Use of CFRP in Confining High Strength Concrete Columns Subject to Axial Loading

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Abstract**—** The present study deals with the analysis of experimental results, regarding of load carrying capacity and strains, obtained from tests on reinforced concrete (RC) columns, strengthened with external carbon fiber reinforced polymer (CFRP) sheets. The experimental parameters include: number of wrap layers, slenderness of the columns (L/a or L/D) and section geometry (circular or square). A total of 48 specimens were subjected to axial compression. All test specimens were loaded to failure. Compressive stress, both axial and hoop strains have been recorded to evaluate the stress-strain relationship, ultimate stress, stiffness, and ductility. First, the effects of test parameters are analysed and compared. Results clearly demonstrate that composite wrapping can enhance the structural performance of RC columns in terms of both maximum strength and ductility.

Keywords**—** RC column, composite material, CFRP, confinement, slenderness, section shape, strength, ductility..

I. Introduction

During the last decade, the use of advanced composite materials such as carbon fiber reinforced polymer (CFRP) sheets or plates has been successfully used for the rehabilitation of concrete structures throughout the world. Their application in civil engineering structures has been growing rapidly in recent years, and is becoming an effective and promising solution for strengthening deteriorated concrete members, because of their high strength-to-weight ratio, good fatigue properties and excellent corrosion resistance. They are also quickly and easily applied; their use minimizes labor costs and can lead to significant savings in overall project costs.

Several studies on the performance of FRP wrapped columns have been conducted, using both experimental and analytical approaches [1-6]. This strengthening technique has proved to be very effective in enhancing column ductility and axial load capacity. Most of the available experimental data regarding FRP-confined columns have been generated from tests on small-scale concrete cylinders with standard strength. The data available for columns with square or rectangular cross sections have increased over recent years but are still limited [7-9]. Also the validation of these results and their applicability to large-scale reinforced concrete (RC) columns is of great practical interest. Published work in this field is relatively scarce [10-11]. More research on this subject is needed to study the effect of slenderness for concrete columns with higher strength.

This study presents a comprehensive experimental investigation on the behavior of axially loaded circular and square reinforced columns strengthened with CFRP wrap. A total of 48 concrete specimens were tested under axial compression. The data recorded included the compressive loads, axial strains, and radial strains. The parameters considered are the number of composite layers and slenderness ratio of the column - L/D and L/a, for circular and square cross sections respectively

II. Procedure for Paper Submission

The concrete mix used to prepare testing specimens had an average strength of 50 MPa. The carbon-fiber sheets used were the SikaWrap®-230 C product, an unidirectional wrap. The Sikadur®-330 epoxy resin was used to impregnate and bond the carbon fabrics to the columns. Eight series of experiments were performed to investigate the behaviour of plain concrete (PC) and RC columns confined by CFRP composite. For all RC specimens the diameter of longitudinal and transverse reinforcing steel bars were respectively 12 mm and 8 mm. The longitudinal steel ratio was constant for all specimens and equal to 2.25%.The yield strength of the longitudinal and transversal reinforcement was 500 MPa and 235 MPa, respectively. Table 1 summarizes the specimens involved in the experimental program.

The specimen notations are as follows. The first two letters refer to the cross section shape: C for circular and S for square, followed by type of concrete: PC for plain concrete and RC for reinforced concrete. The next letter indicates the slenderness ratio: x for L/a=2 (or L/D=2), y for L/a=4 (or L/D=5.08) and z for L/a=7.14 (or L/D=6.45). The last number specifies the number of reinforcing layers. With regards to results, f'cc/fco represents the average ratio of concrete strength of confined to unconfined member. The axial strains εcc and εco correspond respectively to confined and unconfined concrete specimens.

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TABLE I
DETAILS OF TEST SPECIMENS AND EXPERIMENTAL RESULTS (MEAN VALUES)

Specimen designation	Slender ratio L/D or L/a	Nominal dimensions (D x L or a x a x L) [mm]	Number of layers	Number of specimens	f'_{cc} (MPa)	f'_{cc}/f'_{co}	ε_{cc} (‰)	$\varepsilon_{cc}/\varepsilon_{co}$
CPC. x0	2	160 x 320	0	2	49.46	1.00	1.69	1.00
CPC. x1	2	160 x 320	1	2	52.75	2.52	3.85	2.28
CPC. x3	2	160 x 320	3	2	82.91	7.27	6.36	376
CRC. x0	2	160 x 320	0	2	58.24	1.00	3.02	1.00
CRC. x1	2	160 x 320	1	2	77.51	1.33	8.36	2.78
CRC. x3	2	160 x 320	3	2	100.41	1.72	13.58	4.50
CRC. y0	5.08	197 x 1000	0	2	45.00	1.00	1.48	1.00
CRC. y1	5.08	197 x 1000	1	2	68.56	1.51	4.94	3.33
CRC. y3	5.08	197 x 1000	3	2	91.50	2,07	10.54	7.12
CRC. z0	6.45	155 x 1000	0	2	62.68	1.00	2.90	1.00
CRC. z1	6.45	155 x 1000	1	2	88.27	1.40	6.94	2.30
CRC. z3	6.45	155 x 1000	3	2	99.77	1.60	8.57	2.95
SPC. x0	2	140 x 140 x 280	0	2	48.53	1.00	3.39	1.00
SPC. x1	2	140 x 140 x 280	1	2	52.52	1.08	4.03	1.19
SPC. x3	2	140 x 140 x 280	3	2	58.25	1.20	6.72	1.98
SRC. x0	2	140 x 140 x 280	0	2	52.82	1.00	4.08	1.00
SRC. x1	2	140 x 140 x 280	1	2	62.04	1.17	5.42	1.30
SRC. x3	2	140 x 140 x 280	3	2	69.09	1.30	6.89	1.70
SRC. y0	4	140 x 140 x 560	0	2	52.67	1.00	2.11	1.00
SRC. y1	4	140 x 140 x 560	1	2	61.61	1.16	2.92	1.38
SRC. y3	4	140 x 140 x 560	3	2	65.91	1.24	3.26	1.54
SRC. z0	7.14	140 x 140 x 1000	0	2	48.26	1.00	1.38	1.00
SRC. z1	7.14	140 x 140 x 1000	1	2	60.16	1.24	1.88	1.35
SRC. z3	7.14	140 x 140 x 1000	3	2	65.71	1.35	2.86	2.03

After concrete columns were fully cured, CFRP wrapping was performed according to the procedure specified by the manufacturer. Specimens were loaded under monotonic uniaxial compression up to failure. Load was applied at a rate of 0.24 MPa/s and was recorded with an automatic data acquisition system. Axial and lateral strains were measured using extensometers. The instrumentation included either lateral or radial linear variable differential transducer (LVDT) placed as a square frame or a hoop at specimen mid-heigh. Measurement devices also included 3 vertical LVDTs to measure average axial strains. The test setup for the various specimens is shown in Fig. 1.

Fig. 1: Test setups for circular and square columns

III. TEST RESULTS AND DISCUSSION

During the last decade, the use of advanced composite materials such as carbon fiber reinforced polymer (CFRP) sheets or plates has been successfully used for the rehabilitation of concrete structures throughout the world. Their application in civil engineering structures has been growing rapidly in recent years, and is becoming an effective and promising solution for strengthening deteriorated concrete members, because of their high strength-to-weight ratio, good fatigue properties and excellent corrosion resistance. They are also quickly and easily applied, their use minimizes labor costs and can lead to significant savings in overall project costs.

Compression stress-strain curves and failure modes of the CFRP wrapped specimens were very similar in each series. No lateral deflection was observed during any test. All confined concrete columns failed by fracture of the composite wrap in a sudden and explosive way preceded by typical cracking sounds. Regarding square columns, failure occurred at one of the corners, due to high stress concentration at these locations (Fig. 2). For short specimens, fibre rupture starts predominantly at the central zone and then propagates towards other sections. In the case of slender specimens, collapse was mostly concentrated at the end regions, indicating that the greater the slender ratio, the smaller the area of ruptured CFRP.

Fig. 2: Failure of CFRP confined specimens

At ultimate load, when confinement action was no longer provided due to CFRP fracture, the internal steel started buckling and the crushed concrete collapsed inside the fractured CFRP. This indicates the concrete core is significantly damaged, but remains confined, before ultimate load.

For all confined specimens, delamination was never observed at the overlap location of the jacket, which confirmed the adequate stress transfer over the splice. The obtained tensile failure strain values for the CFRP jacket were quite lower than the CFRP failure strain, as many authors have already reported [9, 11].

Representative stress-strain curves for each series of tested CFRP-wrapped specimens are reported in Fig. 3 and Fig. 4, for circular and square specimens, respectively. They show axial stress versus both axial and lateral strains for specimens with zero, 1 and 3 layers of CFRP wrap, for various slenderness ratios.

A. Stress-Strain Response

All CFRP strengthened specimens showed a typical bilinear trend. The first zone is essentially a linear response governed by the stiffness of the unconfined concrete, which indicates 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. With confined specimens, as load increases larger lateral expansions are produced and the CFRP reacts accordingly, thus creating a confining action on the concrete core. It should be noted that the confinement pressure is activated at higher loads - about 70% - 80% of ultimate value of respective unconfined specimen. In the case of circular columns the section is fully confined, therefore the confining pressure capacity is able to limit the effects of the deteriorated concrete core, which allows reaching higher stresses. On the contrary, with square sections, the confining action is mostly located at the corners, therefore not producing sufficient confining pressure to overcome the effect of concrete degradation. 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. No distinct post behaviour is observed for specimens with higher slenderness ratio. Overall, both ultimate compressive strength and ultimate strain are enhanced with increasing number of layers and lower slenderness ratio.

B. Effect of CFRP Strengthening Layers

Test results illustrated in Figures 3 and 4 indicate that FRP-confinement can significantly enhance the ultimate strengths and strains of the specimens. For circular columns, the average ratio of concrete strength of confined to unconfined member (f'cc/fco) increases by 14%□45% for 1 ply, and by 60%□72% for CFRP jackets with 3 plies, whereas the enhancement in the bearing capacity for square columns was lower as the recorded increases were only 8%□24% for 1 ply, and 20%□35% for 3 plies for CFRP jackets. The axial strains corresponding to confined circular specimens (εcc), were higher than that of unconfined concrete (εco) by 50%□180% for 1 layer and by 200%□450% for 3 layers of CFRP wrap, respectively. The increase was relatively moderate for square specimens as the enhancement in the ultimate axial deformations display an increase of 18%□55% for 1 layer and 50%□110% for 3 layers of CFRP wrap, respectively.

As expected, these results clearly show that strength and ductility improvement were more important for circular column because its section is fully confined. It should be emphasized that the presence of quite sharp corners in all tested CFRP jacketed square columns produced a cutting effect on confining sheets and hence affected the level of enhancement in their load carrying and deformation capacities.

C. Effect of Slenderness Ratio

The comparison of results recorded from wrapped RC specimens having equal cross section, shows that the increase of the slenderness ratio within the considered range (2 to ca. 7) leads to a small decrease in the load carrying capacity and a moderate reduction in the axial deformation. In this respect, it is suggested to consider higher values for slenderness ratio (e.g.>12) in order to investigate the actual relevance.

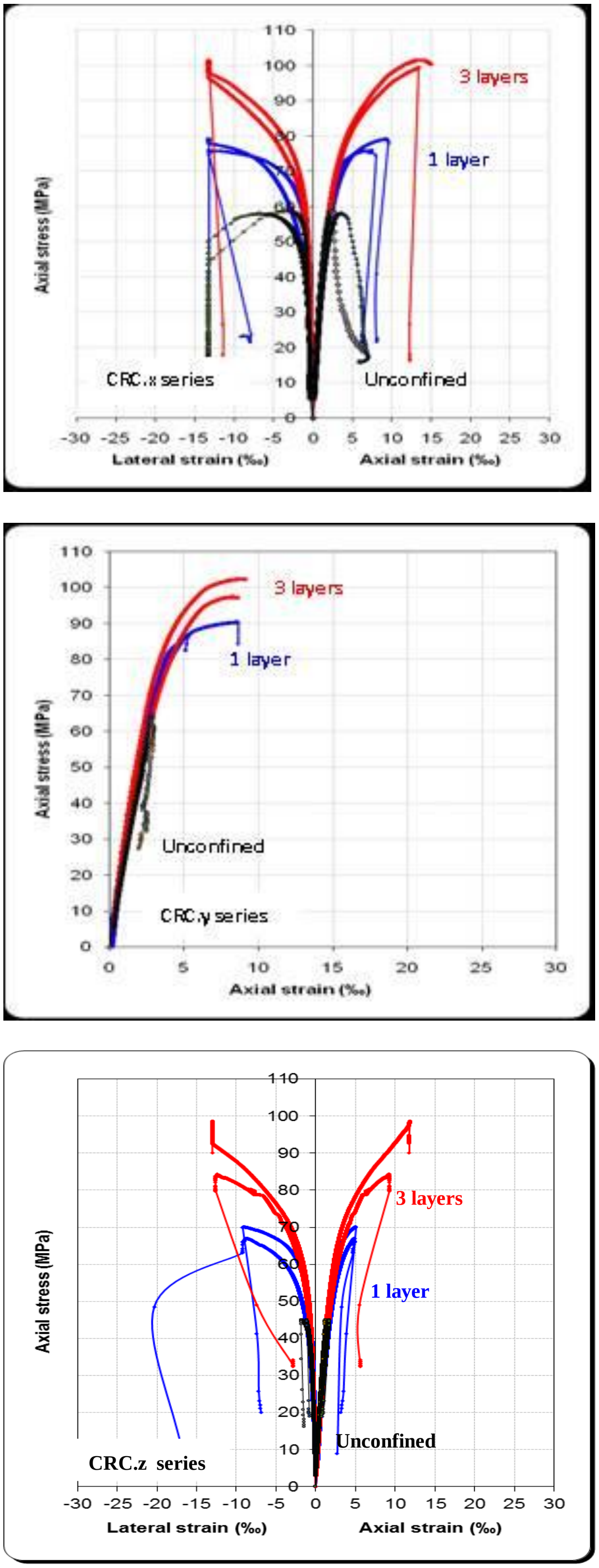

Fig.3. Stress-strain curves for circular columns

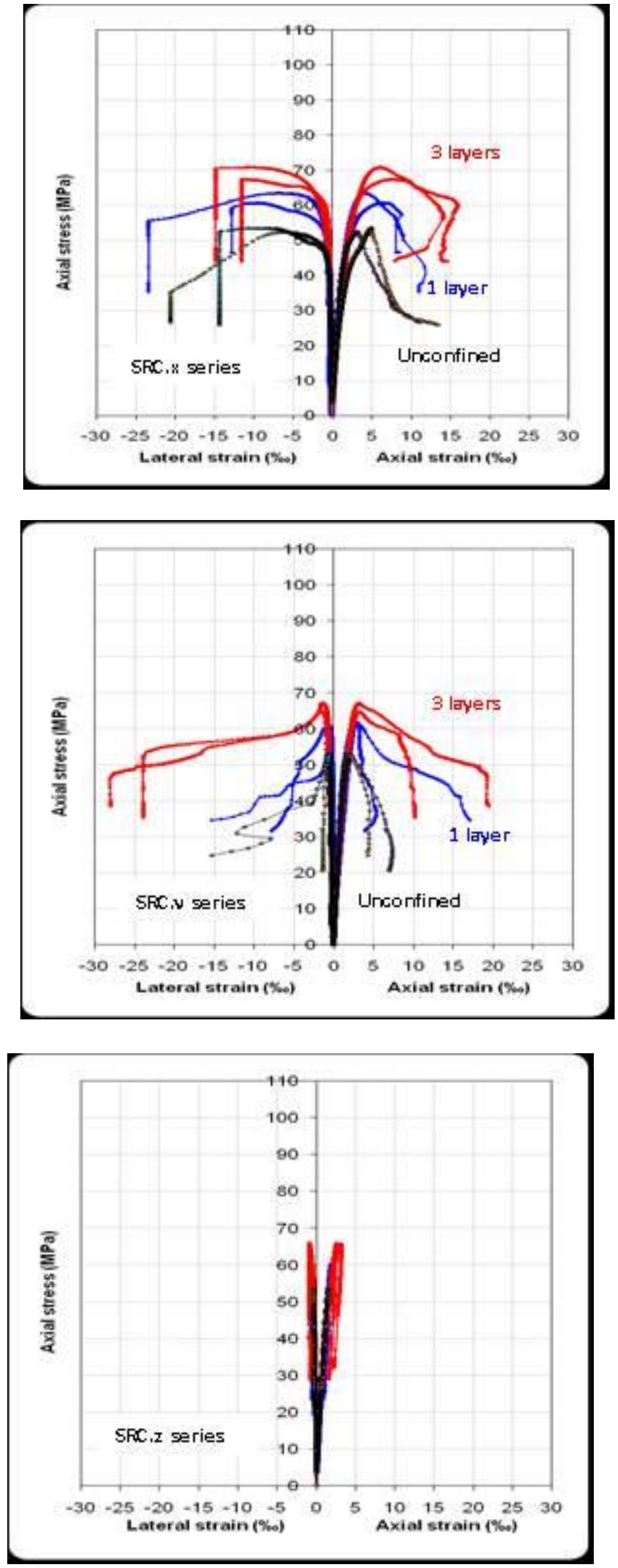

Fig.4. Stress-strain curves for square columns

IV. Conclusions

The results of an experimental investigation on the performance of circular and square 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:

•The confinement provided by the CFRP improves both the load-carrying capacity and ductility of the column. This method of structural rehabilitation was shown to be applicable to both circular and prismatic columns, albeit with different efficiencies.

• The failure of all CFRP wrapped specimens occurred in a sudden and explosive way preceded by typical cracking sounds. Regarding confined square columns, failure initiated at or near a corner, because of the high stress concentration at these locations.

• On overall, CFRP strengthened specimens showed a typical bilinear behaviour. The first zone is essentially a linear response governed by the stiffness of the unconfined concrete. No distinct post behaviour is observed as the slenderness ratio increases.

• Increasing the amount of CFRP sheets produces an increase in the compressive strength of the confined column but at a lower rate compared to that of the deformation capacity.

• The efficiency of the CFRP confinement is higher for circular than for square sections, due to premature damage of the composite wrap at the sharp square column corners.

• The effect of increasing the strengthened columns' slenderness ratio within the investigated range (2 to ca. 7) results in a small effect on its load carrying and deformation capacities.

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