Behavior of CFRP confined RC rectangular columns with different aspect ratios

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***Abstract* — In last decades, the use of externally fiber-reinforced polymer sheets (FRPs) has become increasingly popular for civil infrastructure applications. Early investigate studies have demonstrates that confinement enhancement of FRP wrapped circular columns is more efficient than that of square or rectangular RC columns. Most existing columns however, are square or rectangular in cross section. An experimental study has been carried out on rectangular RC columns strengthened with carbon fiber- reinforced polymer (CFRP) sheets. A total of 9 RC columns were loaded to failure in axial compression and examined in both axial and lateral directions. Number of wrap layers and aspect ratios were the main test parameters. Compression stress, axial and transverse strain have been registered to estimate the stress-strain relationships, ultimate strength and ductility of specimens. Results obviously indicate that CFRP wrapping can improve the structural performance of rectangular RC columns regarding both maximum strength and ductility. The effects of test parameters are evidenced and compared.**

***Index Terms*—RC columns, CFRP, strength, ductility**

I. INTRODUCTION

An increasing number of reinforced concrete structures have reached the end of their service life, either due to deterioration of the concrete and reinforcements caused by environmental factors, or due to an increase in applied loads. These deteriorated structures may be functionally obsolete, and most are now in serious need of extensive rehabilitation. The fiber-reinforced polymer (FRP) wrapping is suitable to improve the performance of columns in terms of the load carrying capacity and ductility. The popularity of using this technique is due to its well-known advantages, including high strength –to-weight ratio, excellent corrosion resistance and ease of onsite handling. For these reasons, FRP has been widely used in construction and structural rehabilitation. Application of CFRP sheets in civil engineering structures has been growing rapidly in recent years, and is becoming an effective solution for strengthening deteriorated concrete members. During the last decade, the use of FRP has successfully promoted for external confinement of reinforced concrete columns all over the world. Many studies on performance of RC columns confined with FRP composite have been conducted, using both experimental and analytical approaches. These investigations have revealed that the strength of RC columns confined with FRP can equal or exceed the original design strength when subjected to axial loads. However, most of the available studies on behavior of FRP confined RC columns have conducted on circular columns (Halil et al 2011 [1], C.Cui and S.A.Sheikh 2010 [2]), while relatively few studies have addresses rectangular and square columns. Yu-Fei Wu 2010 [3] presented effect of cross-sectional aspect ratio on the strength of CFRP-confined rectangular columns. Three series of uniaxial compression tests were conducted on 45 specimens. The parameters considered were the aspect ratio and number of CFRP layers. The test results clearly demonstrate the strength gain in the confined concrete columns relative to the original unconfined columns, f_{cc}/f_{co} decreased as the aspect ratio increased, until it became insignificant when the aspect ratio reached. R.Kumuthan et al 2007 [4] studied the behavior of RC rectangular columns strengthened using GFRP. Three aspect ratio were considered (1, 1.25, and 1.66). Specimens wrapped with 1 and 2 layers of GFRP were investigated. Total nine specimens were subjected to axial compression loads. Effective confinement with GFRP resulted in improving the compressive strength. Better confinement was achieved when the number of layers of GFRP was increased, resulting in enhanced load carrying capacity of the column in addition to the improvement of ductility. Ilki et al 2006 [5] studied the uniaxial compressive behavior of 15 RC columns and one plain concrete column jacketed with CFRP sheets. It was observed that the enhancement in deformability was greater for a rectangular cross-section, whereas the enhancement in strength was more pronounced for a circular cross-section. The test results also showed that CFRP jackets were more effective in enhancing the strength and deformability where the concrete strength was low. Early research studies have indicate that confinement enhancement of FRP wrapped rectangular RC column is less efficient than that of circular column, because of FRP confined are not uniformly confined and the compressive pressure is unevenly distributed which called knife effect (H.Toutanji et al 2010 [6], Silva 2011 [7], Pessikiet al 2001 [8], Pellegrino and Modena 2010 [9]). For square columns, it has been concluded that the most important shape factor that affects the confinement effectiveness is the corner radius ratio (corner radius/half width). While, for rectangular shaped columns, another important factor in addition to the corner radius ratio that governs the confinement effectiveness is the aspect ratio, as has been mentioned (Yu.Fei Wu 2009 & 2006 [10], [11] and L.Wang and Yu.Fei Wu 2008 [12]). However, data for rectangular columns that can be used for the quantification of the isolated effect of the aspect ratio are scarce. This scarcity of test data clearly indicates the need for more quantitative experimental investigations on the effect of the aspect ratio for the development of theoretical models. The main objective of this work is thus to experimentally investigate the behavior of rectangular concrete columns, focusing on the effect of the aspect ratio.

II. EXPERIMENTAL PROGRAM

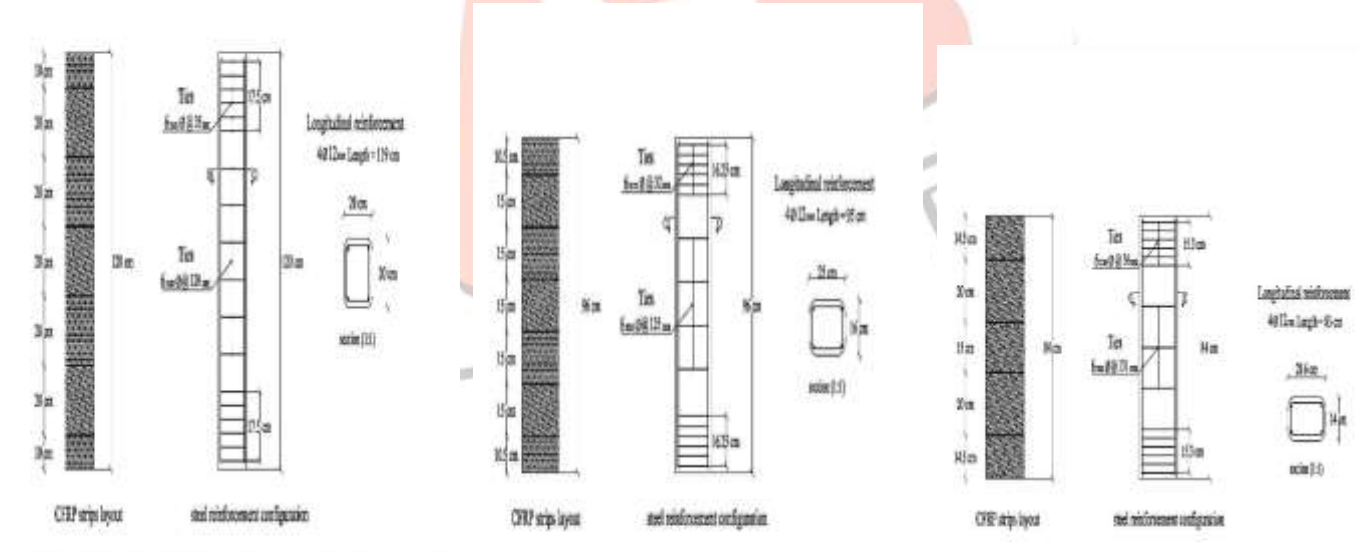
Specimen design

Nine rectangular RC columns were casted with 26 MPa concrete and deformed to achieve a slenderness ratio (H/b) equal to 6 to represent short columns and to avoid the formation of considerable secondary moment due to the slenderness effect, where H and b are the column's height and the shorter side dimension of cross-section. All RC specimens have the same cross-section area with corner radius of 40 mm. The longitudinal steel ratio and transverse steel ratio were constant for all specimens and equal to 1.3%.and 0.4% respectively. The variables considered in this investigation include the aspect ratio L/b, where L is the longer side dimension of the cross-section and thickness of CFRP jacket. Aspect ratios 1, 1.5, and 2 were tested. The jacket thickness varied from non to one and two layer of CFRP with confinement ratio $\mu_f = 0.332$ $\mu_f = 0.664$ for one and two layer respectively, see **Figure.1** shows the cross-section of the test specimens and their steel configuration reinforcement.

The test specimens are summarized in **Table 1**. The specimens are labeled as XS (or R)-Y, where X is the number of CFRP layers, S stands for a square cross-section and R for a rectangular cross-section, and Y specifies the aspect ratio (H/b).

Table 1. Details of test specimens

Series	Specimen Identification	Column Dimensions L X b	Number of CFRP layers	Column Reinforcement As	Column Reinforcement Internal Stirrups
1	0S-1	200 x 200	0	4 Φ 12 mm	1 Φ 6 mm @ 120 mm
	0R-1.5	160 x 250	0		1 Φ 6 mm @ 125 mm
	0R-2	140 x 286	0		1 Φ 6 mm @ 131 mm
2	1S-1	200 x 200	1		1 Φ 6 mm @ 120 mm
	1R-1.5	160 x 250	1		1 Φ 6 mm @ 125 mm
	1R-2	140 x 286	1		1 Φ 6 mm @ 131 mm
3	2S-1	200 x 200	2		1 Φ 6 mm @ 120 mm
	2R-1.5	160 x 250	2		1 Φ 6 mm @ 125 mm
	2R-2	140 x 286	2		1 Φ 6 mm @ 131 mm



(a) RC column with aspect ratio 1 (b) RC column with aspect ratio 1.5 (c) RC column with aspect ratio 2

Figure 1. Configuration of internal reinforcement for the tested columns

Materials

Fine & coarse aggregate: angular crushed coarse aggregates were used in experimental work with maximum size of 20 mm. River sand was as a fine aggregate. The properties of used aggregate are shown in **Table 2.**

Cement: ordinary Portland cement of 32.5 grade was used in the current experimental work. The test properties of Portland cement are given in **Table 3**.

Water: tap water was used for experimentation as well as for curing purpose.

Table 2. Properties of fine and coarse aggregates

property	**gravel**	**sand**
Maximum nominal size	20 mm	--
Fine modulus	6.2	2.56
Fine materials	0.6	1.6
Volume weight (t/m^3)	1.67	1.68
Specific gravity	2.52	2.56
Crashing strength value	19.5	--
Water absorption (%)	0.7	1
Sulphate content (%)	0.003	0.012
Chloride content (%)	0.004	0.015
PH	7.5	8

Table 3. Properties of cement

Properties		Results
Fineness of cement cm^2/gm		2880
Compressive strength kg/cm^2	3 days	198
	7 days	298
Setting Time	Initial	80 minute
	Final	290 minute
soundness		5 mm

Steel: high tensile steel deformed steel bars of 12 mm diameter (with proof (yield) stress and ultimate tensile strength of 424 MPa and 690 MPa, respectively) were used in all RC columns as longitudinal reinforcement; and 6 mm plain steel bars (with yield and ultimate strength of 302 MPa and 380 MPa respectively) were used as transverse reinforcement. See **Table 4**
CFRP sheets & epoxy resin: a high tensile strength carbon fiber Sika-wrap 300 was used for jacketing, and a two-part sikadur-330 epoxy impregnation was used as adhesive. The CFRP materials had a nominal thickness of 0.166 mm. Details of materials properties of CFRP are presented in **Table.5**

Table 4. Properties of mild and high tensile steel

Steel type	**Commercial diameter (mm)**	**Yield or proof strength (N/mm^2)**	**Ultimate strength (N/mm^2)**	**Elongation %**
M.S	6	302	380	0.26
H.T.S	12	424	690	0.126

Table 5. Properties of CFRP sheets

Weight g/m^2	**Considering thickness (mm)**	**Tensile strength of fibers (N/mm^2)**	**Tensile modulus of fibers (N/mm^2)**
230	0.166	3900	230000

Concrete mix proportions: the specimens were cast in specially manufactured steel moulds, by using concrete mix with average compressive strength for three standard cubes (F_{cu}) of 26 MPa and corresponding concrete cylinder compressive strength (f_{cy}) of 21 MPa after 28 days. the concrete mix proportions are shown in **Table.6**

Table 6. Concrete mix proportions

Concrete strength N/mm^2	**Cement**	**Sand**	**Gravel**	**Water**
26	1	1.74	3.2	0.54

Specimen preparation

One day after casting, the specimens were removed from the moulds and cured with water at a constant temperature of 27 c° for 28 days. After concrete columns were fully cured. The surface of the specimens was lightly sanded to remove surface contaminants, and was then cleaned with water and left to dry, see **Figure 2**. The two-part epoxy impregnation resin was then thoroughly mixed in according to manufacture's specifications. Frist, the epoxy resin was directly applied onto the substrate, and then the fabric was carefully placed into resin with gloved hands and smooth out any irregularities or air pockets using a plastic laminating roller. The roller was continuously used until the resin was appeared on the surface of the fabric, as an indication of fully saturating. A second layer of resin was applied to allow the impregnation of CFRP. The second layer was applied in the same way. Finally, a layer of resin was applied to complete the operation as shown in **Figure 3**. Each layer was wrapped around the columns with an overlap of 150 mm to avoid sliding or deboning of fibers during tests. The wrapped specimens were left at room temperature for one week before testing.

(a) scrapping surface | (b) finish surface preparation

Figure 2. Preparing concrete surface

(a) Coating a layer of resin | (b) Applying CFRP sheet strap | (c) Rolling CFRP sheet | (d) Impregnation FRP with epoxy

Figure 3. CFRP application

Instrumentation

Four electrical strain gauges were attached to the surface of bonded CFRP sheets to measure the hoop strain at the column mid-height, and two linear variable displacement transducer (LVDT) was used to measure the average axial deformation of column through a gauge length equal to the column the column height. The LVDT used measured the upward movement of the lower rigid head of the testing **Figure.4**, so the measured deformations represented the average axial shortening of tested columns. Both the strain gauge and the LVDT were connected to a data acquisition system, which in turn was connected to a computer to regularly record all measurements. The load was measured by load cell placed above the specimens its capacity 2000 KN and was connected to a data acquisition system.

Testing

All of specimens were tested under centric loads monotonically applied using a compression testing machine of 5000 KN capacity with load-controlled rate of 180 KN/min till failure load. All columns were capped with steel plate to ensure parallel surface and to distribute the load uniformly, moreover to avoid concentration stress at specimen's ends causing premature failure. Axial and hoop strain were measured during the test until failure.

Figure 4. Details of test setup

III. TEST RESULTS AND DISCUSSION

Table.7 summarizes several response characteristics of the tested columns, including the maximum load (P_{max}); the ratio (R) of the maximum compressive strength of CFRP confined RC column (f_{cc}) to their counterparts of the unconfined RC control columns (f_{co}); and the mean axial strain $\varepsilon_{cc} = \Delta_{max}/L$, where Δ_{max} is the measured axial shortening of tested columns at the ultimate load and L is the column height. In addition, it includes the transverse strains of the CFRP sheets ε_{hz1} & ε_{hz2} at long directions, which represent by average value ε_{HZL} and ε_{hz3} & ε_{hz4} at short directions, which represent by average value ε_{HZS} corresponding to the failure load and the failure modes of all columns.

Compressive strength and failure modes

It can be revealed that confinement with CFRP wrap increased the compressive strength. The greater the number of CFRP layers, the greater the gain in the compressive with respect to the corresponding unconfined column. For a given number of CFRP layers, the increase in aspect ratio resulted in a decrease in load capacity. The maximum increase were achieved in square columns, which showed a 34% and87.5% increase against the control columns for two-ply and one-ply CFRP confined columns respectively.

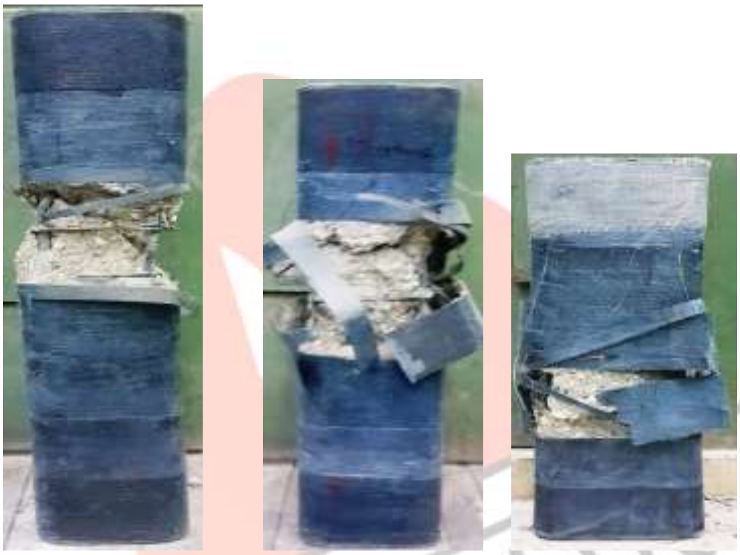
The typical failure modes of the confined columns are shown in **Figure. 5, 6, and 7**. Two modes of failure were observed during the experimental tests of RC columns. The first mechanism (FM1) was due to the crushing of concrete at either the middle third zone or the upper third zone as shown in **Figure 5**. the second failure mechanism (FM2) was observed for confined RC columns at either one-ply or two-ply CFRP due to rapture of CFRP sheet at the mid-height of specimen and it was accompanied with both a partial delamination of concrete cover and local concrete crushing, see **Figure 6 and 7**. During the loading, clicking sound could be heard, signifying the straining of CFRP sheet and the cracking of the epoxy resin. The final failure occurred suddenly with explosive sound.

Table 7. Experimental results of tested columns

Columns	P_{max}	f_{co}	f_{cc}	R	Mean axial strain	$\varepsilon_{cc}/\varepsilon_{co}$	Horizontal strains						Mode of failure
							Long direction			Short direction			
	KN	N/mm^2	N/mm^2		ε_{cc} (%)		ε_{hz1}	ε_{hz2}	ε_{HZL}	ε_{hz3}	ε_{hz2}	ε_{HZS}	
0S-1	1152	29.5	--	1	0.196	1	0.243	0.307	0.275	0.15	0.09	0.12	FM1
0R-1.5	1105	28.3	--	1	0.188	1	0.33	0.29	0.31	0.05	0.119	0.0845	FM1
0R-2	936	24	--	1	0.17	1	0.27	0.23	0.25	0.03	0.076	0.053	FM1
1S-1	1545	--	39.6	1.34	0.411	2.10	0.9	0.996	0.948	0.75	0.986	0.868	FM2
1R-1.5	1452	--	37.23	1.31	0.338	1.80	0.59	0.73	0.66	0.89	0.978	0.934	FM2
1R-2	1163	--	29.82	1.24	0.284	1.67	0.48	0.46	0.47	0.8	0.72	0.76	FM2
2S-1	2160	--	55.38	1.875	0.664	3.39	0.592	0.63	0.611	0.3	0.34	0.32	FM2
2R-1.5	1973	--	50.6	1.785	0.552	2.94	0.48	0.542	0.511	0.85	0.91	0.88	FM2
2R-2	1500	--	38.46	1.602	0.456	2.68	0.356	0.28	0.318	0.36	0.356	0.358	FM2

(a) 0S-1 (b) 0R-1.5 (c) 0R-2

Figure 5. Failure mechanism (FM1) for unconfined RC columns



(a) 1S-1 (b) 1R-1.5 (c) 1R-2

Figure 6. Failure mechanism (FM2) for one-layer confined RC columns

(a) 2S-1 (b) 2R-1.5 (c) 2R-2

Figure 7. Failure mechanism (FM2) for two-layer confined RC columns

Stress-VL strain response

The typical relationship between the applied axial stress and the corresponding axial strain of tested columns are presented in **Figures 8 and 9**. The axial vertical strains are calculated from the average readings of the two vertical LVDTs divided by the gauge length, which represent the column's height. An examination of the load –VL strain curves declare the following observations:

- The CFRP-confined columns had almost a linear relationship up to an axial strain of 0.0026 and afterwards a non-linear behavior was observed
- The control columns approximately failed without warning at maximum achieved strength.
- In the initial elastic zone, the confined and unconfined specimens behave in the same manner, irrespective of the number of layers.
- The strengthening effect of the CFRP layers begins only after the concrete has reached the peak strength of unconfined concrete, thus transversal strains in the concrete activate the CFRP jacket.

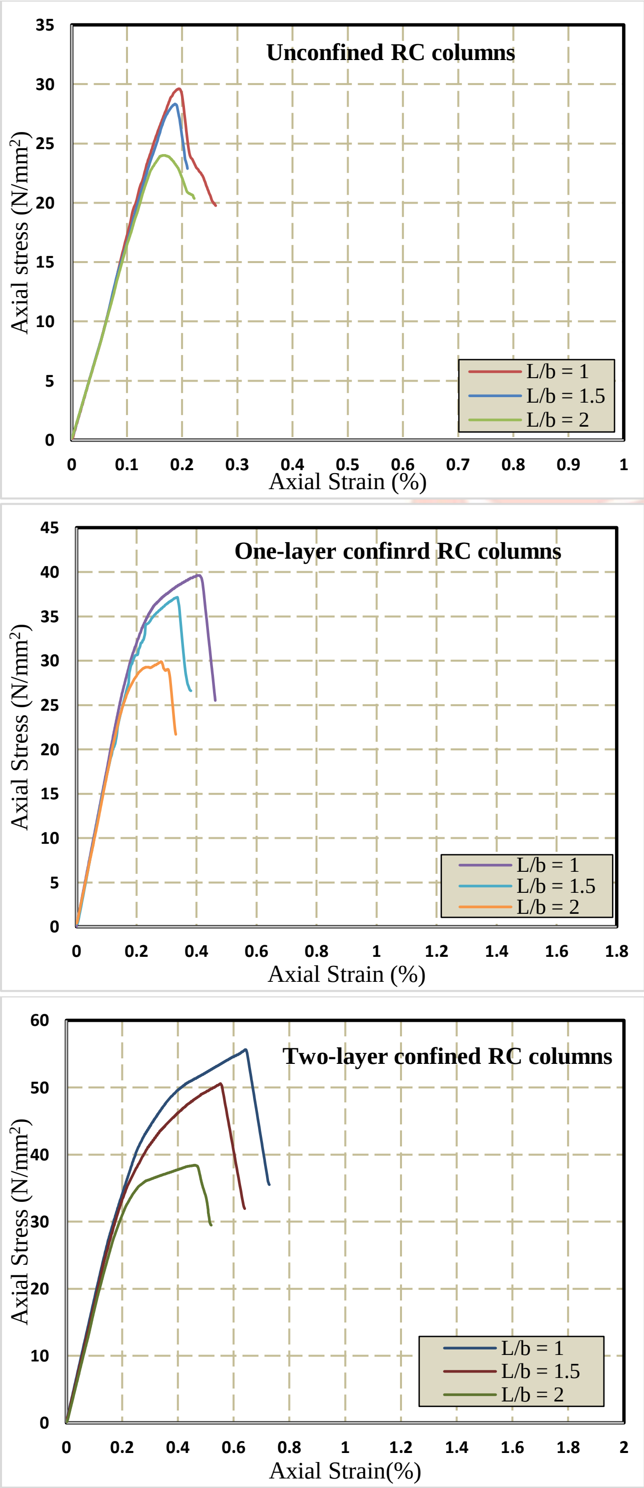


Figure 8.stress-axial strain responses for a certain CFRP thickness

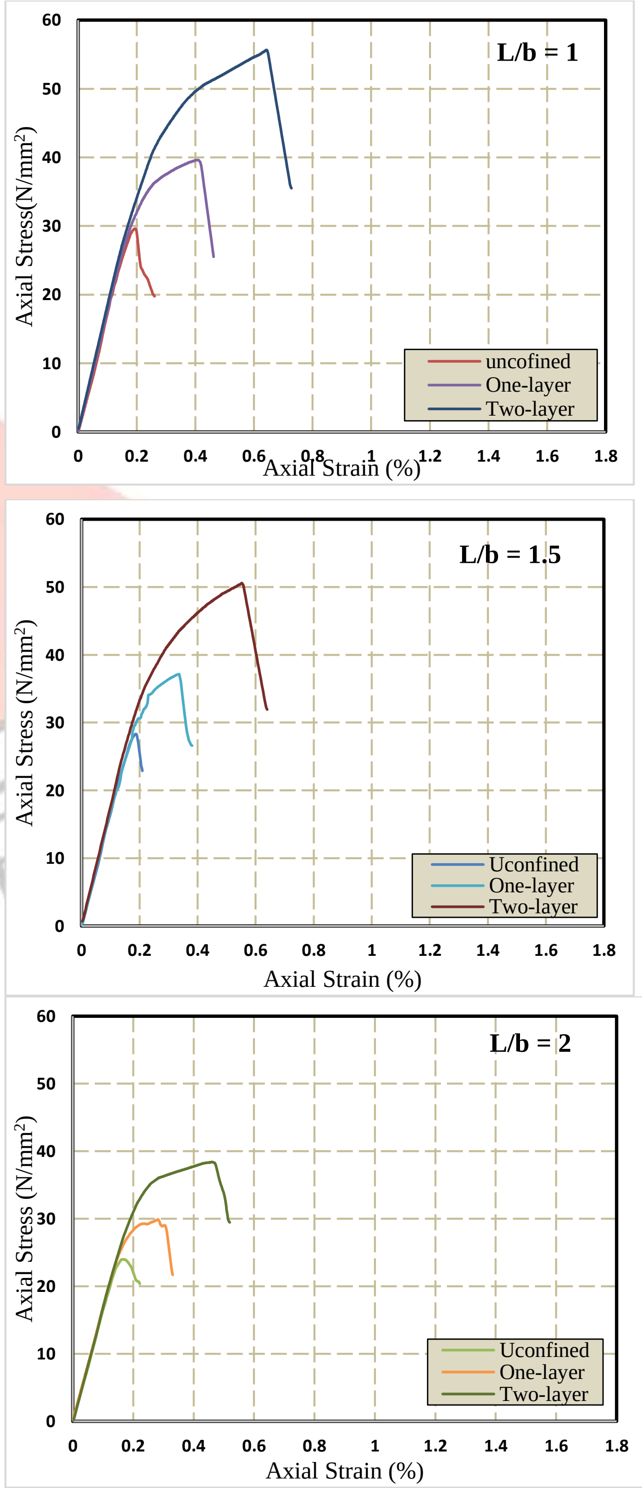


Figure 9.stress-axial strain responses for a certain aspect ratio

CFRP transverse strains

Figures 10 and 11 show the relationship between the applied axial Stress versus the transverse strains of the CFRP confined columns. The circumferential strains were measured at mid-height at long and short directions of columns. Two opposite transverse strains (hz1 & hz2), which represent by average value ε_{HZL} and (hz3 & hz4), which represent by average value ε_{HZS} were attached to the middle of faces of the column for long and short directions respectively. The figures indicate that each two opposite CFRP strains show comparable curves; where all strains increase linearly with the increase of applied load up to stress equal 23, 18, and 13 N/mm^2 for rectangular with aspect ratios 1, 1.5, and 2 respectively; and with further loading a non-linear relationship could be noticed up to axial load of 36, 33.3, and 28 N/mm^2. At this point, the strain values increased dramatically. It is noteworthy that for a certain thickness of CFRP, the ultimate lateral strains on longer side generally decrease as the aspect ratio increase, whereas the ultimate lateral strains on shorter side increase as the aspect ratio increase.

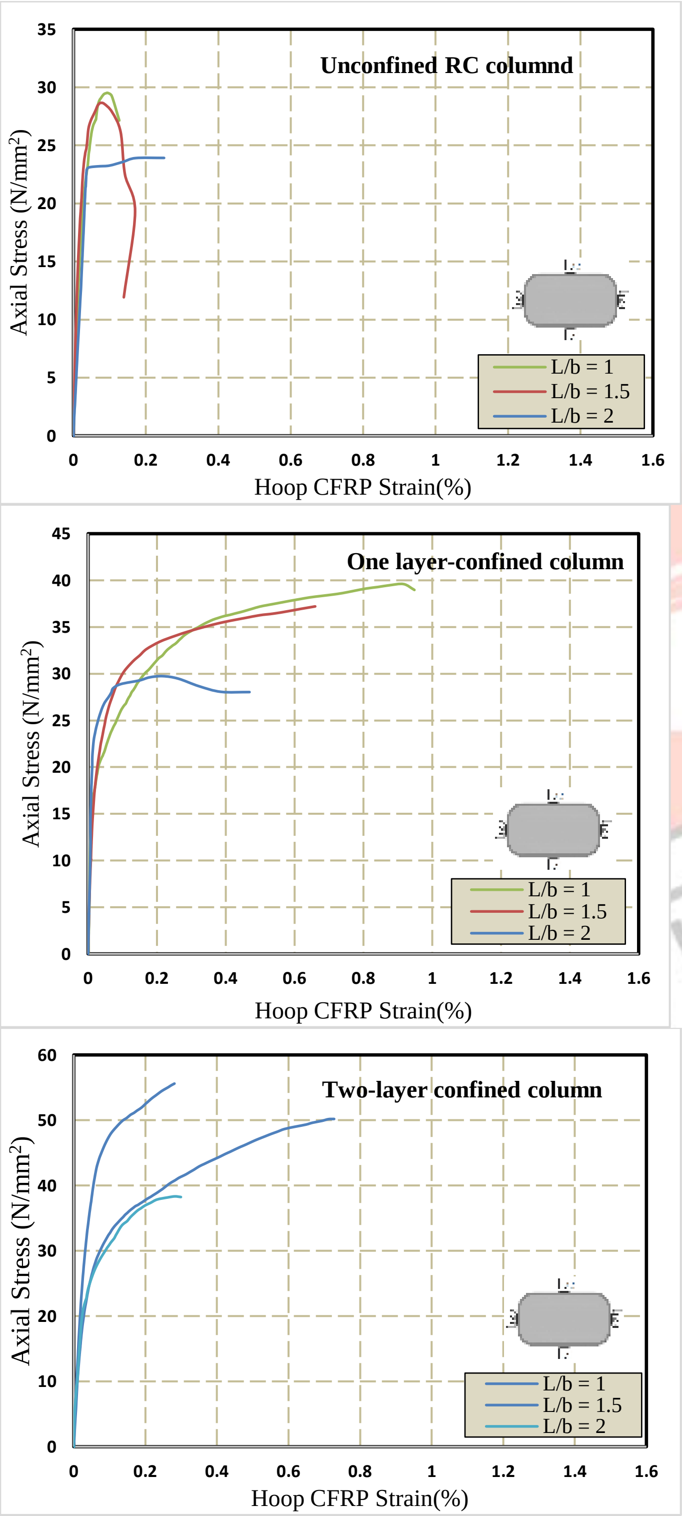


Figure 10.stress-lateral strain responses for a certain CFRP thickness at long direction

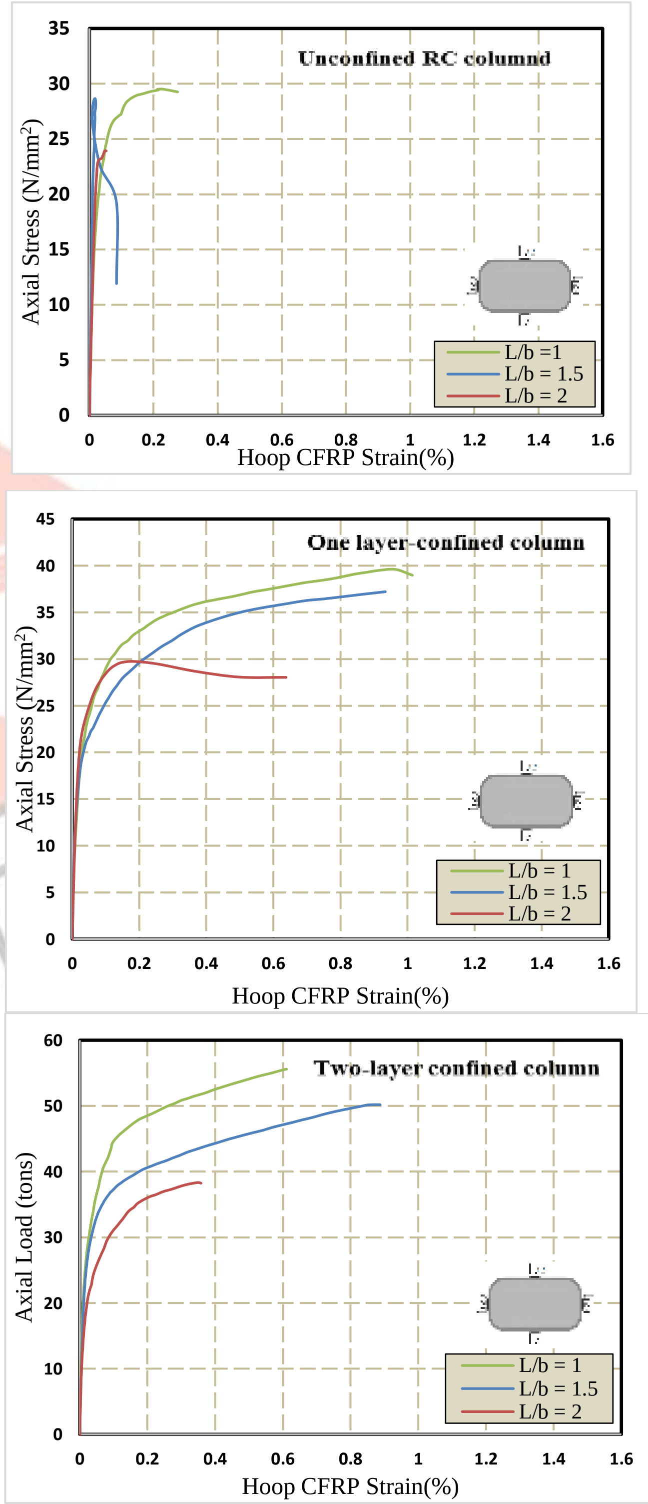


Figure 11. stress-lateral strain responses for a certain CFRP thickness at short direction

Effect of CFRP strengthening ratio.

Increase the number of CFRP layers generates an increase of compressive strength for all cases of RC columns with different aspect ratios. The ultimate strain in both axial and lateral direction increase as the number of CFRP layers increase, **see Figures 12 and 13.** From the results shown in **Table**.7. It can be extracted two observation, the first one is the increase rate of gained strength and axial strain due to changing confinement state from one (μ_f = 0.332) to two (μ_f = 0.664) layer is bigger than those results in changing from none to one layer. These results reveal that efficiency of confinement is more significant for two layer-confined state. The second one is the increase in the CFRP layers has a significant influence although, the increase in compressive strength is not as important as that axial deformations which increase dramatically with increasing CFRP layers.

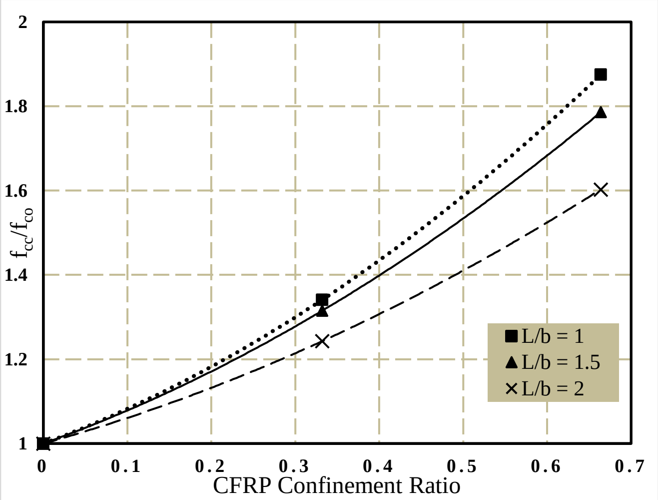


Figure 12.strength gain of confined concrete versus CFRP ratio

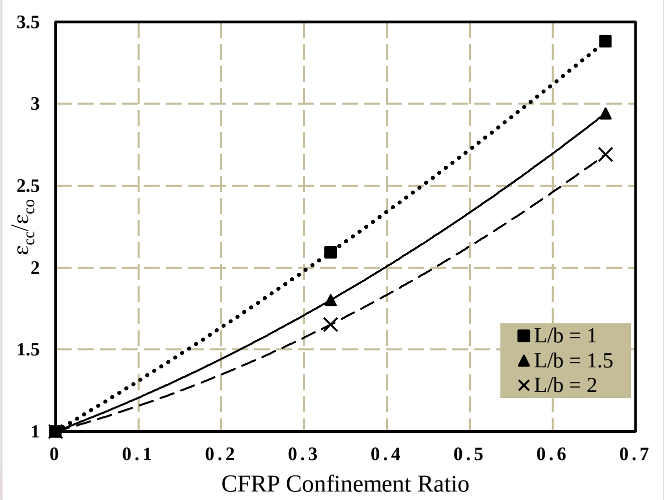


Figure 13. ductility gain of confined concrete versus CFRP ratio

Effect of aspect ratio

The CFRP wrapping is more effective in square sections than in rectangular sections, the ultimate confined strength decrease as the aspect ratio increase see **Figures 14 and 15**. The charts reveal that the strength gain of the confined concrete decrease when the aspect ratio increase, and there is no significant strength gain for columns with an aspect ratio of 2. **Table.7** shows the ultimate axial strains and corresponding lateral strains at the two sides. The values of ultimate strains are taken at the point of CFRP rupture, from these results it can be indicated that the ultimate axial strain and lateral strain at longer side decrease when the aspect ratio increase, whereas the ultimate lateral strain at shorter side increase as the aspect ratio increase.

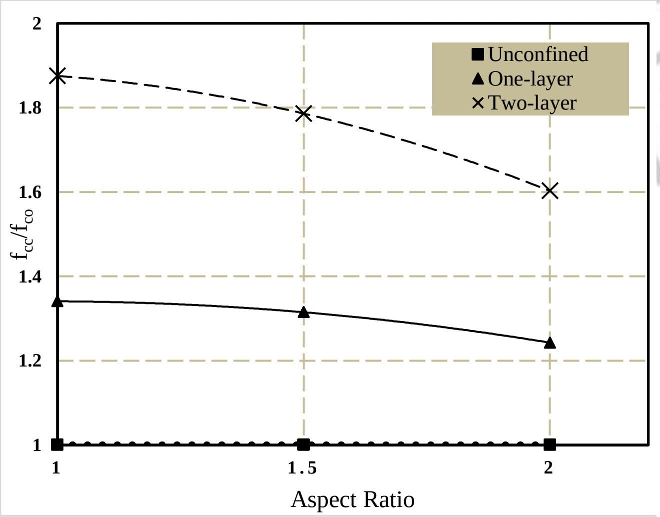


Figure 14. strength gain of confined concrete versus aspect ratio

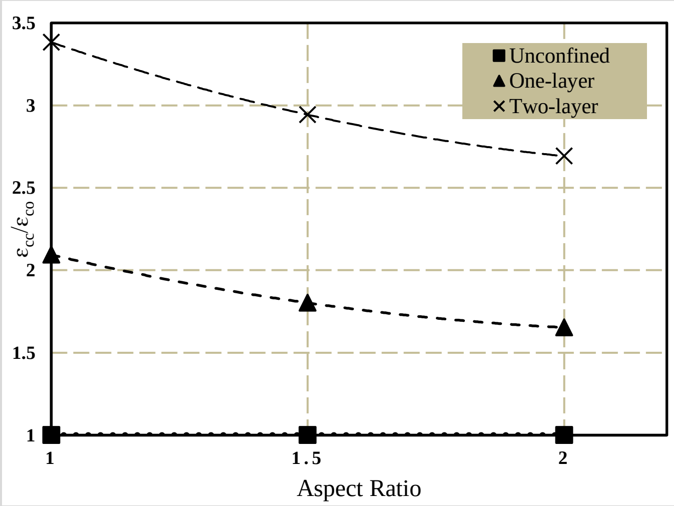


Figure 15. ductility gain of confined concrete versus aspect ratio

IV. CONCLUSIONS

An experimental study on axial compression behavior of rectangular RC columns confined externally with CFRP was presented. The main purpose of this study was to investigate the effect of the aspect ratio of cross section on the effectiveness of CFRP confinement. Two main parameters were considered; the aspect ratio (1, 1.5, and 2) and the number of CFRP layer (none, one, and two). Based on the test results, the findings can be summarized as follows.

- CFRP wrapping enhances the behavior of rectangular columns regardless of aspect ratio. CFRP confinement is more effective for square section than rectangular section. As the aspect ratio increase from one to two, the strength gain in confined concrete f_{cc}/f_{co} decrease until it becomes insignificant at aspect ratio equal to 2.
- The stress-strain response changes from a monotonically increasing to strain-hardening type for CFRP wrapped columns. CFRP confined square columns exhibited more ductile behavior as compared with rectangular one.
- Increasing number of CFRP layers produce an increase in compressive strength for the confined RC column but with lower rate as compared to the deformation capacity.
- All CFRP wrapped RC columns failed suddenly and explosively without any warning. The failure of rectangular columns placed with the combination of delamination as well as the rupture of CFRP sheets.

REFERENCES

[1] H. Sezen and E. A. Miller (2011), "Experimental evaluation of axial behavior of strengthened circular reinforced-concrete columns," *J. Bridg. Eng.*, vol. 16, no. 2, pp. 238–247.

[2] C. Cui and S. a. Sheikh (2010), "Analytical Model for Circular Normal- and High-Strength Concrete Columns Confined with FRP," *J. Compos. Constr.*, vol. 14, no. 5, pp. 562–572.

[3] Y. F. Wu and Y. Y. Wei (2010), "Effect of cross-sectional aspect ratio on the strength of CFRP-confined rectangular concrete columns," *Eng. Struct.*, vol. 32, no. 1, pp. 32–45.

[4] R. Kumutha, R. Vaidyanathan, and M. S. Palanichamy (2007), "Behaviour of reinforced concrete rectangular columns strengthened using GFRP," *Cem. Concr. Compos.*, vol. 29, no. 8, pp. 609–615.

[5] "Ilki A, Peker O, Karamuk E, Demir C, Kumbasar N.(2006) " Axial behavior of RC columns retrofitted with FRP composites. Adv Earthq Eng Urban Risk Reduction 2006; 66:301 16,".

[6] H. Toutanji, M. Han, J. Gilbert, and S. Matthys (2010), "Behavior of Large-Scale Rectangular Columns Confined with FRP Composites," *J. Compos. Constr.*, vol. 14, no. 1, pp. 62–71.

[7] M. A. G. Silva (2011), "Behavior of square and circular columns strengthened with aramidic or carbon fibers," *Constr. Build. Mater.*, vol. 25, no. 8, pp. 3222–3228.

[8] B. S. Pessiki, K. A. Harries, J. T. Kestner, R. Sause, and J. M. Ricles (2001), "of R Einforced C Oncrete C Olumns C Onfined," *Gg*, vol. 5, no. November, pp. 237–245.

[9] C. Pellegrino and C. Modena (2010), "Analytical Model for FRP Confinement of Concrete Columns with and without Internal Steel Reinforcement," *J. Compos. Constr.*, vol. 14, no. 6, pp. 693–705.

[10] Y. Wu, T. Liu, and D. Oehlers (2006), "Fundamental principles that govern retrofitting of reinforced concrete columns by steel and FRP jacketing," *Adv. Struct. Eng.*, vol. 9, no. 4, pp. 507–534.

[11] Y. Wu and L. Wang, "Columns Confined by External Jacket (2009)," vol. 135, no. March, pp. 253–261.

[12] L. M. Wang and Y. F. Wu (2008), "Effect of corner radius on the performance of CFRP-confined square concrete columns: Test," *Eng. Struct.*, vol. 30, no. 2, pp. 493–505.