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Enhancement of the Structural Performance of Circular RC Columns with CFRP Wrapping

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ABSTRACT: This study deals with the analysis of experimental results, in terms of load carrying capacity and strains, obtained from tests on circular reinforced concrete (RC) columns, strengthened or repaired with external carbon fiber reinforced polymer (CFRP) sheets. The experimental parameters include: number of wrap layers, concrete strength and the initial damage rate. All test specimens were loaded to failure in axial compression. The data recorded included the compressive loads, axial and hoop strains, which allowed the evaluation of the stress-strain relationship, ultimate strength, stiffness, and ductility of the specimens. Results clearly demonstrate that composite wrapping can enhance the structural performance of concrete columns in terms of both maximum strength and ductility. The effects of test parameters are evidenced and compared. The increase produced by the CFRP jackets on tested damaged specimens regarding their bearing and deformation capacities was particularly very important.

1 INTRODUCTION

The use of fiber reinforced polymer (FRP) materials as a confinement wrap has become an attractive solution to repairing or strengthening deteriorated concrete members. The method is considered superior to conventional methods in terms of confinement strength, post-retrofit ductility, sectional areas, weight, corrosion resistance, application ease, and overall project costs. During the last decade, the use of FRP composites has been successfully promoted for external confinement of RC columns all over the world. Several studies on the performance of FRP wrapped columns have been conducted (Saadatmanesh et al., 1994); (Nanni and Bradford, 1995); (Miraman et al., 1998); (Thériault et al. 2004) ; (Berthet et al., 2005) and (Pan et al., 2007) and has proved that such strengthening technique is very effective in enhancing their ductility and axial load capacity. However, most of the available experimental data regarding FRP-confined columns have been generated from tests on undamaged columns concrete cylinders with normal strength. The data available for deteriorated RC columns repaired with CFRP wraps and high strength RC columns strengthened are still limited (Saadatmanesh et al., 1997); (Tastani and Pantazoupoulou, 2004); (Yalcin et al., 2008) and (Wei et al., 2009). More research investigation is needed on this subject.

This study deals with a series of axial compression tests on circular RC column, strengthened or repaired with CFRP sheets. The data recorded included the compressive loads, axial strains, and radial strains. The main objective is to investigate the influence of some important parameters such as: the compressive strength of the unconfined concrete (normal strength 27MPa and high strength 62MPa), the number of wrap layers (1 and 3), and the rate of column's damage expressed by the amount of preloading (0%, 40%, 60%, 80% and 100% of the respective ultimate load). All test specimens were loaded to failure in axial compression.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

Two kind of concrete mix have been realised to investigate the influence of concrete strength as indicated in Table 1. The two categories represent normal strength concrete (NSC) and high strength concrete (HSC).

Table 1. Concrete mix proportions

Concrete mixture No.	I	II
Concrete strength f'_{co}, MPa	26.93	61,81
Cement, kg/m^3	280	450
Water, kg/m^3	180.00	170.00
Crushed gravel, kg/m^3		
Ø 4/6	122.90	115.60
Ø 6/12	258.20	242.80
Ø 12/20	769.50	728.50
Sand Ø 0/4, kg/m^3	729.10	685.60
Sika Viscorete-Tempo12, ml	-	1550.00
W/C	0.64	0.38

The carbon-fiber sheets used were the SikaWrap-230C product, a unidirectional wrap. The manufacturer's guaranteed tensile strength for this CFRP is 4300 MPa, with a tensile modulus of 238 GPa, an ultimate elongation of 1.8% and a fiber thickness of 0.13mm. The Sikadur-330 epoxy resin was used to bond the carbon fabrics over the circular columns. Various series of experiments were performed to investigate the behaviour of undamaged and damaged concrete circular columns confined by CFRP composite. Table 2 summarizes the specimens involved in the experimental program. 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. The specimen notations are as follows. The specimen notations are as follows. The first letter C refers to the circular shape of the column, followed by followed by the concrete mixture: I for normal strength (26.93 MPa) and II for high strength (61.81 MPa). The next number indicates the rate of preloading (0%, 40%, 60%, 80% and 100% of the respective ultimate load). The last number specifies the number of layers.

Table 2. Details of test specimens

Specimen designation	Concrete mixture	Number of layers	Unconfined concrete strength (MPa)	Number of specimens
CI-0%-0L	I	0	26.93	2
CI-0%-1L		1		2
CI-0%-3L		3		2
CI-40%-3L		3		2
CI-60%-3L		3		2
CI-80%-3L		3		2
CI-100%-3L		3		2
CII. 0%-0L	II	0	61.81	2
CII. 0%-1L		1		2
CII. 0%-3L		3		2

2.2 *Specimen preparation*

After 28 days of curing, the CFRP jackets were applied to the specimens by manual wet lay-up process. The operation of CFRP wrapping was performed according to the procedure specified by the manufacturer. Damaged concrete specimens were obtained by applying a compression preloading of 40%, 60% and 80% of the ultimate load. Ten cycles of loading-unloading were applied to each specimen with to achieve a stabilised damage rate. The resulting cracks and detached concrete were repaired using cement mortar. Testing specimens were loaded up to failure with a uni-axial compressive load applied at a rate corresponding to 0.24 MPa/s and was recorded with an automatic data acquisition system. Axial and lateral strains were measured using extensometers. The instrumentation included both vertical and radial linear variable differential transducer (LVDT). Prior to testing, all CFRP-wrapped columns were capped with sulfur mortar at both ends. The test setup for the various specimens is shown in Figure 1.

Figure 1. Test set up.

3 TEST RESULTS AND DISCUSSION

Failure modes of each series of tested CFRP-wrapped specimens were mostly similar. No lateral deflection was observed during all tests. All confined concrete columns failed by fracture of the composite wrap in a sudden and explosive way preceded by typical creeping sounds. The location of failure was observed mainly in their central zone and then delamination spread towards other sections. None of the specimens failed at the overlap location of the jacket, which confirmed the adequate stress transfer over the splice. The strain values observed for the jacket tensile failure were substantially lower than the FRP failure strain, as many authors have already published.

Figure 2. Failure of CFRP confined specimens

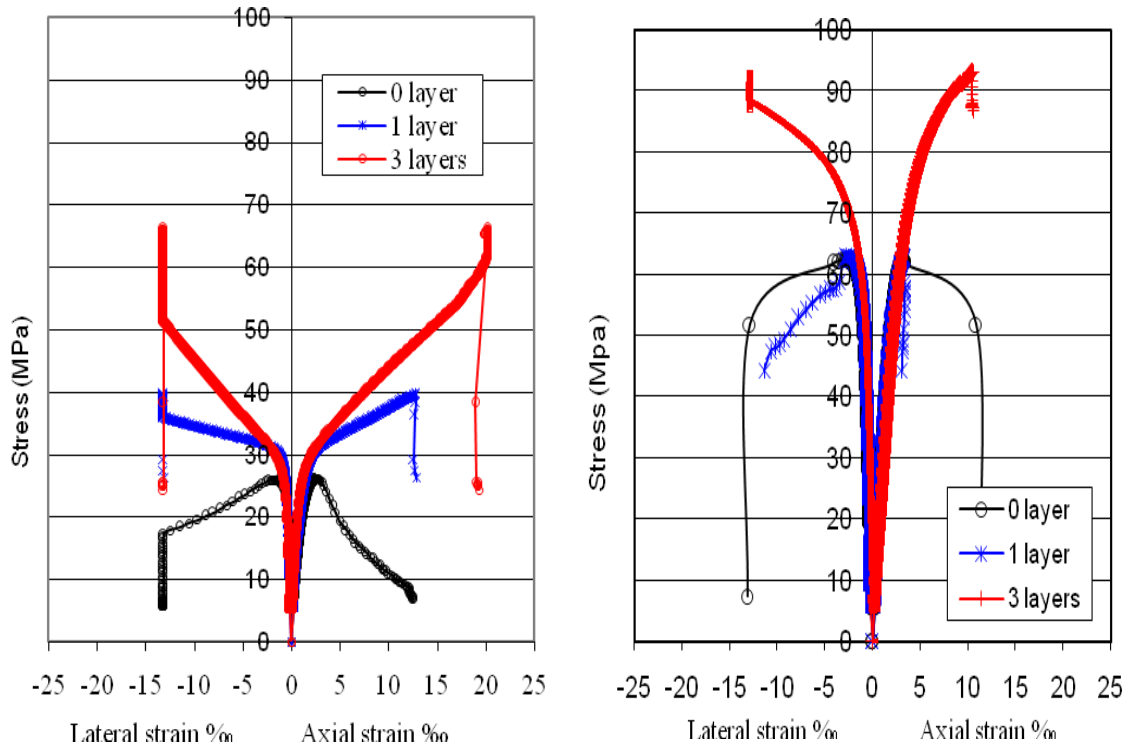
The average experimental results are reported in Table 2, with the increase in terms of compressive strength (f'_{cc}/f_{co}) and ductility ($\varepsilon_{cc}/\varepsilon_{co}$) intended as ultimate axial displacement. It is evident that in all cases the presence of external CFRP jackets increased the mechanical properties of RC columns in different amount according to the number of layers of CFRP wrap, concrete strength and damage rate. Representative stress-strain curves for each series of tested CFRP-wrapped specimens are reported in Figure 3 and 4 giving the axial stress versus the axial and lateral strains for tested specimens.

Table 2. Details of test results

Specimen designation	f'_{cc} (MPa)	f'_{cc}/f'_{co}	ε_{cc} (‰)	$\varepsilon_{cc}/\varepsilon_{co}$	ε_r (‰)	$\varepsilon_r/\varepsilon_{ro}$
CI-0%-0L	29.51	1.00	3.77	1.00	4.95	1.00
CI-0%-1L	49.69	1.68	15.13	4.01	13.74	2.77
CI-0%-3L	74,50	2,40	21,43	5,50	13,23	2,75
CI-40%-3L	74,40	2,40	20,14	5,17	13,92	2,89
CI-60%-3L	73,19	2,36	22,45	5,77	13,13	2,72
CI-80%-3L	72,91	2,35	26,27	6,75	13,94	2,89
CI-100%-3L	70,47	2,27	26,38	6,78	14,07	2,92
CII. 0%-0L	63.01	1.00	2.69	1.00	4.90	1.00
CII. 0%-1L	76.21	1.20	3.75	1.39	5.20	1.06
CII. 0%-3L	94.71	1.50	8.49	3.15	7.15	1.45

3.1 Stress strain response

All CFRP strengthened or repaired specimens showed a typical bilinear trend with a transition zone as illustrated by Figures 3 and 4. The first zone is essentially a linear response governed by the stiffness of the unconfined concrete. The strengthening effect of the CFRP layers begins only after the concrete has reached the peak strength of the unconfined concrete: transversal strains in the concrete activate the CFRP jacket. The increase of load would produce large lateral expansions, and consequently a higher confining pressure, provided that the number of composite layers is quite sufficient. This will limit the effects of the deteriorated concrete, which allows reaching higher stresses. The confinement provided by the CFRP wraps seems to have restored for the damaged specimens their initial mechanical properties. Thus both confined and unconfined specimens behave in the same manner irrespective of the rate of initial damage. After reaching the maximum load point, the unconfined concrete specimens show a sudden drop in stiffness and strength. In the second zone, a nonlinear transition occurs as the concrete expands, thus producing larger lateral expansions. The CFRP wrap reacts accordingly and a confining action is created on the concrete core. During this stage a loss of stiffness occurs due to the rapidly growing network of cracks in the concrete.



(a) CI-0%-series (b) CII-0%-series

Figure 3: Stress strain curves for strengthened specimens

In the third zone, the concrete is fully cracked and the CFRP confinement is activated to provide additional load carrying to overcome the effect of concrete degradation. 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. As the CFRP stress-strain behaviour is essentially linear elastic up to failure, this explains the linearity of this zone.

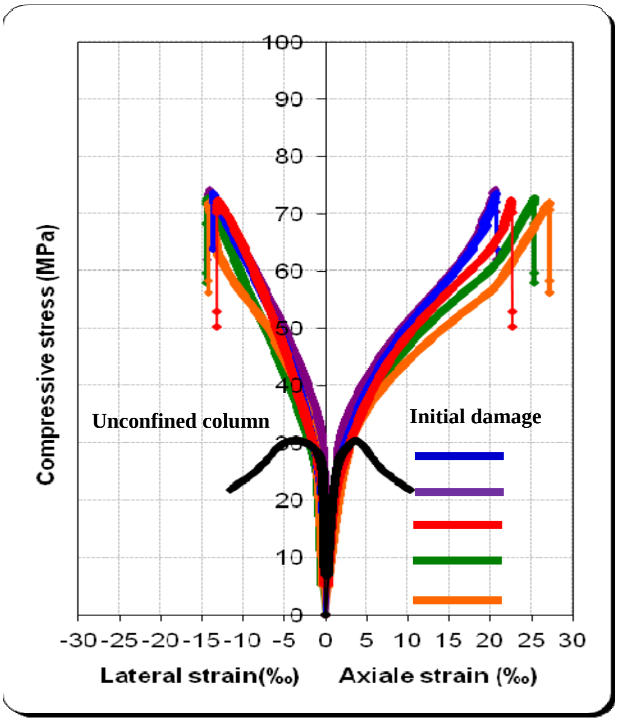


Figure 4: Stress strain curves for repaired specimens

3.2 *Effect of CFRP Strengthening Ratio*

In all cases the increase of the numbers of sheets generated an increase of compressive strength as well as axial deformation capacity. The level of increase is very important for NSC specimens. Considering the cases of 1 and 3 CFRP layers, from results displayed in Figure 3 and Table 2, it can be evaluated that the increase in the bearing capacity varies roughly from 60% to 140% with respect to the relative unconfined specimens, while the ultimate vertical deformations increase on average from 400% to 550%. From these findings, it is possible to assert that the increase in the number of CFRP sheets has a significant influence even though the increase in terms of strength is not as important as that of axial deformations which increase almost proportionally to the FRP strengthening ratio. The effect of the number of CFRP on layers HSC specimens is relatively moderate compared to previously. In this situation, the confinement pressure is activated at higher load (around 70% of the ultimate value). Consequently, the enhancement in the loading carrying capacity is reduced and varies roughly from 20% to 50%, whereas the ultimate axial deformations undergo a significant reduction displaying an increase on average from 40 to 215%, as illustrated in Figure 3 and table 3.

3.3 *Effect of Concrete Strength*

To investigate the effects of concrete quality, different concrete strength (25.93 MPa and 61.81 MPa) have been used to carry out this experimental program. Considering others experimental parameters, it can be seen from stress strain curves in Figure 3 (a- b) a varying strength decrease of 30÷40% from NSC specimens to HSC specimens. This effect is even more pronounced on the axial deformations, the relative varying decrease is 45÷70%. Hence, the influence on the strength and ductility capacities decreases with increasing concrete strength, as found by other authors.

3.4 *Effect of initial damage rate*

In all cases, the confinement provided by the CFRP wraps for damaged specimens generated an increase of compressive strength as well as axial deformation capacity. The level of increase is very important as displayed in Figure 4 and Table 3, it can be evaluated that the increase in the bearing capacity varies from 125% to 140% with respect to the relative unconfined specimens, while the ultimate vertical deformations increase on average from 515% to 680%. From these findings, it is possible to assert that the CFRP jackets in upgrading damaged circular concrete columns has an significant influence even though the increase in terms of strength is not as important as that of axial deformations.
By referring to results gathered in Table 3 and curves displayed in Figure 4, it can be seen that an increase in the initial damage rate of the tested specimens from 0% to 100% produced on overall a very moderate decrease in their carrying load capacity and axial deformation, except for rate damage ≥ 60 % in which case the ductility is slightly increased.

4 CONCLUSIONS

Loading capacity and strains of initially damaged circular RC columns, strengthened or repaired with external carbon fiber reinforced polymer (CFRP) sheets, were tested and evaluated. The main findings of this investigation can be summarized as follows:

- The use of CFRP jackets in strengthening circular RC columns or upgrading damaged ones is very efficient.
- The failure of all CFRP wrapped specimens occurred in a sudden and explosive way preceded by typical creeping sounds. The fiber rupture starts mainly in their central zone and then propagates towards both ends.
- All CFRP repaired specimens showed a typical bilinear trend with a transition zone. The confinement provided by the CFRP wraps seems to have restored for the damaged specimens their initial mechanical properties.
- 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 which almost proportional to the CFRP strengthening ratio.
- The CFRP confinement on low-strength concrete specimens produced higher results in terms of strength and strains than for high-strength concrete similar specimens. Therefore, the effect of CFRP confinement on the bearing and deformation capacities decreases with increasing concrete strength.
- The effect of increasing the initial damage rate of the tested specimens lead on overall to a moderate decrease in their carrying load capacity and ductility.

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