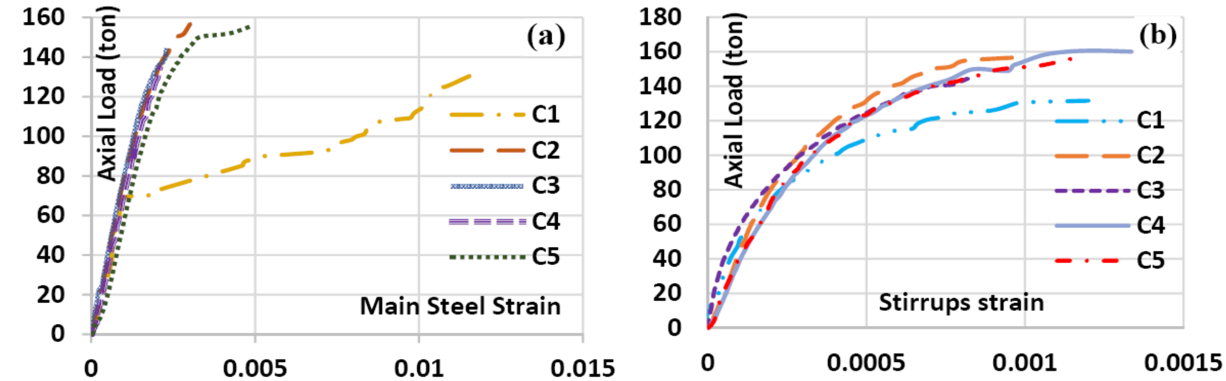
- By extrapolating the results of samples (C1), (C2) and (C4), the ultimate concentric capacity when the spacing between the CFRP bands equals to zero (full wrapping) is 162.5 tons. This value matches the predicted value using the formula developed by Zaher & Ebid (2014), where the capacity ratio between fully wrapped confined to unconfined columns equals to (1+confining stress (MPa)/30) [8].
- The exaggeration in some post-yielding strain values listed in Table (3) was due to the sudden collapse of tested samples. Charts in Figure (3) illustrate strain values from test beginning up to yield point and also post yielding zone.

Regarding the eccentrically loaded set of samples, observed modes of failure of both tension and compression were expected. The theoretical yield strains for main steel, stirrups and CFRP sheets are as mentioned above, while the theoretical ultimate strain of concrete is about 3000 μ-strain. Comparing the theoretical yield strain values with those shown in Figure (4) shows the following:

- Load-main steel strain chart of (C6) shows that sample failed at strain of 400 μ-strain. This value makes sense because that strain was measured for main steel bars in compression zone, while the sample was failed due to yielding in tension steel bars. Also, the measured strain in stirrups was limited to 130 μ-strain because of the tension failure mode.
- The behavior of sample (C7) is nearly the same of (C6) because both of them shared the same tension mode of failure. Also, the measured strains in concrete and CFRP of sample (C7) are below the theoretical ultimate/yield values which confirm the tension failure mode.
- Samples (C8-C10) suffered compression failure due to small eccentricity. Load-strain charts in figure (4) showed that strains of main steel, stirrups, concrete and CFRP sheets at mid height are below the theoretical yielding values, which makes sense because they are out of failure zone (in the top third of column).

Listed values in Table (3) indicate the following:

- Comparing ultimate load of samples (C6) and (C7) shows that CFRP bands don't have any effect on the capacity in tension failure mode which is reasonable because the tension failure mode occurs in tension steel bars, hence, confining the concrete will not make any difference in the results.
- Comparing ultimate load of samples (C8) and (C9) shows that using CFRP anchors decreased the capacity in compression failure mode to 96% that can be attributed to the CFRP sheets did not debonding from the concrete surface, so the Anchors did not make any improvements in the capacity for the columns.
- Comparing ultimate load of samples (C3) and (C10) shows that the compression capacity of the sample wrapped with 4 bands and fixed with anchors decreased to 76% when the eccentricity (e/t=1/6), i.e. when the eccentric load acts just on the core of the cross section.
- The lateral Deformation for C7 is 96% from the lateral deformation in C6.
- The lateral Deformation for C9 is 67% from the lateral deformation in C8.



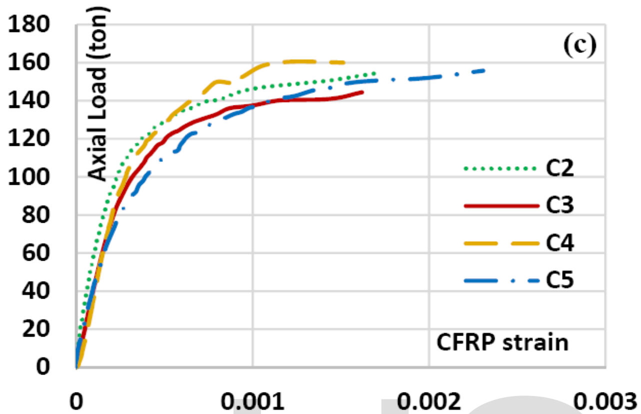


Figure (3): Measured strains for axially loaded samples (C1 to C5)
a) Strain in main steel
b) Strain in stirrups
c) Strain in CFRP sheets

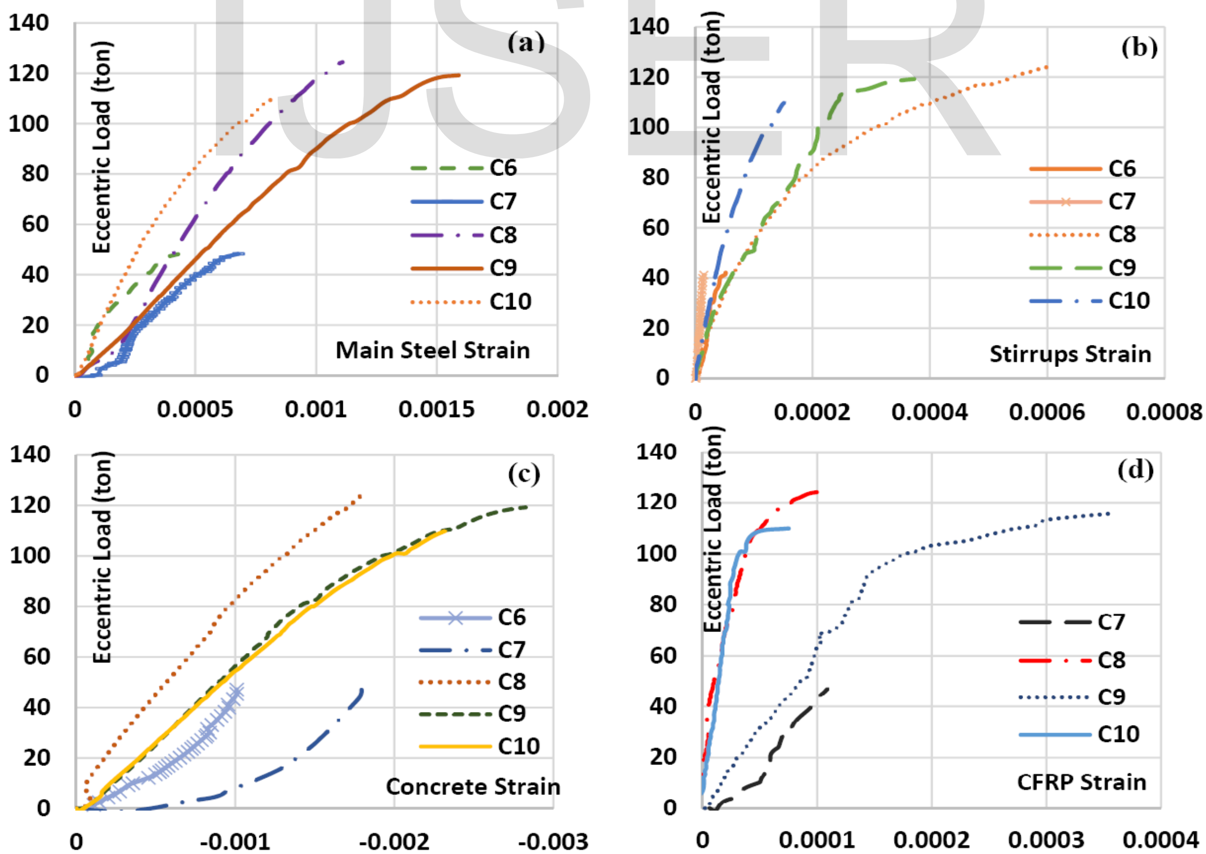


Figure (4): Measured strains for eccentrically loaded samples (C6 to C10)
a) Strain in main steel, b) Strain in stirrups, c) Strain in Concrete d) Strain in CFRP sheets

TABLE (3): SUMMARY OF MEASURED RESULTS

Col. ID	Ult. Load (ton)	Strain (μ-strain)				Lateral Defor. mm	Failure mode
		Main Steel	Ties	Conc. (Comp.)	CFRP (Ten.)		
C1	131	12000	1200	-	-	2.00	Comp. at mid height
C2	156	3100	1000	-	1718	1.82	Comp. at mid height
C3	144	2280	800	-	1600	1.68	Comp. at mid height
C4	160	1790	1330	-	1512	1.50	Comp. at mid height
C5	155	4900	1100	-	2306	1.48	Comp. at mid height
C6	48	42.8	15	-1000	-	5.50	Ten. At top third
C7	48	679	48	-1739	109	5.29	Ten. At top third
C8	124	1109	611	-1792	109	2.91	Comp. At top third
C9	119	1590	373	-2820	374	1.97	Comp. At top third
C10	110	829	152	-2320	75	3.50	Comp. At top third

4 CONCLUSIONS

Based on the test results and discussion, the following conclusions can be made:

- Comparing the results of (C2, C3) & (C4, C5) & (C8, C9) shows that anchors have no significant effect on the capacity eccentric or concentric axially loaded columns, which indicates that the standard overlap length of wrapped sheets is enough to prevent debonding between concrete and CRFP sheets. On the other hand, the results shows that anchored columns have less lateral deformations than un-anchored ones (about 95% for concentric and 66%for eccentric loads)
- From the results of un-anchored concentric axially loaded specimens (C1, C2, C4) shows that decreasing the spacing between CFRP bands from 200mm to 80mm (40%) increases the axial concentric capacity from 118% to 122%and deceases the lateral deformations from 90% to 75%.
- From the results of anchored concentric axially loaded specimens (C1, C3, C5) shows that decreasing the spacing between CFRP bands from 200mm to 80mm (40%) increases the axial concentric capacity from 110% to 118% and deceases the lateral deformations from 85% to 74%.
- Based on the results of un-anchored eccentric axially loaded specimens (C6, C7) shows that CFRP bands have no effect on the eccentric capacity or lateral deformations of samples with big eccentricity (that failed in tension) because failure occurred in tension steel bars not confined concrete. And the lateral deformation was increased in the column without anchored CFRP sheets.
- The results of specimens (C2, C3, C4, C5) show that lateral deformations decreases with decreasing the spacing between CFRP bands. Also, anchored columns showed less lateral deformations than equivalent un-anchored ones.
- The extrapolated concentric axial capacity of full wrapped RC column matches the predicted value using Zaher & Ebid formula.

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