An efficient confinement strategy with CFRP sheets to increase the energy absorption capacity of RC concrete columns

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ABSTRACT: The present work evidences the performances of distinct partial and full confinement CFRP systems, in terms of increasing the load carrying capacity and energy absorption capacity of reinforced concrete column elements. The influence of the strip's width, the number of CFRP layers per strip and the stiffness of the CFRP sheet for these properties, is assessed. The experimental program is described and the main results are presented and analyzed.

Keywords: Concrete confinement, CFRP, energy absorption capacity

1 INTRODUCTION

Since the beginning of the nineties, wet lay-up carbon fiber reinforced polymer (CFRP) sheets have been used to increase the load carrying capacity and the energy absorption capacity of reinforced concrete columns (Mirmiran and Shahawy 1997, Xiao and Wu 2000). According to the applied technique, the exposed area of the concrete column is fully-wrapped by the CFRP.

However, preliminary tests with concrete elements submitted to direct compression loading revealed that partial-wrapping (strips of CFRP sheets) is a promising confinement technique, since significant increments on the load carrying capacity and energy absorption capacity were obtained using discrete confinement arrangements (Ferreira and Barros 2003, Barros and Ferreira 2005). Concrete columns deserving strengthening intervention have, always, a certain percentage of steel hoops. Therefore, applying strips of CFRP in-between the existent steel hoops can be an efficient confinement technique with technical and economic advantages, when full-wrapping is taken for basis of comparison.

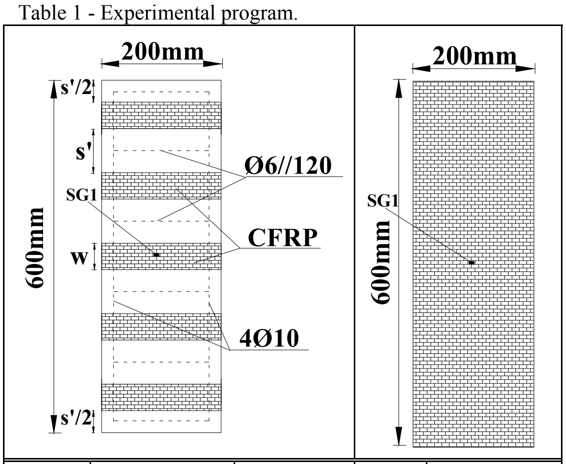
To assess the efficacy of the partial-wrapping technique, 54 reinforced concrete column elements were confined by distinct CFRP arrangements and tested under direct compression. The experimental program was designed to evaluate the influence of the stiffness of the wet lay-up CFRP sheet, the distance between strips, the width of the strip, the number of layers per each strip, the concrete strength class and the longitudinal and transversal steel reinforcement ratios, on the load carrying capacity and energy absorption capacity of the tested reinforced concrete column elements. From the time spent on applying the distinct CFRP arrangements and the amount of applied CFRP material for this experimental program, it was concluded that the partial-wrapping is the most profitable confinement system. The partial-wrapping technique has also the advantage of providing more ductile failure modes than those observed in fully-wrapped specimens, since a "gradient" of energy is dissipated by plastic deformation of the concrete between strips, in the specimens confined by the former technique.

2 CONFINEMENT ARRANGEMENTS AND EXPERIMENTAL PROGRAM

The experimental program deals with direct compression tests with reinforced concrete column elements of 600 mm length and 200 mm diameter. This program is composed by several groups of tests in order to evaluate the influence of the following parameters on the compressive strength and energy absorption capacity of elements submitted, predominantly, to compression loading: concrete strength class, stiffness of the confinement

CFRP system; width (W) and spacing (s') of the CFRP strips, number of CFRP layers per strip (L) and the percentage of the longitudinal, ρ_{sl} , and transversal, ρ_{st} , steel reinforcement ratio. Due to lack of space, only the groups of tests indicated in Table 1 were analyzed in the present paper.

Table 1 - Experimental program.



W [mm]	Designation	s' [mm]	W [mm]	Designation
45	W45S5L3	75	600	W600S1L3
	W45S5L5			
60	W60S5L3	60		W600S1L5
	W60S5L5			
Concrete strength class C12/15				
Longitudinal bars ϕ10				

Type of CFRP sheet		Group of test series	
	CF130 S&P 240 (300 gm/m^2)		C15S300ϕ10
	CF120 S&P 240 (200 gm/m^2)		C15S200ϕ10

One group was confined with a CFRP sheet of 300 g/m^2 of fibers, with the tradename of CF130 S&P 240. The specimens of the other group of tests were confined with a CFRP sheet of 200 g/m^2 of fibers, with the tradename of CF120 S&P 240. The specimens of the two groups were manufactured with a concrete of C12/15 strength class and were reinforced longitudinally with four steel bars of 10 mm diameter (ρ_{sl} =1%), and reinforced transversally with steel hoops of 6 mm diameter, spaced at 120 mm. Each group was constituted by three test series, being distinguished by the width of the of CFRP strip: 45 mm (W45), 60 mm (W60) and 600 mm (W600 – fully-wrapped). The partially-wrapped specimens were confined by five strips (W45S5 and W60S5), while one strip was applied in the fully-wrapped specimens (see Figure 1). These three test series have two sub-series, one of three layers per strip (L3) and the other with five layers per strip (L5). Previous research revealed that, above five layers per strip, the benefits in terms of specimen load carrying capacity and energy absorption capacity are marginal (Ferreira and Barros 2004).

W45S5 W60S5 W600S1

Figure 1. Confinement systems

3 MATERIALS

An average compressive strength of 15 MPa was obtained for the concrete used in the specimens of the test groups considered in the present paper. This value was obtained from direct compression tests carried out at 28 days with concrete cylinder specimens of 150 mm diameter and 300 mm height.

According to the supplier, the CF130 and CF120 sheets have a thickness of 0.167 mm and 0.117mm, respectively, an elasticity modulus and an ultimate strain in the fiber direction of about 240 GPa and 15‰, respectively, and a tensile strength higher than 3700 MPa, (degussa, 2003). To evaluate these properties, samples of CFRP were tested according to ISO recommendations (2003). The tensile specimen configuration is represented in Figure 2. To avoid localized fracture at the specimen's extremities fixed to the machine grips, layers of the same CFRP sheet were epoxy-glued to these extremities, as represented in Figure 2. The obtained results are included in Table 2. The strain was measured from a clip gauge of 50 mm of measuring length and 0.5% accuracy (see Figure 3). The tests were carried out under displacement control at a rate of 1 mm/minute.

The thickness values determined experimentally, included in Table 2, were used in the evaluation of the elasticity modulus and tensile strength of the CFRP sheets.

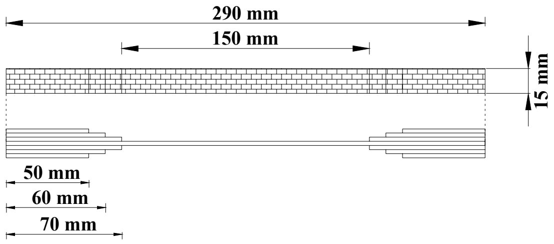


Figure 2 - CFRP tensile test specimen.

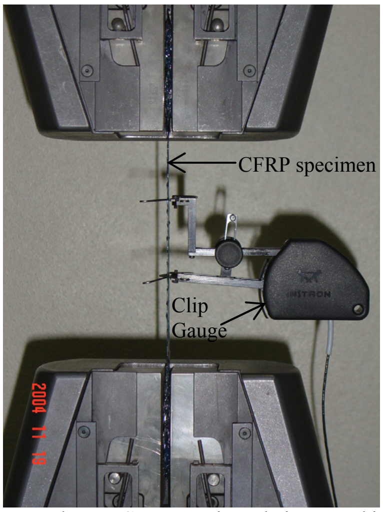


Figure 3 - Wet lay-up CFRP specimen being tested in direct tension.

Table 2 – CFRP properties (average of five tests).

CFRP Sheets	Thickness (mm)	Tensile strength (MPa)	Ultimate strain (%)	Elasticity modulus (GPa)
CF120	0.113	3539	1.53	232
CF130	0.176	3250	1.46	223

4 TEST SETUP

Three displacement transducers were positioned at 120 degrees around the specimen and registered the displacements between the steel load plates of the equipment (see figure 4). This test setup avoids that the deformation of the test equipment is added to the values recorded by the LVDTs. Taking the values registered in these displacement transducers, the displacement at the specimen axis was determined for each scan reading (Ferreira and Barros 2004), and the corresponding strain was obtained dividing this displacement by the measured specimen's initial height. To decrease the restriction imposed by the machine load plates to the radial expansion of the specimen's extremities, a system of two sheets of teflon with oil between them was applied in-between the bottom plate of the test machine and the bottom specimen's extremity. The Teflon system was not applied in-between the top plate and the top specimen's extremity, since this plate was connected to a spherical steel hinge. Strains in the CFRP fiber direction were measured by a strain gauges (SG1) placed at a mid-height of the specimen, see schemes into Table 1. A detailed description of the test equipment and test procedures can be found elsewhere (Ferreira and Barros 2004).

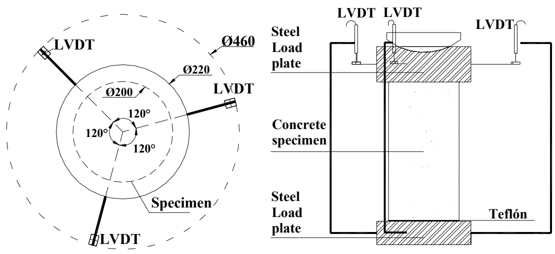


Figure 4 - Position of the LVDTs.

5 EXPERIMENTAL RESULTS

The relationship between compressive concrete stress, σ_c, and both the specimen axial strain, ε_c, and the CFRP compressive strain in the fiber direction, ε_f, for the series of the test groups C15S200ϕ10 and C15S300ϕ10 are depicted in Figures 5 and 6, respectively. Each curve is the average response recorded in the two specimens of each test series. The concrete stress is the ratio between the applied load and the specimen cross section area. In these figures, UPC represents the unconfined plain concrete specimens, URC,ϕ10 the unconfined reinforced (longitudinally and transversally) concrete specimens. In each graph, the CFRP confinement ratio is also included, where $\rho_f = A_f/A_{c,t}$, with $A_f = 2\times S\times W\times L\times t_f$ mm^2 being the cross section area of the confinement system (t_f is the thickness of the wet lay-up CFRP sheet), and $A_{c,t}$ is the specimen longitudinal cross section ($A_{c,t} = 200\times600$ mm^2).

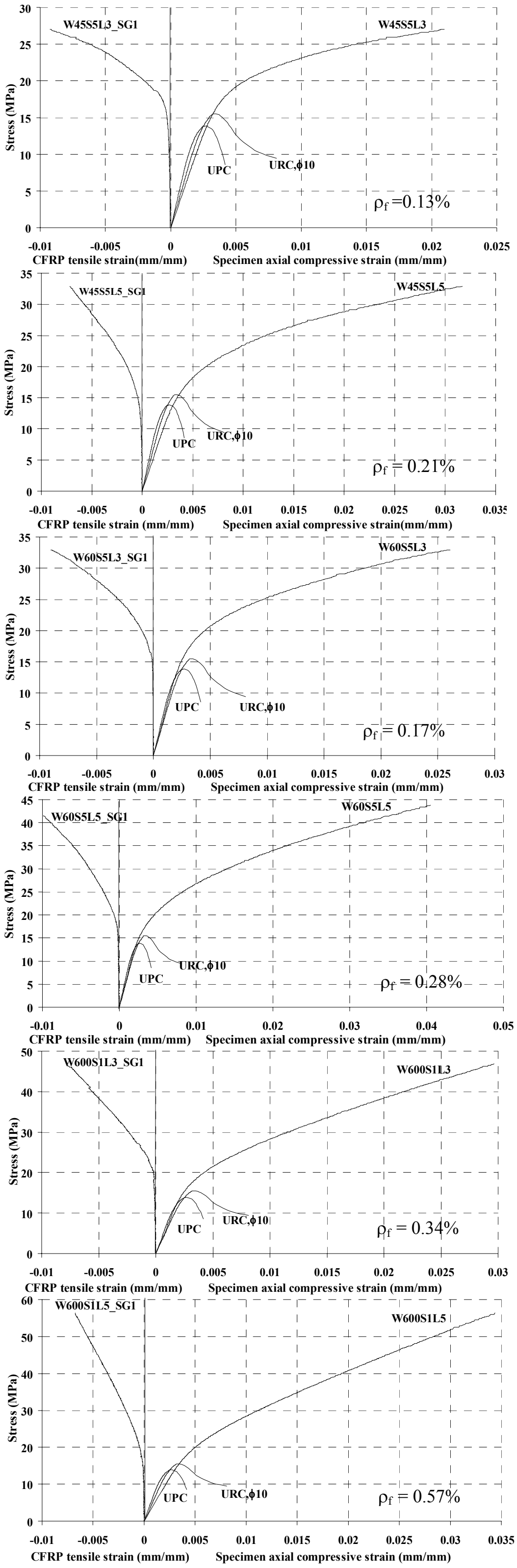


Figure 5 - Test group C15S200ϕ10.

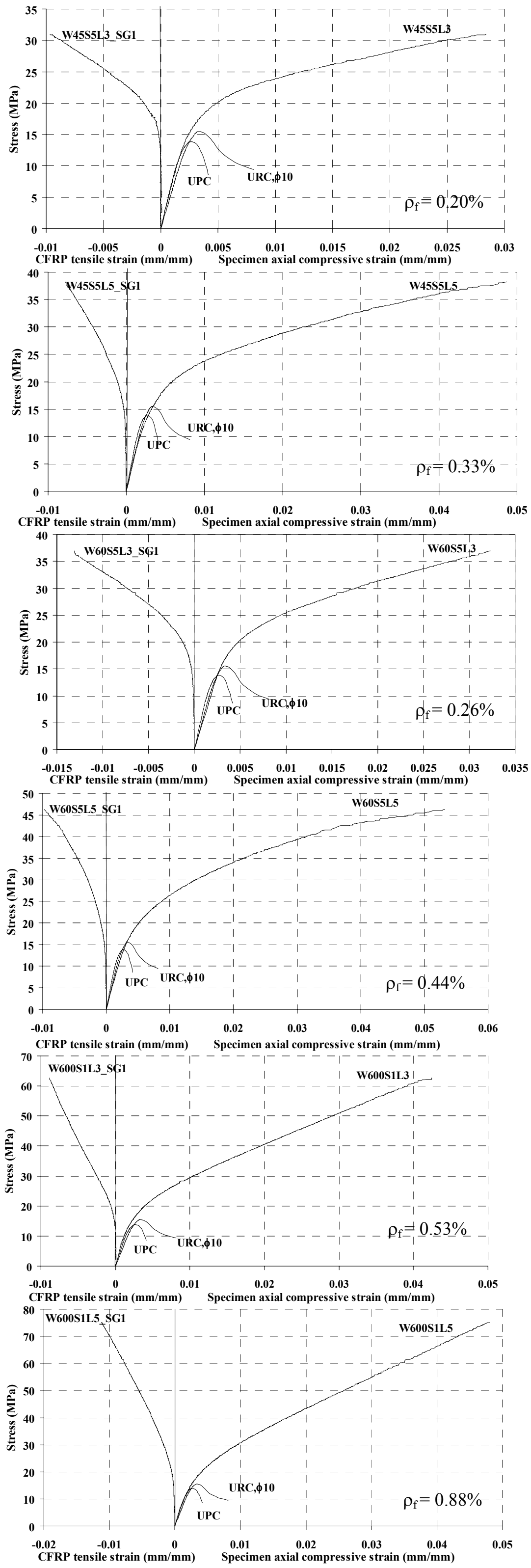


Figure 6 - Test group C15S300ϕ10.

Tables 3 and 4 include de main indicators of the efficacy provided by the applied confined systems. In these tables, $f_{co,UPC}$ is the compressive strength of unconfined plain concrete specimens (UPC), $f_{co,\phi10}$ is the compressive strength of unconfined reinforced concrete specimens, $\varepsilon_{co,UPC}$ is the specimen axial strain corresponding to $f_{co,UPC}$, $\varepsilon_{co,\phi10}$ is the specimen axial strain corresponding to $f_{co,\phi10}$, f_{cc} is the compressive strength (corresponding to the specimen's failure) of confined specimens, ε_{cc} is the specimen axial strain corresponding to f_{cc}, ε_{fmax} is the maximum tensile strain in the CFRP fiber's direction and ε_{fu} is the CFRP ultimate strain indicated in Table 2. Each value of Tables 3 and 4 is the average of the values obtained in the two specimens of each series.

From the analysis of Figures 5 and 6 and the results included in Tables 3 and 4 it can be concluded that $f_{cc}/f_{co,\phi10}$ increased with ρ_f. Figure 7 shows that this increase is almost linear in the considered ρ_f ranges.

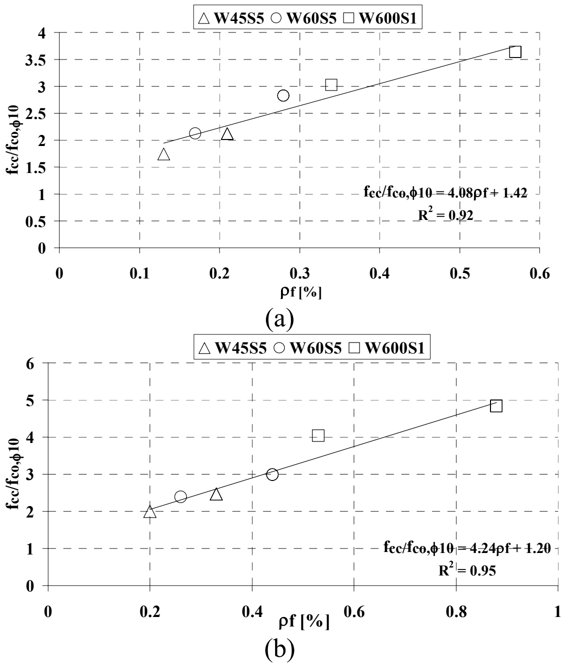


Figure 7 - $f_{cc}/f_{co,\phi10}$ vs. ρ_f for (a) C15S200ϕ10 (b) C15S300ϕ10 series.

In C15S200ϕ10, $f_{cc}/f_{co,\phi10}$ has varied from 1.7 in series confined with strip of 45 mm width and three layers per width (W45S5L3), ρ_f=0.13%, up to 3.6 in series fully-wrapped with five layers, ρ_f=0.57%. For C15S300ϕ10 these limit values have increased to 2.0 and 4.8, respectively, since the CFRP confinement ratio augmented due to the higher thickness of the CF130 sheet (from ρ_f=0.20% up to ρ_f=0.88%).

The specimen ultimate axial strain, ε_{cc}, has also increased significantly with ρ_f, having the limits of $\varepsilon_{cc}/\varepsilon_{co,\phi10}$ varied from 6.4 to 12.1 in C15S200ϕ10, and 8.5 to 16.1 in C15S300ϕ10. However, in both groups of tests, the increase of $\varepsilon_{cc}/\ \varepsilon_{co,\phi10}$ ratio with ρ_f was more pronounced in specimens of discrete confinement arrangements than in fully-wrapped specimens. The plastic deformation of the concrete in-between the CFRP strips can justify this occurrence. If the analysis are restricted to the discrete confinement arrangements, an increasing linear trend was observed between $\varepsilon_{cc}/\varepsilon_{co,\phi10}$ and ρ_f, as illustrated in Figure 9.

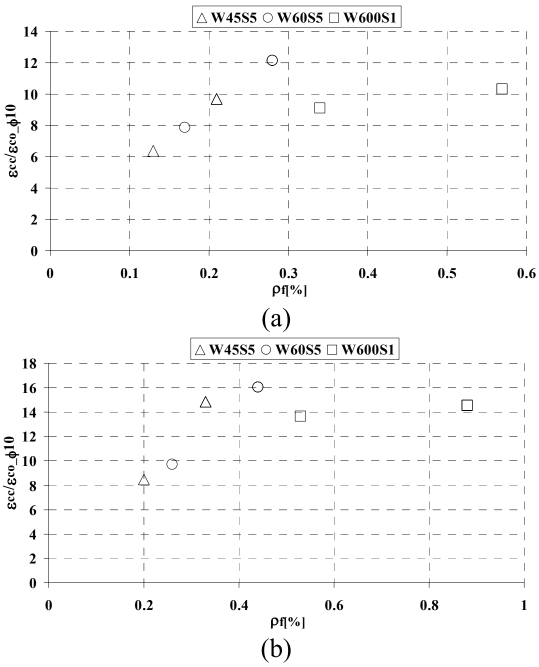


Figure 8 - $\varepsilon_{cc}/\varepsilon_{co,\phi10}$ vs. ρ_f for (a) C15S200ϕ10 (b) C15S300ϕ10 series.

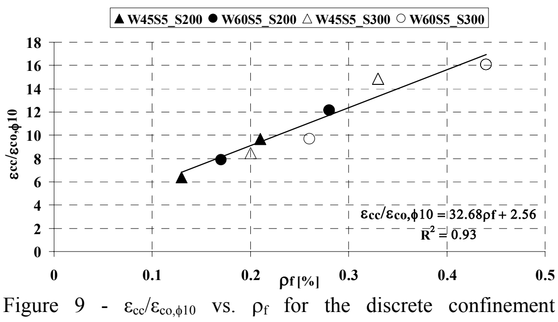


Figure 9 - $\varepsilon_{cc}/\varepsilon_{co,\phi10}$ vs. ρ_f for the discrete confinement arrangements of C15S200ϕ10 and C15S300ϕ10 series.

The increase of the energy absorption capacity provided by the considered confinement arrangements can be estimated using the concepts of U_{cc} and $U_{co,\phi10}$, schematically represented in Figure 10. $U_{co,\phi10}$ and U_{cc} are the energy dissipated in the softening phase of the unconfined and confined specimen, respectively.

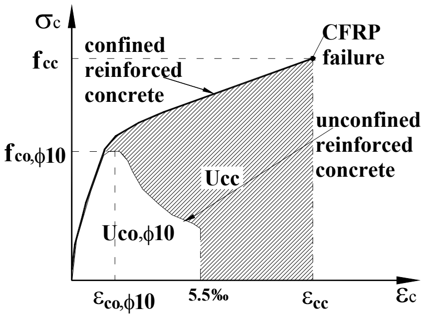
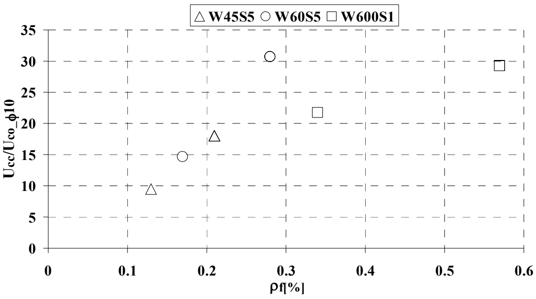
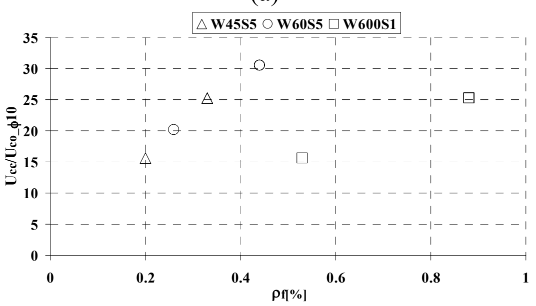


Figure 10 – Stress-strain diagram for the evaluation of Ucc.

Figure 11 represents the variation of the $U_{cc}/U_{co,\phi10}$ ratio with ρ_f, from which it can be concluded that $U_{cc}/U_{co,\phi10}$ increased significantly with ρ_f, from 9.5 for ρ_f=0.13% up to 30.7 for ρ_f=0.28%. The increase of $U_{cc}/U_{co,\phi10}$ with ρ_f for fully-wrapped specimens was not so high, as occurred in the discrete confinement arrangements, due to the reasons already pointed out for the variation of $\varepsilon_{cc}/\varepsilon_{co,\phi10}$ with ρ_f.



(a)



(b)

Figure 11 - $U_{cc}/U_{co,\phi10}$ vs. ρ_f for (a) C15S200ϕ10 (b) C15S300ϕ10 series.

If the analysis are restricted to the discrete confinement arrangements, an increasing linear trend was observed between $U_{cc}/U_{co,\phi10}$ and ρ_f, as illustrated in Figure 11.

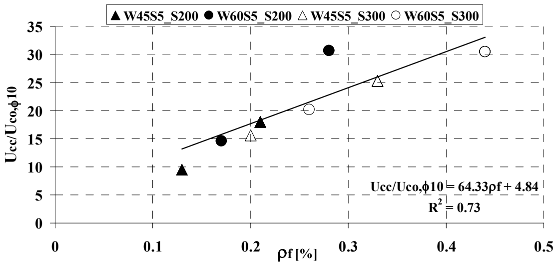


Figure 12 - $U_{cc}/U_{co,\phi10}$ vs. ρ_f for the discrete confinement arrangements of C15S200ϕ10 and C15S300ϕ10 series.

The last column of Tables 3 and 4 shows that, at the failure of the specimens, which always occurred by the CFRP tensile rupture, the maximum tensile strain in the direction of the fibers, ε_{fmax}, has varied from 44% up to 83% of the CFRP ultimate tensile strain, ε_{fu}. As already reported by other authors (Lam and Teng, 2003), the variation of the strain field in CFRP depends considerably on the distribution of the damage in the concrete specimen. Taking this into account and considering that only one strain gauge was applied, per specimen, for recording the CFRP strain variation, it is not surprising that a tendency was not determined for the $\varepsilon_{fmax}/\varepsilon_{fu}$ ratio.

6 CONCLUSIONS

To decrease the human-time and material resources applied on the confinement practice of reinforced concrete columns, but maintaining high levels of concrete confinement, the efficiency of distinct partial- and full-wrapping confinement arrangements was compared. Two types of wet lay-up carbon fiber reinforced polymer (CFRP) sheets, of distinct fiber content (200 and 300 g/m^2), were used as the confinement material. In the present paper, the influence of the width of the CFRP strips, number of CFRP layers per strip, and percentage ratio of the CFRP confinement arrangement, ρ_f, was analyzed in terms of the specimen load carrying capacity and energy absorption capacity. Series of column elements of 600 mm height and a cross section of 200 mm diameter, manufactured by a concrete of average compressive strength of 15 MPa, reinforced with four steel bars of 10 mm diameter and confined by steel hoops of 6 mm diameter spaced at 120 mm, were submitted to direct compression up to failure.

From the results the following main observations can be pointed out:

- In comparison to the full-wrapping confinement system, the partial confinement arrangements are easier and faster to apply, and consume few CFRP and epoxy resin materials;
- The compressive strength ratio, $f_{cc}/f_{co,\phi 10}$ increased from 1.7 for ρ_f=0.13% up to 4.8 for ρ_f=0.88%;
- A linear increasing trend was observed between $f_{cc}/f_{co,\phi 10}$ and ρ_f;
- For the partial-wrapping arrangements, the $\varepsilon_{cc}/\varepsilon_{co,\phi 10}$ ratio increased almost linearly with ρ_f. This ratio varied from 6.4 for ρ_f=0.13% up to 16.1 for ρ_f=0.44%;
- The increase of $\varepsilon_{cc}/\varepsilon_{co,\phi 10}$ with ρ_f was not so pronounced in the series with fully-wrapped specimens than in specimens of discrete confinement arrangements, since in these last ones a high concentration of concrete plastic strain occurred in the concrete between CFRP strips. In consequence, the increase of the energy absorption capacity ratio, $U_{cc}/U_{co,\phi 10}$, with ρ_f was more pronounced in series of partially-wrapped specimens. For these series, the relationship $U_{cc}/U_{co,\phi 10}$-ρ_f had a linear increasing trend;
- For the partial-wrapping arrangements, the $U_{cc}/U_{co,\phi 10}$ ratio varied from 9.5 for ρ_f=0.13% up to 30.7 for ρ_f=0.28%;
- At the failure of the specimens, the maximum tensile strain in the CFRP confinement material varied from 44% up to 83% of the CFRP ultimate tensile strain;
- In W45S5L5 partially-wrapped series and in W600S1L3 fully-wrapped series, of identical CFRP confinement ratio (0.33% and 0.34%, respectively), $f_{cc}/f_{co,\phi 10}$ was 2.5 and 3.0, respectively, $\varepsilon_{cc}/\varepsilon_{co,\phi 10}$ was 14.9 and 9.1, respectively, and $U_{cc}/U_{co,\phi 10}$ was 25.3 and 21.7. Therefore, the confinement benefits are similar but the costs of confinement technique for W45S5L5 are lesser than the costs of the one for W600S1L3.

7 ACKNOWLEDGMENTS

The authors of the present work wish to acknowledge the generous support provided by MBT Bettor Portugal and S&P Clever Reinforcement. The second author would like to thank the financial support by PRODEP action 5.3/N/199.014/01.

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Table 3. Main indicators of the efficacy of the confinement systems in the C15S200ϕ10 test group.

Specimen designation	S	L	ρ_f[%]	f_{cc} (MPa)	ε_{cc} (μm/m)	f_{cc}/f_{co}	$\varepsilon_{cc}/\varepsilon_{co}$	ε_{fmax} (μm/m)	$\varepsilon_{fmax}/\varepsilon_{fu}$
Uncon. Plain Conc. (UPC)				13.87 ($f_{co,UPC}$)	0.0027 ($\varepsilon_{co,UPC}$)	-	-	-	-
Uncon. ϕ10 Reinf. Conc.				15.52 ($f_{co,\phi 10}$)	0.0033 ($\varepsilon_{co,\phi 10}$)	-	-	-	-
W45S5L3	5	3	0.13	27.04	0.021	1.74 (ϕ10)	6.36 (ϕ10)	0.00924	0.596
W45S5L5		5	0.21	32.89	0.032	2.12 (ϕ10)	9.70 (ϕ10)	0.00717	0.463
W60S5L3	5	3	0.17	32.92	0.026	2.12 (ϕ10)	7.88 (ϕ10)	0.00901	0.581
W60S5L5		5	0.28	43.81	0.040	2.82 (ϕ10)	12.12 (ϕ10)	0.00989	0.638
W600S1L3	1	3	0.34	46.88	0.030	3.02 (ϕ10)	9.09 (ϕ10)	0.00783	0.505
W600S1L5		5	0.57	56.38	0.034	3.63 (ϕ10)	10.30 (ϕ10)	0.00675	0.435

Table 4. Main indicators of the efficacy of the confinement systems in the C15S300ϕ10 test group.

Specimen designation	S	L	ρ_f[%]	f_{cc} (MPa)	ε_{cc} (μm/m)	f_{cc}/f_{co}	$\varepsilon_{cc}/\varepsilon_{co}$	ε_{fmax} (μm/m)	$\varepsilon_{fmax}/\varepsilon_{fu}$
Uncon. Plain Conc. (UPC)				13.87 ($f_{co,UPC}$)	0.0027 ($\varepsilon_{co,UPC}$)	-	-	-	-
Uncon. ϕ10 Reinf. Conc.				15.52 ($f_{co,\phi 10}$)	0.0033 ($\varepsilon_{co,\phi 10}$)	-	-	-	-
W45S5L3	5	3	0.20	30.96	0.028	1.99 (ϕ10)	8.48 (ϕ10)	0.00965	0.623
W45S5L5		5	0.33	38.23	0.049	2.46 (ϕ10)	14.85 (ϕ10)	0.00784	0.506
W60S5L3	5	3	0.26	36.95	0.032	2.38 (ϕ10)	9.70 (ϕ10)	0.01310	0.845
W60S5L5		5	0.44	46.29	0.053	2.98 (ϕ10)	16.06 (ϕ10)	0.00967	0.624
W600S1L3	1	3	0.53	62.70	0.045	4.04 (ϕ10)	13.64 (ϕ10)	0.00887	0.572
W600S1L5		5	0.88	75.12	0.048	4.84 (ϕ10)	14.55 (ϕ10)	0.0112	0.72