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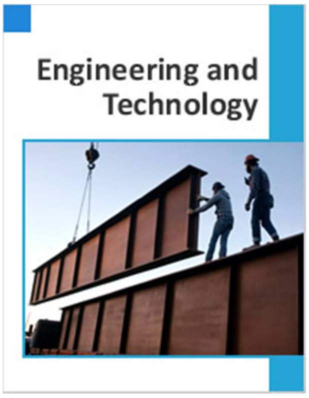

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Experimental Investigation of Concrete Externally Confined by CFRP Composites

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Abstract
The present study deals with the analysis of experimental results, in terms of load carrying capacity and strains, obtained from tests on reinforced concrete (RC) columns, strengthened with external carbon fiber reinforced polymer (CFRP) sheets. In this work, we are interested in the effect of the volumetric ratio of the fiber-reinforced polymer (ρ_{FRP}) on the effectiveness of the CFRP external confinement. A total of 36 specimens were subjected to axial compression. All test specimens were loaded to failure in axial compression. Compressive stress, axial and hoop strains have been recorded to evaluate the stress-strain relationship, ultimate strength and ductility of the specimens. Results clearly demonstrate that for a given confinement level, the increase in cross-sectional dimensions of the columns would result in a decrease in the volumetric ratio of the fiber-reinforced polymer (ρ_{FRP}), which will result in a decrease in the strength of the externally-confined-concrete columns. On the other hand, composite wrapping can enhance the structural performance of RC columns in terms of both maximum strength and ductility.

1. Introduction

The use of fiber reinforced polymer (FRP) confined concrete columns has been proven in enhancing the strength and the ductility of columns. Over the last two decades, a large number of experimental and analytical studies have been conducted to understand and simulate the compressive behavior of FRP confined concrete [1-6]. Such strengthening technique has proved to be very effective in enhancing their ductility and axial load capacity. Most of the available experimental data regarding FRP-confined columns have been generated from tests on small-scale concrete specimens with normal strength [7-14]. So, the validation of these results and their applicability to large-scale RC columns is of great practical interest. Published work in this field is relatively few [15-17]. More research investigation is needed on this subject to study the effect of column’s diameter on the effectiveness of the CFRP external confinement. The present paper deals with the analysis of experimental results, in terms of load carrying capacity and strains, obtained from tests on circular reinforced concrete columns, confined with external CFRP composite. The principal study parameter was the volumetric ratio of the fiber-reinforced polymer (ρ_{FRP}).

2. FRP-Confined Concrete in Circular Columns

The confinement action exerted by the FRP on the concrete core is of the passive type, that is, it arises as a result of the lateral expansion of concrete under axial load.

As the axial stress increases, the corresponding lateral strain increases and the confining device develops a tensile hoop stress balanced by a uniform radial pressure which reacts against the concrete lateral expansion [12, 18]. When an FRP confined column is subject to axial compression, the concrete expands laterally and this expansion is restrained by the FRP. The confining action of the FRP composite for circular concrete columns is shown in Figure 1. For circular columns, the concrete is subject to uniform confinement, and the maximum confining pressure provided by FRP composite is related to the amount and strength of FRP and the diameter of the confined concrete core. The maximum value of the confinement pressure that the FRP can exert is attained when the circumferential strain in the FRP reaches its ultimate strain and the fibers rupture leading to brittle failure of the column. This confining pressure is given by:

$$f_l = \frac{2\ t_{frp}\ E_{frp}\ \varepsilon_{fu}}{d} = \frac{2\ t_{frp}\ f_{frp}}{d} = \frac{\rho_{frp}\ f_{frp}}{2} \tag{1}$$

Where f_l is the lateral confining pressure, E_{frp} is the elastic modulus of the FRP composite, ε_{fu} is the ultimate FRP tensile strain, f_{frp} is the ultimate tensile strength of the FRP composite, t_{frp} is the total thickness of the FRP, d is the diameter of the concrete column, and ρ_{frp} is the FRP volumetric ratio given by the following equation for fully wrapped circular cross section:

$$\rho_{frp} = \frac{\pi\ d\ t_{frp}}{\pi\ d^2/4} = \frac{4\ t_{frp}}{d} \tag{2}$$

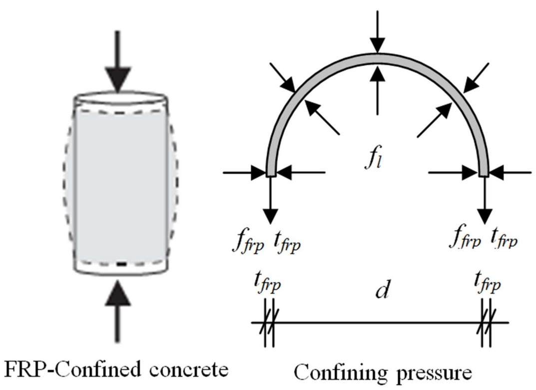


Figure 1. *Confinement action of FRP jacket in circular sections.*

3. Experimental Program

3.1. Materials Properties

Concrete mixtures: Three concrete mixtures were used to achieve the desired range of unconfined concrete strength (26, 50 and 62 MPa), as shown in Table 1. Mixtures were prepared in the laboratory using a mechanical mixer and were used to cast the concrete specimens which were wrapped with CFRP sheets after drying.

Table 1. *Concrete mixture proportions.*

Mixture no.	I	II	III
Compressive cylinder strength, f'_{co} (MPa)	25.93	49.46	61.81
Cement (kg/m^3)	280[a]	400[b]	450[c]
Water (kg/m^3)	180	183.86	170
Crushed gravel (kg/m^3)			
Ø 4/6	122.90	115.70	115.60
Ø 6/12	258.20	243.00	242.80
Ø 12/20	769.50	724.20	723.50
Sand Ø 0/4 (kg/m^3)	729.10	686.30	685.60
Sika Viscocrete-Tempo12 (l/ m^3), [d]	-	0.85	1.55
Air content (%)	2.3	2.5	2.7
W/C	0.64	0.46	0.37

[a]Portland cement: CPA CEM II R 32.5 MPa, [b]Portland cement: CPA CEM I R 42.5 MPa, [c]Portland cement: CPA CEM I R 52.5 MPa, [d]Sika Viscocrete-Tempo 12: High-range water reducing and super-plasticizing admixture.

CFRP composites: The carbon-fiber fabric used in this study were the SikaWrap-230C/45 product, a unidirectional wrap. The resin system that was used to bond the carbon fabrics over the specimens in this work was the epoxy resin made of two-parts, resin and hardener. The mixing ratio of the two components by weight was 4:1. SikaWrap-230C/45 was field laminated using Sikadur-330 epoxy to form a carbon fiber reinforced polymer wrap (CFRP) used to strengthen the concrete specimens.

3.2. Fabrication of Test Specimens

The experimental program was carried out on circular columns of 1000 mm height with two different diameters of 160 mm and 200 mm. For all RC specimens the longitudinal steel ratio was constant for all specimens and equal to 2.25%. Transverse ties (Ø 8 mm) were spaced every 140 mm. Series definition and details are given in Table 2.

Table 2. *Details of test specimens.*

Specimen designation	Dimensions (mm)	Number of CFRP layers	f'_{co} (MPa)	Slenderness (L/ Ø)
Col.160-RC26-0L$_1$	Ø160 x 1000	0	26 MPa	6,25
Col.160-RC26-0L$_2$		0		
Col.160-RC26-1L$_1$		1		
Col.160-RC26-1L$_2$		1		
Col.160-RC26-3L$_1$		3		
Col.160-RC26-3L$_2$		3		
Col.200-RC26-0L$_1$	Ø200 x 1000	0	26 MPa	5
Col.200-RC26-0L$_2$		0		

Specimen designation	Dimensions (mm)	Number of CFRP layers	f'_{co} (MPa)	Slenderness (L/ Ø)
Col.200-RC26-1L_1		1		
Col.200-RC26-1L_2		1		
Col.200-RC26-3L_1		3		
Col.200-RC26-3L_2		3		
Col.160-RC50-0L_1	Ø160 x 1000	0	50 MPa	6,25
Col.160-RC50-0L_2		0		
Col.160-RC50-1L_1		1		
Col.160-RC50-1L_2		1		
Col.160-RC50-3L_1		3		
Col.160-RC50-3L_2		3		
Col.200-RC50-0L_1	Ø200 x 1000	0	50 MPa	5
Col.200-RC50-0L_2		0		
Col.200-RC50-1L_1		1		
Col.200-RC50-1L_2		1		
Col.200-RC50-3L_1		3		
Col.200-RC50-3L_2		3		
Col.160-RC62-0L_1	Ø160 x 1000	0	62 MPa	6,25
Col.160-RC62-0L_2		0		
Col.160-RC62-1L_1		1		
Col.160-RC62-1L_2		1		
Col.160-RC62-3L_1		3		
Col.160-RC62-3L_2		3		
Col.160-RC62-0L_1	Ø200 x 1000	0	62 MPa	5
Col.160-RC62-0L_2		0		
Col.160-RC62-1L_1		1		
Col.160-RC62-1L_2		1		
Col.160-RC62-3L_1		3		
Col.160-RC62-3L_2		3		

The specimen notations are as follows: the first letter refers to column; the next two letters indicate the type of concrete (RC for reinforced concrete), followed by the compressive strength of unconfined concrete f'_{co} (26 MPa, 50 MPa and 62 MPa). The last letters specifies the number of CFRP layers (0L, 1L and 3L), followed by the number of specimen.

After 28 days of curing, the CFRP jackets were applied to the specimens by manual wet lay-up process. The concrete specimens were cleaned and completely dried before the resin was applied. The mixed Sikadur-330 epoxy resin was directly applied onto the substrate at a rate of 0.7 kg/m^2. The fabric was carefully placed into the resin with gloved hands and any irregularities or air pockets were smoothened out using a plastic laminating roller. The roller was continuously used until the resin was reflected on the surface of the fabric, an indication of fully wetting. After the application of the first CFRP wrap, a second layer of resin at a rate of 0.5 kg/m^2 was applied to allow the impregnation of the second layer of the CFRP. The following layer is applied in the same way. Finally, a layer of resin was applied to complete the operation. The last CFRP layer was wrapped around the column with an overlap of 1/4 of the perimeter to avoid sliding or deboning of fibers during tests and to ensure the development of full composite strength [10, 19]. The wrapped specimens were left at room temperature for 1 week for the epoxy to harden adequately before testing. The test setup is shown in Figure 2.

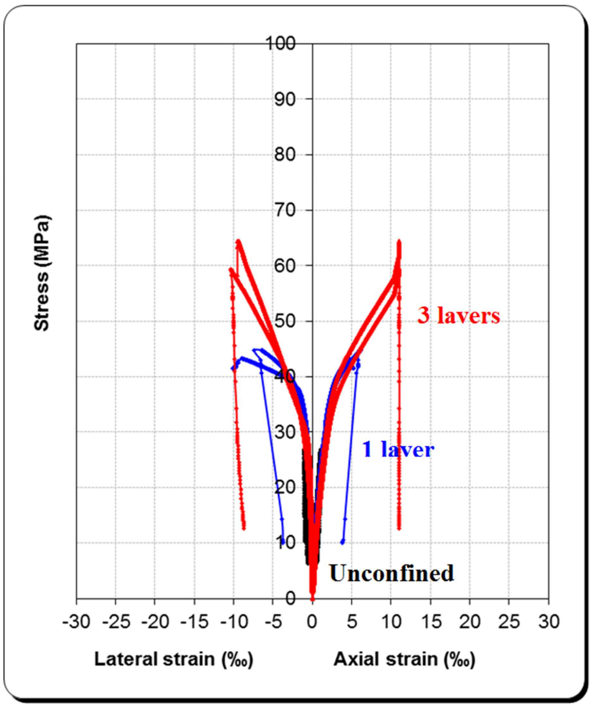
Figure 2. *Test setup.*

4. Test Results and Discussion

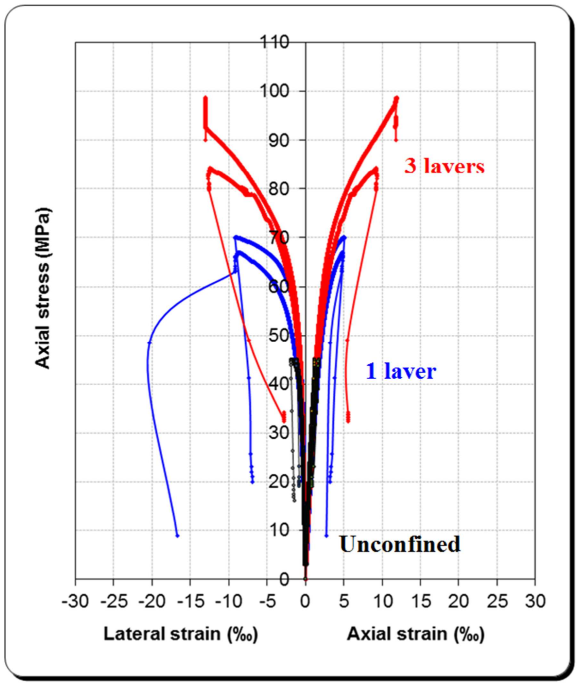
4.1. Stress-Strain Response

Representative stress-strain curves for each series of tested CFRP-wrapped columns are reported in Figures 3 and 4. It is found that for low strength concrete specimens of series 1: 26 MPa (classified as ordinary in some codes), the stress-strain curves are bilinear with shape softening (Figure 3a, 3b, 4a and 4b). On the other hand, for similar medium or high strength concrete specimens (Series 2: 50 MPa and Series 3: 62 MPa), when the strength of the unconfined concrete f'_{co} increases, the slope of the second branch of the bilinear curve progressively recovers downward and eventually to a bilinear downward shape with a substantial reduction in ductility (Figure 3c and 4c).

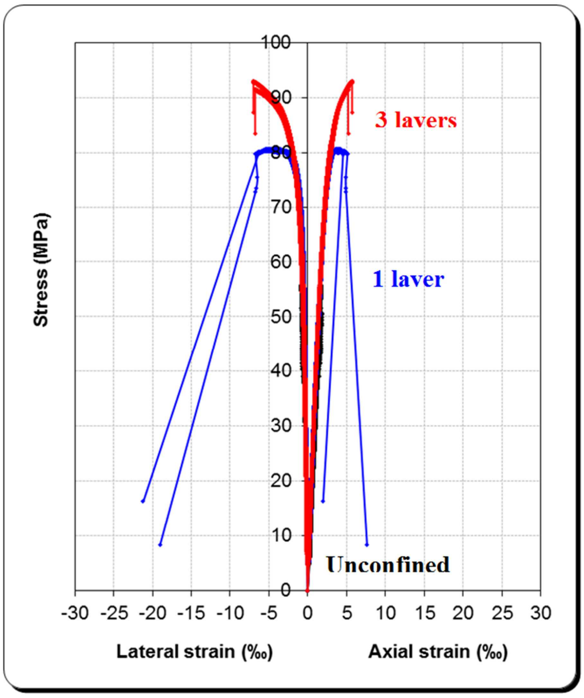
In the case of stress-strain curves with a bilinear trend. The first zone is essentially a linear response governed by the stiffness of the unconfined concrete, which indicates that no confinement is activated in the CFRP wraps since the lateral strains in the concrete are very small. Hence the confined and the unconfined specimens behave in the same manner, irrespective of the number of layers. After reaching the maximum load point, the unconfined concrete specimens show a sudden drop in stiffness and strength. The increase of load produces large lateral expansions, and consequently the CFRP wrap reacts accordingly and a confining action is created on the concrete core. In the second zone, the concrete is fully cracked and the activated CFRP confinement provides additional load carrying capacity by keeping the concrete core intact. The stress-strain curve here increases linearly up to failure. The stiffness of the specimen in this zone depends on the modulus of elasticity of the CFRP material and on the level of confinement (Figure 3a, 3b, 4a and 4b).



(a) RC columns Ø160x1000 mm (series-1: f'_{co} = 26 MPa)



(b) RC columns Ø160x1000 mm (series-2: f'_{co} = 50 MPa)

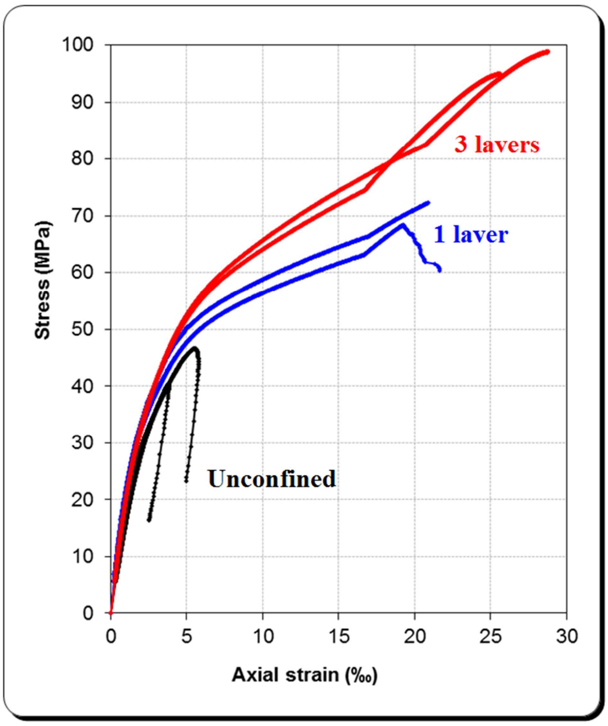


(c) RC columns Ø160x1000 mm (series-3: f'_{co} = 62 MPa)

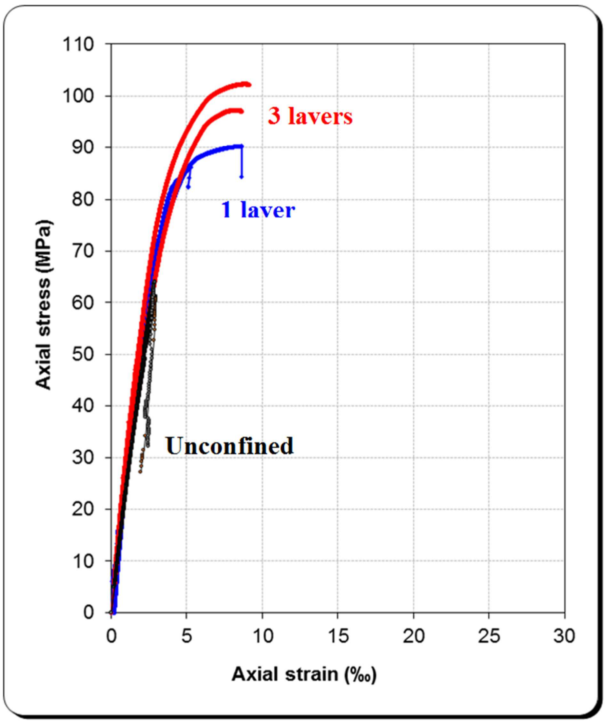
Figure 3. *Stress-strain curves of FRP confined columns (Ø160x1000 mm).*

However, when a concrete column is provided with little confinement, the bilinear stress-strain behaviour described above may not exist. Such a situation arises when the volumetric ratio of FRP composite is very small (Figure 3c and 4c).

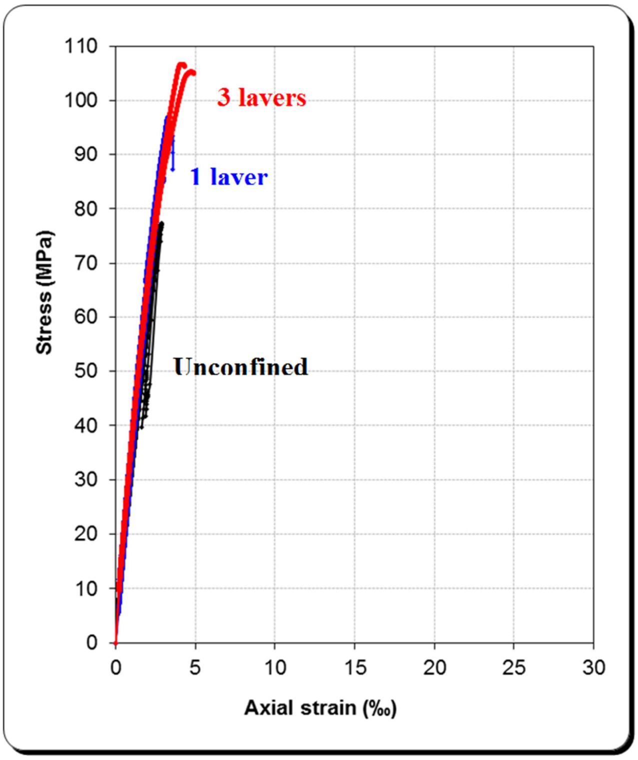
On overall, both ultimate compressive strength and ultimate strain are variably enhanced depending on the number of CFRP layers.



(a) RC columns Ø200x1000 mm (series-1: f'_{co} = 26 MPa)



(b) RC columns Ø200x1000 mm (series-2: f'_{co} = 50 MPa)



(c) RC columns Ø200x1000 mm (series-3: f'_{co} = 62 MPa)

Figure 4. *Stress-strain curves of FRP confined columns (Ø200x1000 mm).*

4.2. Failure Mode

All confined concrete columns failed by fracture of the composite wrap in a sudden and explosive way preceded by typical creeping sounds. For all confined specimens, delamination was not observed at the overlap location of the jacket, which confirmed the adequate stress transfer over the splice.

In the category of the (Ø160x1000 mm) reinforced concrete columns confined with CFRP, the rupture of the composite envelope was perpendicular to the carbon fibers followed by circumferential fracture of different widths which is located generally in the upper or lower half of the height of the columns (Figure 5). For the concrete columns of series 2 (50 MPa) confined with 3 CFRP layers, as well as all series 3 columns (62 MPa), the rupture zone approaches the middle of the column.

Col.160-RC26-1L_1 Col.160-RC50-1L_1 Col.160-RC62-1L_1

Figure 5. *Failure mode of CFRP-confined columns (Ø160x1000 mm).*

The failure of the (Ø200x1000 mm) reinforced concrete columns confined with CFRP was generally located in the middle of the columns for the three series of tested concrete (Figure 6).

Col.200-RC26-0L_1 Col.200-RC26-1L_1 Col.200-RC26-3L_1

Figure 6. *Failure mode of CFRP-confined columns (Ø200x1000 mm).*

4.3. Effect of Columns Diameter on FRP-Confinement Effectiveness

In the following, we compare the results obtained for reinforced concrete columns with circular cross-section Ø200x1000 mm with respect to columns Ø160x1000 mm for the three series of concrete tested in the main program of the present study (series 1: 26 MPa, series 2: 50 MPa and 3: 62 MPa).

4.3.1. Reinforced Concrete Columns

The columns with a diameter of 200 mm recorded an axial compression strength greater than that of the 160 mm diameter columns for the three-concrete series (26 MPa, 50 MPa and 62

MPa). Table 3 shows that unconfined columns with a diameter of 200 mm offer more confinement (lateral stiffness provided by concrete) than that of columns of 160 mm. This efficiency of the confinement of the columns Ø200x1000 mm with respect to that of Ø160x1000 mm decreases with the compressive strength of the concrete. It was of the order of 69.94% for the concrete of the series 1 (26 MPa) and only of 43.99% for the concrete of the series 3 (62 MPa).

Table 3. *Axial compressive strength of RC columns (control specimens).*

Concrete Series	RC columns Ø 160x1000 mm	Ø 200x1000 mm	$(f'_{c200} - f'_{c160}) / f'_{c160}$ (%)
1 (26 MPa)	25,59	43,49	69,94
2 (50 MPa)	44,99	62,68	39,31
3 (62 MPa)	53,14	76,52	43,99

4.3.2. RC columns Externally Confined with CFRP

The gains in compressive strength and axial deformation as a function of the column diameter are shown in Figure 7 for two different confinement levels (1 and 3 carbon fiber-reinforced polymer layers). Unlike unconfined columns, those with a diameter of 160 mm confined with 1 or 3 layers of carbon fiber-reinforced polymer (CFRP) sheets have achieved gains in compressive strength (f'_c) and axial deformation (ε_{cc}) greater than those recorded for the 200 mm diameter columns as illustrated in Figure 7. However, confinement with CFRP composite materials reversed the trend in similar unconfined columns (see Table 3).

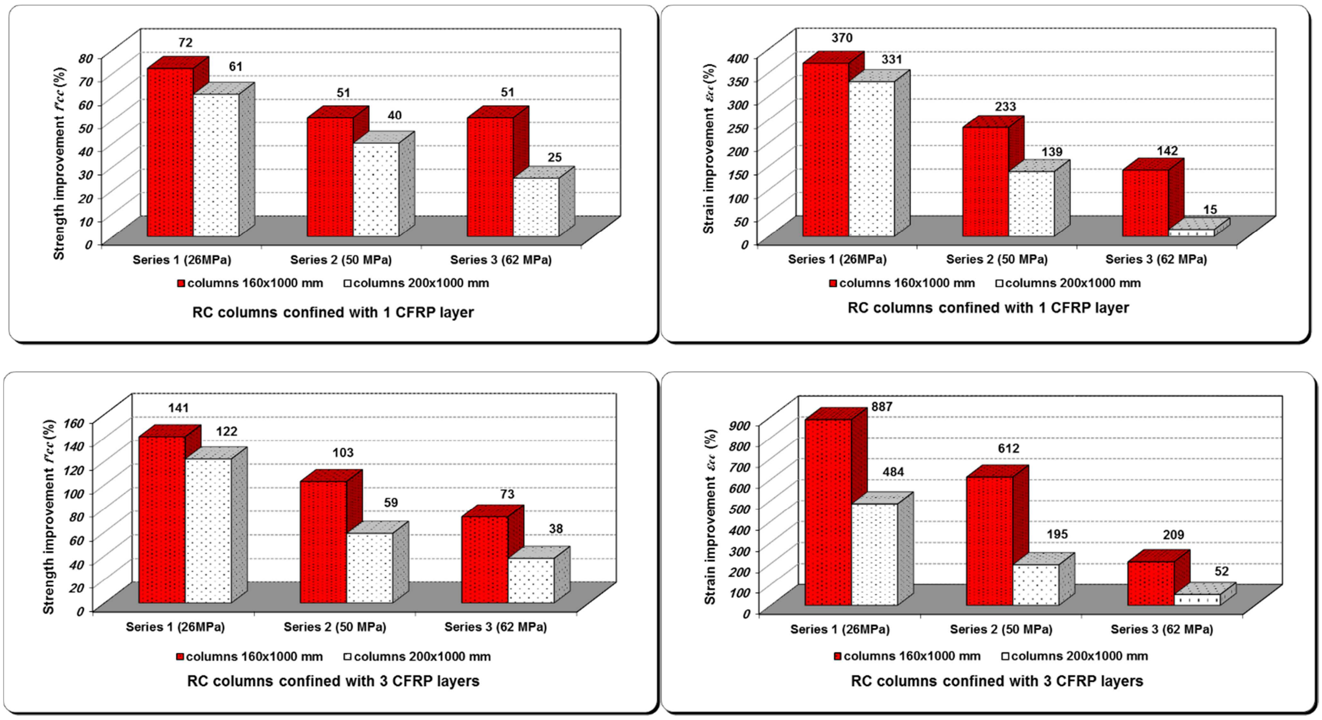
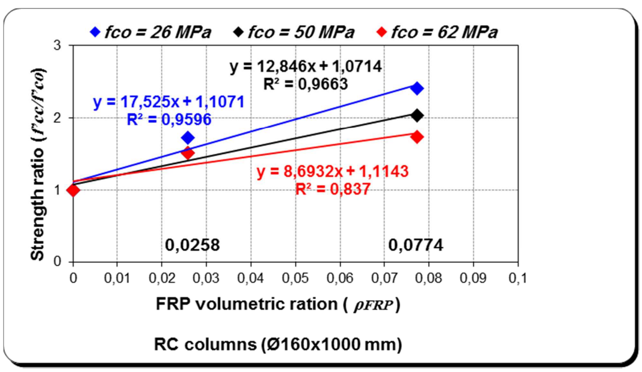


Figure 7. *Effect of column diameter on the effectiveness of external CFRP confinement.*

It should be noted that for a given confinement level, the increase in cross-sectional dimensions of the specimens would result in a decrease in the volumetric ratio of the fiber-reinforced polymer ($\rho_{FRP:}$ defined as the ratio of the cross-sectional area of the composite to that of the concrete), which will result in a decrease in the strength of the confined concrete. Figures 8 and 9 show the strength ratio (f'_{cc}/f'_{co}) and the strain ratio ($\varepsilon_{cc}/\varepsilon_{co}$) as a function of the volumetric ratio of the fiber-reinforced polymer (ρ_{FRP}) for all tested specimens. In general, increasing ρ_{FRP} involves more effective confinement.

However, after confinement with CFRP composite materials, the 160 mm diameter columns had a $\rho_{FRP} = 0.0258$ and 0.0774 respectively for 1 and 3 layers of CFRP, greater than those of the columns with a diameter of 200 mm which had $\rho_{FRP} = 0.0203$ and 0.0609 for 1 and 3 layers of CFRP, respectively. This explains the confinement efficiency for columns (Ø160x1000 mm) after confinement with CFRP composite compared to columns (Ø200x1000 mm) despite their smaller diameters.

Figures 8 and 9 shows that the variation of the strength ratio (f'_{cc}/f'_{co}) and the strain ratio ($\varepsilon_{cc}/\varepsilon_{co}$) as a function of the volumetric ratio ρ_{FRP} corresponds in the majority of cases to a linear function with a coefficient of variation (R^2) greater than 0.90.



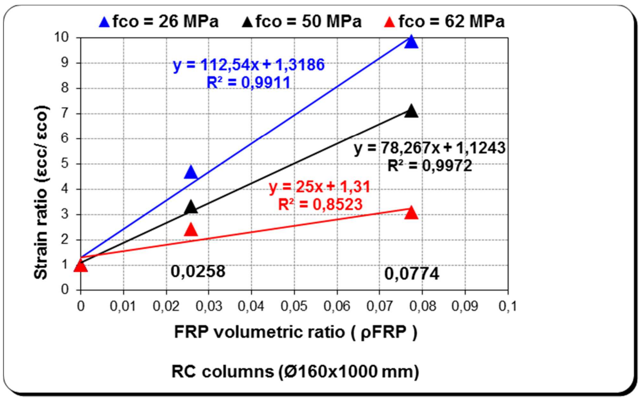


Figure 8. *Strength and strain ratios depending on the volumetric ratio (columns with Ø160x1000 mm).*

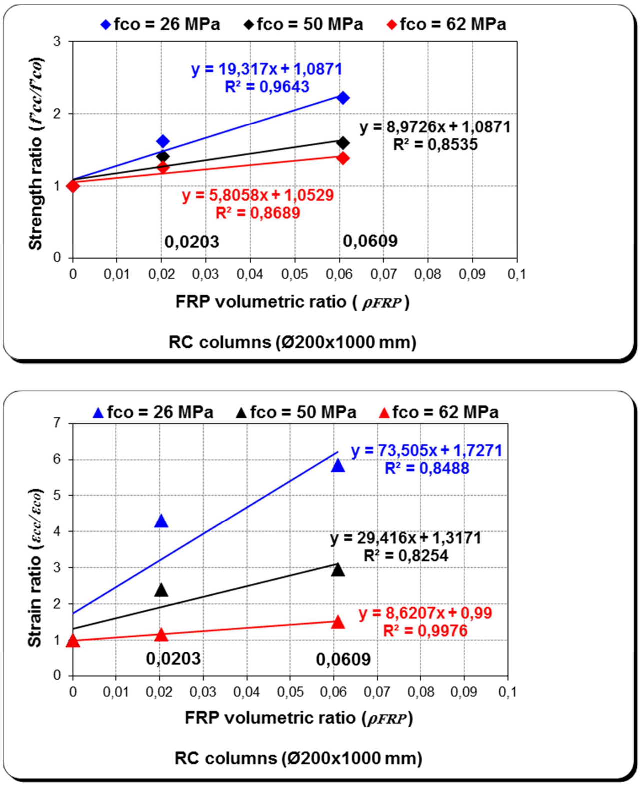


Figure 9. *Strength and strain ratios depending on the volumetric ratio (columns with Ø200x1000 mm).*

5. Conclusions

The results of an experimental investigation on the performance of reinforced concrete columns strengthened with externally applied uni-directional carbon fiber reinforced plastic material were presented. The main findings of this research can be summarized as follows:

a. For a given confinement level, the increase in cross-sectional dimensions of the columns would result in a decrease in the volumetric ratio of the fiber-reinforced polymer (ρ_{FRP}), which will result in a decrease in the strength and ductility of the externally-confined-concrete columns.
b. The confinement provided by the CFRP improves both the load-carrying capacity and the ductility of the column.
c. The failure of all CFRP wrapped specimens occurred in a sudden and explosive way preceded by typical creeping sounds.
d. On overall, CFRP strengthened specimens showed a typical bilinear curve. The first zone is essentially a linear response governed by the stiffness of the unconfined concrete. In the second zone, the stiffness of the specimen depends on the modulus of elasticity of the CFRP material and on the FRP volumetric ratio.
e. Increasing the amount of CFRP sheets produce an increase in the compressive strength of the confined column but with a rate lower compared to that of the deformation capacity.

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