Strategies for concrete confinement with strips of CFRP sheet

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ABSTRACT: To increase the strength and the energy absorption capacity of concrete elements submitted to compression loading, concrete cylinder specimens of 150 mm diameter and 300 mm height were confined with strips of wet lay-up carbon fiber sheet (CFRP). To assess the influence of the width and number of CFRP strips, and the number of CFRP layers per strip in the concrete compression strength and ductility, distinct confinement arrangements were applied. The main results obtained are presented and analyzed in the present work.

1 INTRODUCTION

Earthquakes in urban areas have repeatedly demonstrated the vulnerabilities of older reinforced concrete columns to seismic deformations demands, (Xiao *et al.* 1999). The full wrap of the concrete column with Carbon and Glass fiber reinforcement polymer (CFRP, GFRP) sheets is a general practice to increase the load bearing capacity, the ductility and the shear strength of this type of structural elements (CEB-FIB, 2001; Seible et al., 1997, Mirmiran e Shahawy, 1997; Untiveros, 2002). In spite of the success attained by the application of C(G)FRP confinement systems on laboratory specimens, on prototypes and on real applications, the knowledge of the confinement mechanisms involved are not yet quite assessed and the experimental results available for developing design guidelines are not sufficient. The present work aims to contribute for the knowledge in this area.

2 CONFINEMENT SYSTEMS

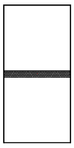
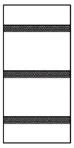
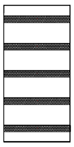
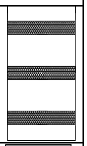
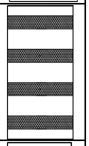
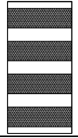
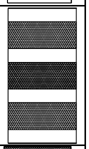
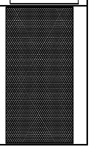
The confinement systems adopted are represented in Figure 1a and Table 1. Figure 1b to 1f includes photos of representative specimens of some of these confinement systems. They are composed by strips of CFRP sheet bonded to concrete and to subjacent layers by epoxy resin. The influence of the strip width, W, the number of strips along the specimen, S, and the number of CFRP layers per strip, L, on the specimen compression behavior was analyzed. The series indicated in Table 1 were tested, each one was composed by three specimens. Varying W, S and L led to series of different confinement ratio ($\rho_f = A_f/A_{c,t}$), where $A_f = 2\times S\times W\times L\times 0.167$ mm^2 is the cross section area of the confinement system (according to the manufacturer, the CFRP has 0.167 mm of thickness) and $A_{c,t} = 150\times 300$ mm^2 is the longitudinal section of the cylinder specimen (150 mm width by 300 mm height). Each specimen is designated by W*i*S*j*L*k*, where *i* is the strip width, *j* is the number of strips along the specimen and *k* is the number of CFRP layers per each strip. A detailed description of the confinement arrangements and procedures are given elsewhere (Ferreira and Barros 2003).

3 MATERIALS

From uniaxial compression tests carried out at 28 days with concrete cylinder specimens of 150 mm diameter and 300 mm height, an average compression strength of 23 MPa was obtained.

The wet lay-up carbon fibre sheet used has the trade name of Mbrace C1-30. According to the supplier, the Mbrace C1-30 is 0.167 mm thick, can attain a tensile strength higher than 3700 MPa, an elasticity modulus in the fibre direction of about 240 GPa and an ultimate strain of about 15‰.

Table 1 – Test series

W [mm]	S [-]	t [mm]	L [-]	A_f [mm^3]	ρ_f [%]	Specimen designation	Conf.system
15	1	-	1	5.01	0.011	W15S1L1	
			2	10.02	0.022	W15S1L2	
			3	15.03	0.033	W15S1L3	
			4	20.04	0.045	W15S1L4	
			6	30.06	0.069	W15S1L6	
	3	85	1	15.03	0.033	W15S3L1	
			2	30.06	0.069	W15S3L2	
			3	45.09	0.100	W15S3L3	
			4	60.12	0.134	W15S3L4	
			6	90.18	0.200	W15S3L6	
	5	45	1	25.05	0.058	W15S5L1	
			2	50.1	0.111	W15S5L2	
			3	75.15	0.167	W15S5L3	
			4	100.2	0.223	W15S5L4	
			6	150.3	0.334	W15S5L6	
30	3	70	3	90.18	0.200	W30S3L3	
			5	150.3	0.334	W30S3L5	
			7	210.4	0.468	W30S3L7	
	4	45	3	120.2	0.267	W30S4L3	
			5	200.4	0.445	W30S4L5	
			7	280.6	0.623	W30S4L7	
45	4	30	3	180.4	0.401	W45S4L3	
			5	300.6	0.668	W45S4L5	
			7	420.8	0.935	W45S4L7	
60	3	40	3	180.4	0.401	W60S3L3	
			5	300.6	0.668	W60S3L5	
			7	420.5	0.935	W60F3L7	
300	1	-	3	300.6	0.668	W300S1L3	
			5	501	1.11	W300S1L5	
			7	701.4	1.56	W300S1L7	

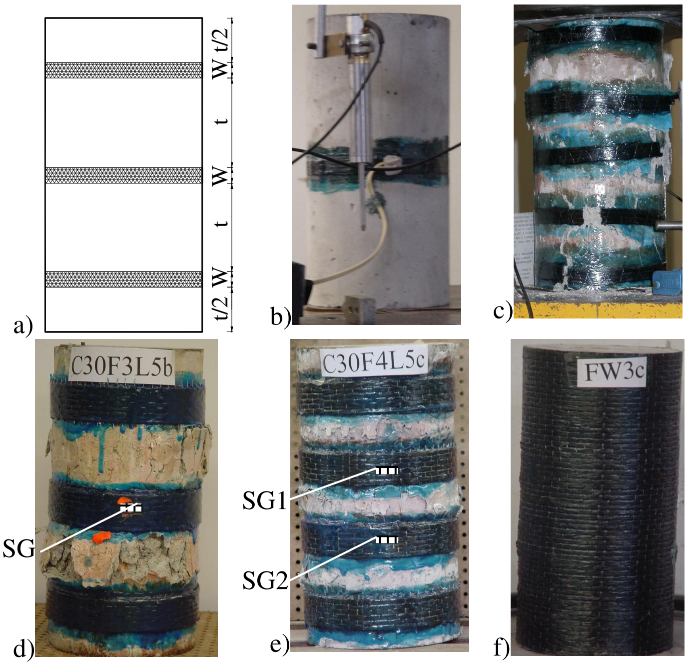


Figure 1 - Generic confinement system and photos of some adopted confinement systems.

4 EQUIPMENT AND MEASURING DEVICES

Three LVDTs were used to evaluate the specimen axial deformation. To decrease the confinement effect on the specimen, a teflon system was applied in-between the platens of the testing rig and the specimen extremities. Strains in the fiber direction of the CFRP strips were measured by strain gauges (SG) placed at half height of the strip, accordingly to the arrangement represented in Figure 1. A detailed description of the test equipment and test procedures can be found in (Ferreira and Barros 2003).

5 RESULTS

Figure 2 shows the relationship between concrete stress and specimen axial strain on specimens of series W15S1 and W15S5. The concrete stress-specimens' axial strain-CFRP strain relationship of the remainder series is depicted in Figure 3. Each curve represents the average response registered on the three specimens that compose each series. The concrete stress is the ratio between the applied load and the specimen cross section.

From the analysis of the graphics of figure 2a and 3a it is verified that the confinement system of series W15S1 was not effective, and the confinement system of series W15S3 provided an increase on the energy absorption capacity, but the maximum stress did not exceed the strength of the corresponding unconfined concrete (UC). In series W15S3 the maximum strain in the CFRP increased with the number of layers per each strip. From Figure 2b it is verified that, after the strain at peak stress of UC series (ε_{cp}), the specimens of series W15S5 with three or more CFRP layers per each strip had a hardening branch.

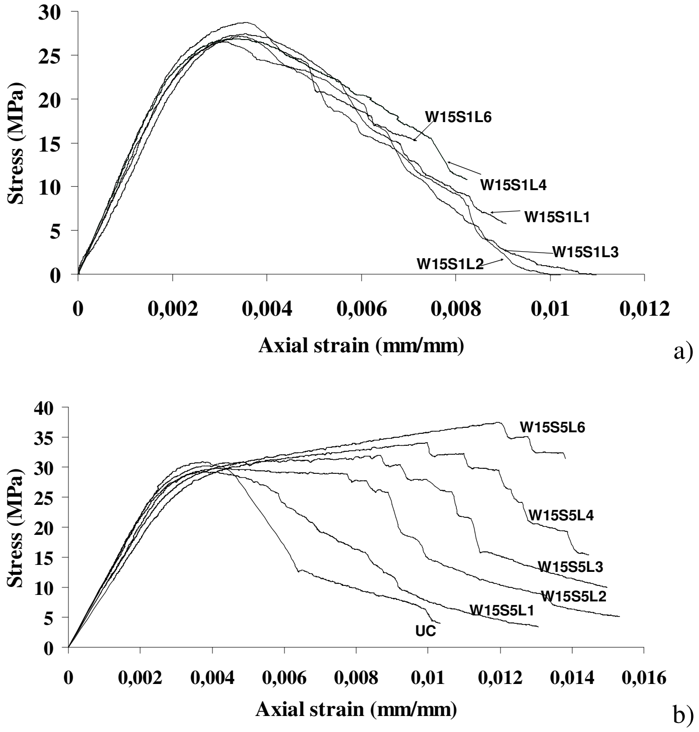


Figure 2 –Stress-axial strain relationship.

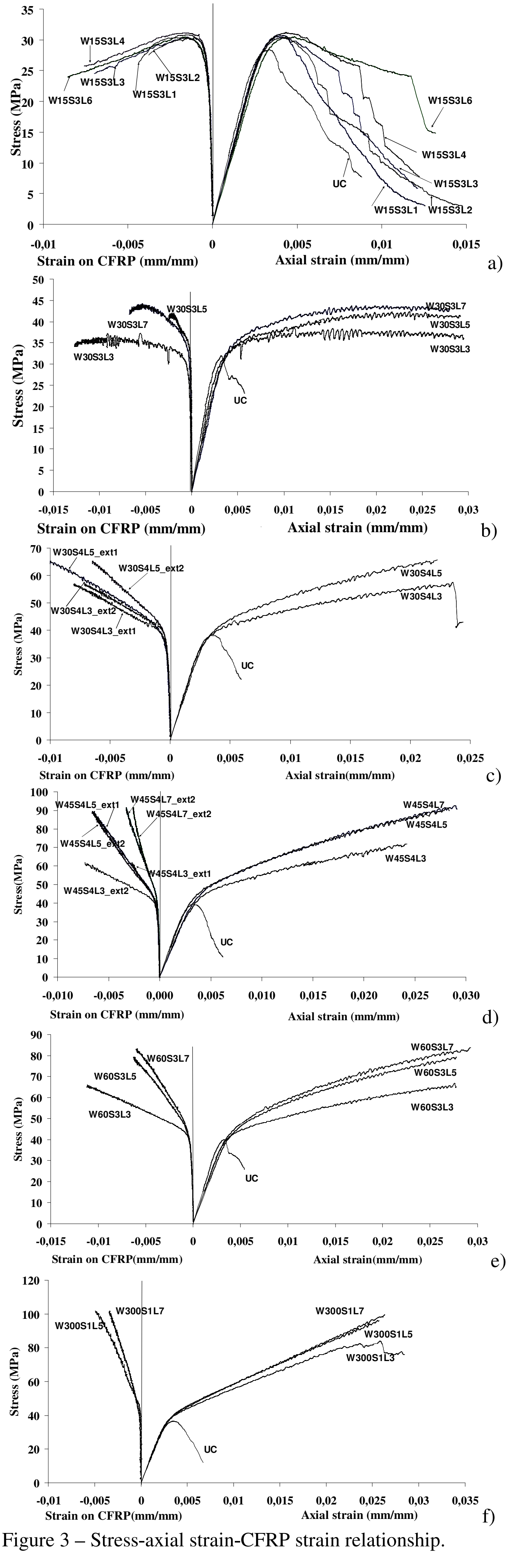


Figure 3 – Stress-axial strain-CFRP strain relationship.

In specimens confined with strips of width larger than 15 mm, not only the energy absorption capacity increased significantly, but also the load bearing capacity. After ε_{cp}, the load bearing capacity of specimens confined with three strips of 30 mm width (W30S3, Figure 3b) increased smoothly with the specimens' axial deformation up to its failure. In this series the increase on the load bearing capacity was more pronounced from three to five layers per strip, than from five to seven layers.

In specimens confined with four strips of 30 mm width (W30S4, Figure 3c) after ε_{cp} the stiffness of the deformational response increased significantly with the number of layers per each strip. The maximum strains in the two CFRP strips of the series confined with three layers per strip were similar, having attained a value of about 7.6‰, which corresponds to 50% of the CFRP ultimate strain (ε_{fu}). In specimens of five layers per strip, the maximum strain on the top strip (SG1, Figure 1e) was larger (≈10‰) than the strain on the bottom strip (SG2, 6.5‰). This was due to the larger concrete dilatancy occurred on the top part of these specimens.

In specimen with four strips of 45 mm width (W45S4, Figure 1d) it was observed a behavior similar to the one of series W30S4. However, series W45S4 provided a larger increase on the load bearing capacity and on the energy absorption capacity. For more than layers per strip, the benefits in terms of load and energy increment were marginal. The maximum strains decreased with the increase of the number of layers per each strip. In series with five and seven layers per strip, the maximum strains on top and on bottom strips were similar, while in series with three layers, the maximum strain in the top strip was again larger than the maximum strain in the bottom strip. In series W45S4 the maximum strain in the CFRP was about 48% of the ε_{fu}.

In spite of series W45S4 and W60S3 have equal ρ_f, they have provided different levels of confinement. Series W45S4 assured a larger increment on the load bearing capacity, revealing that, for this purpose, the number of strips is more influent than the width of the strip. However, the largest values of the maximum strains in the CFRP were registered in series W60S3.

In series of full wrapping (W300S1, Figure 1f) above five layers per each strip the increase on the load bearing capacity and on the energy absorption capacity was marginal. In these series it was also observed a decreasing of the maximum strain in CFRP with the number of layers.

Table 2 summarizes the results obtained, where σ_{max} is the maximum concrete compression stress (in series of UC specimens, σ_{max} represents the average value of the concrete compression strength, f_c), ε_{cfp} is the axial strain corresponding to σ_{max} (in series of UC specimens $\varepsilon_{cfp} = \varepsilon_{cp}$) and ε_{fmax} is the maximum strain in the CFRP. To graphically represent the efficacy of the confinement systems in terms of increasing the load bearing capacity and the energy absorption capacity, it was obtained the σ/f_c-ρ_f and $\Delta U/Uc$-ρ_f relationships, represented in Figure 4 and 6, respectively, for different levels of relative axial strain of confined specimens, $\varepsilon/\varepsilon_{cp}$, namely, $\varepsilon/\varepsilon_{cp}$=2, 3, 4, 6 e 8. ΔU is the exceeding energy provided by the confinement arrangement and Uc is the energy dissipated in the deformation of the unconfined specimens up to a strain of 5.5‰, see Figure 5.

From the analysis of the values included in Table 2 and from the curves represented in Figure 5, it was verified that: the load bearing capacity increases with ρ_f; confinement systems of $\rho_f < 0.167$ did not provide an increase on the load bearing capacity of the corresponding UC series; it was not effective to apply more than 5 layers per strip; in the confinement systems made by strips of 15mm width, the increase of the load bearing capacity was only significant in series of five strips of six layers per strip (increase of 21%); in series W30S3 the increase of the load bearing capacity was 19%, 28% e 33% for three, five and seven layers per strip, respectively; in series W30S4 the increase of the load bearing capacity was 48% and 70% for three and five layers, respectively; comparing the results obtained in series W30S3 and W30S4 it was verified that, for the purpose of increasing the load bearing capacity, it is more efficacy to decrease the distance between strips than increase the number of layers, as more volume of concrete is effectively confined. This conclusion can also be extracted analyzing the results obtained in series W45S4 and W60S3 that, despite having the same percentage of CFRP, the load bearing capacity was higher in series W45S4, whose distance between strips was 30 mm, while in series W60S3 was 40 mm; in series W300S1 the increase of the load bearing capacity was 127%, 162% e 172% on specimens with three, five and seven layers per strip, respectively; the compression strength of unconfined concrete can be duplicated using one of the following confinement systems: W45S4L4, W60S3L5, W300S2; the $\varepsilon_{cfp}/\varepsilon_{cp}$ was increased with the confinement percentage, ρ_f. Up to ρ_f=0.2, $\varepsilon_{cfp}/\varepsilon_{cp}$ was less than three. For $\rho_f > 0.2$, $\varepsilon_{cfp}/\varepsilon_{cp}$ increased significantly, having attained a maximum value of nine.

It should be emphasized that, as the load bearing capacity of the equipment was limited to 2000 kN, the failure load of some confined specimens was not attained, by the way, the values of the $\varepsilon_{cfp}/\varepsilon_{cp}$ ratio and the maximum load of these specimens would be larger than those registered. The maximum strain in the CFRP ranged from 16% to 82% of the CFRP ultimate strain, ε_{fu}. W30S4 was the series with more homogeneous values, with a variation from 46% to 65% of the ε_{fu}.

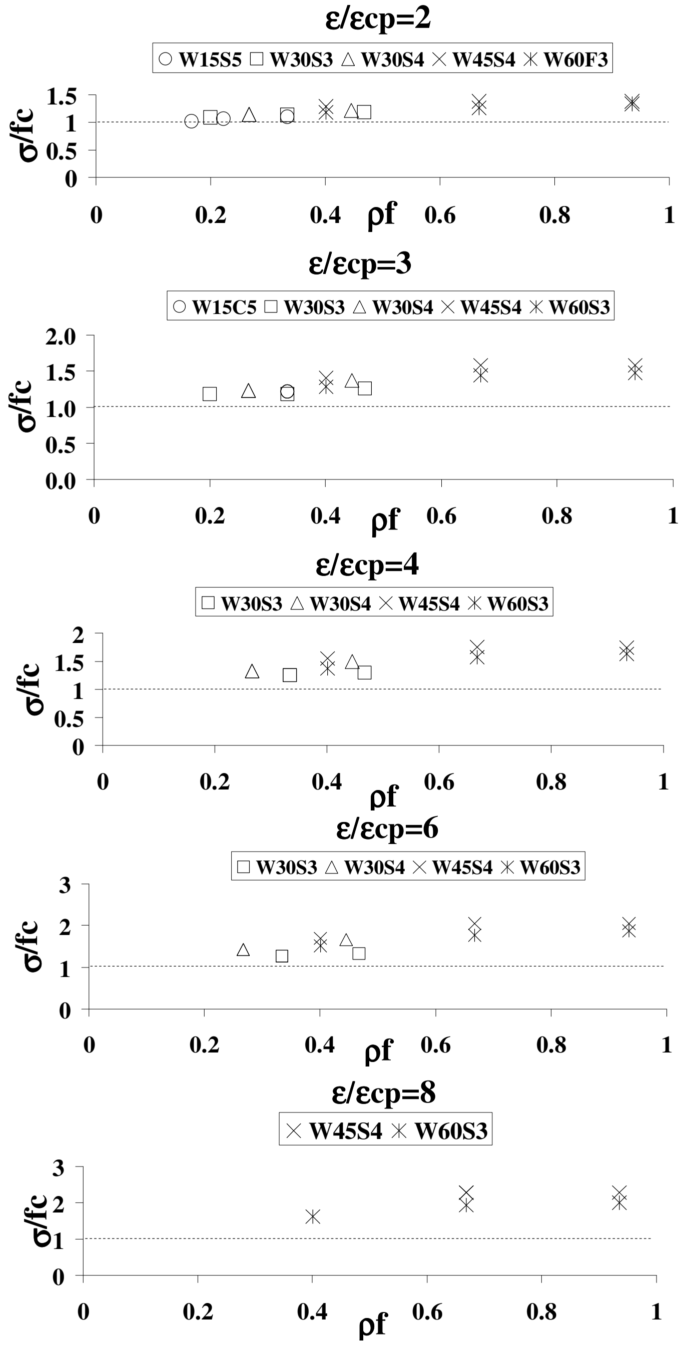


Figure 4 – σ/f_c versus confinement percentage (ρ_f)

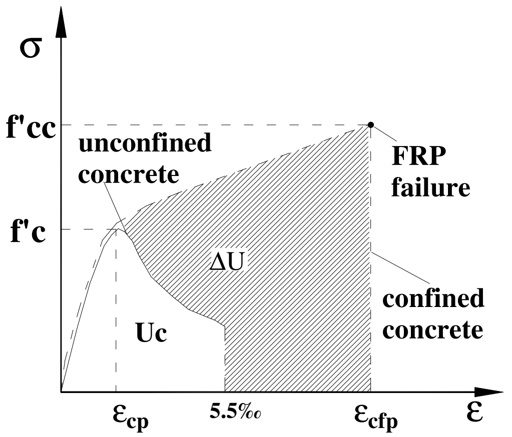


Figure 5 – Stress-strain model in compression for calculation of ultimate concrete strain

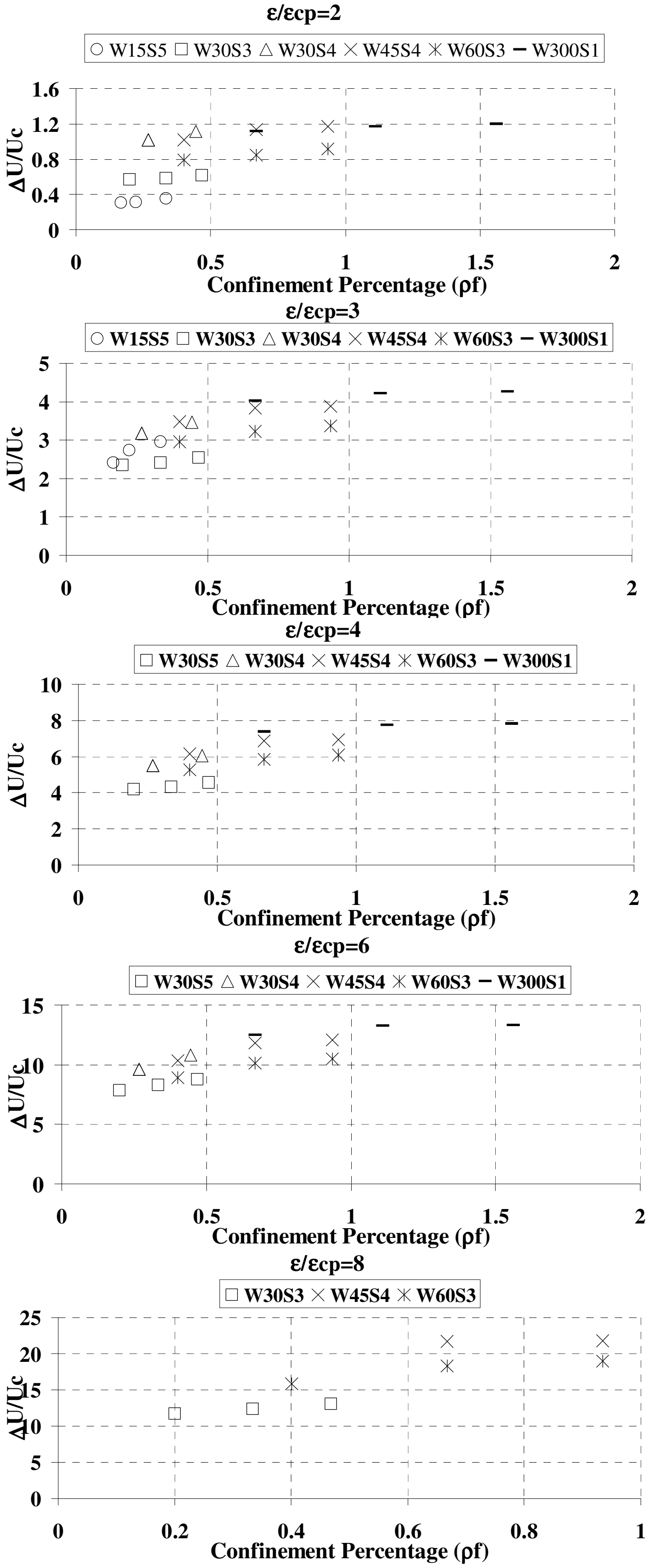


Figure 6 - Normalized increment of energy (ΔU/Uc) versus confinement percentage (ρ_f), at five $\varepsilon/\varepsilon_{cp}$ levels

From Figure 6 the following observations can be pointed out: the energy absorption capacity increased with ρ_f, but the increment ratio decreased with ρ_f; the increment of ΔU/Uc was more pronounced in series W60S3 and W45S4; for a strain level twice the strain corresponding to the strength of unconfined specimens ($\varepsilon/\varepsilon_{cp}=2$) ΔU/Uc is only a little bit higher than the unit value. For $\varepsilon/\varepsilon_{cp}=8$ a ΔU/Uc of about 22 was attained; in series W45S4 and W60S3, of equal ρ_f, series W45S4 was more efficacy in terms of energy absorption capacity; for equal ρ_f, the efficacy of series W45S4 was similar to the series W300S1 (full wrapping); for $\varepsilon/\varepsilon_{cp}=8$ the energy absorption capacity of specimens of series W45S4 was not increased with the increase of ρ_f (increase the number of layers per strip from five to seven); for a strain level near 10‰ ($\varepsilon/\varepsilon_{cp}=4$), which can be expected in some reinforced concrete elements of structures submitted to seismic loading, ΔU/Uc varied between the limits of about 4 and 6, which is important in terms of safety.

CONCLUSIONS

In the present work the compression behavior of concrete cylinder specimens confined by strips of wet lay-up carbon fiber sheet (CFRP) was analyzed, carrying out uniaxial compression tests under displacement control. The strips were differently arranged for leading confinement configurations that can reveal the relative importance of the number and width of the strips, and the number of layers per strip, on the increase of the load bearing capacity and on the energy absorption capacity. From the analysis of the results obtained it was observed that, the compression strength of unconfined concrete specimens was only exceeded on series with CFRP confinement percentage, ρ_f, larger that 0.17. In series with $\rho_f < 0.17$, only the energy absorption capacity was increased. Increasing the number of CFRP layers, the load bearing capacity and the energy absorption capacity were increased in all series. However, above five layers per strip, the increase was not so significant than the increase registered up to five layers. The influence of the strip width and the number of strips on the confinement level attained is related to the free space of concrete between CFRP strips. In series of equal ρ_f, larger increase of the load bearing capacity and ductility was observed in series with lower distance between CFRP strips. This is due to the fact that the concrete damage was concentrated in these gaps. In general, the maximum strain in the CFRP decreased with the increase of the number of layers per strip. The load bearing capacity of unconfined concrete specimens of compression strength ranged from 30 to 40 MPa can be doubled using one of the following confinement systems: four strips of 45 mm width and four layers per strip; three strips of 60 mm width and five layers per strip; full wrapping with two layers.

Table 3 - Main indicators of the efficacy of the confinement systems

Specimen designation	**S**	**L**	ρ_f [%]	σ_{max} (MPa)	σ_{max}/f_c	ε_{cfp} (μm/m)	$\varepsilon_{cfp}/\varepsilon_{cp}$	ε_{fmax} (μm/m)	$\varepsilon_{fmax}/\varepsilon_{fu}$
Unconfined concrete	-	-		-	-	-	-	-	-
W15S1	1	1	1.11E-02	27.46	-	3511	-	-	-
		2	2.23E-02	27.12	-	3488	-	-	-
		3	3.34E-02	26.48	-	3098	-	-	-
		4	4.45E-02	26.86	-	3347	-	-	-
		6	6.68E-02	28.68	-	3598	-	-	-
Unconfined concrete	-	0		28.5 (f_c)	1.0	3298 (ε_{cp})	1.0	-	
W15S3	3	1	3.34E-02	30.6	1.07	3975	1.20	4375.4	0.284
		2	6.68E-02	30.3	1.06	4228	1.28	3775.9	0.245
		3	1.00E-01	30.4	1.07	4038	1.22	6990.3	0.454
		4	1.34E-01	31.2	1.09	4358	1.32	7588.9	0.493
		6	2.00E-01	30.5	1.07	4982	1.51	8560.2	0.556
Unconfined concrete	-	0		30.8 (f_c)	1.0	3922 (ε_{cp})	1.0	-	
W15S5	5	1	5.57E-02	29.2	0.95	4040	1.03	-	
		2	1.11E-01	29.8	0.97	4119	1.05	-	
		3	1.67E-01	32.0	1.04	8685	2.21	-	
		4	2.23E-01	34.0	1.10	9990	2.55	-	
		6	3.34E-01	37.4	1.21	12062	3.08	-	
Unconfined concrete	-	0		32.7 (f_c)	1.0	3807 (ε_{cp})	1.0	-	
W30S3	3	3	2.00E-01	38.85	1.19	11220	2.94	12706.2	0.825
		5	3.34E-01	42.04	1.28	23644	6.21	2485.3	0.161
		7	4.68E-01	43.46	1.33	24108	6.33	6748.1	0.438
Unconfined concrete	-	0		38.8 (f_c)	1.0	3411 (ε_{cp})	1.0	-	-
W30S4	4	3	2.67E-01	57.48	1.48	23540	6.9	Ext1- 7959.1	0.517
								Ext2- 7159.1	0.465
		5	4.45E-01	65.76	1.70	22235	6.5	Ext1- 10036	0.652
								Ext2- 6493.5	0.422
Unconfined concrete	-	0		39.2 (f_c)	1.0	3339 (ε_{cp})	1.0	-	
W45S4	4	3	4.01E-01	71.99	1.84	24182	7.24	Ext1- 2686.6	0.175
								Ext2- 7321.9	0.475
		5	6.68E-01	91.05	2.33	28239	8.45	Ext1- 6491.0	0.422
								Ext2- 6632.6	0.431
		7	9.35E-01	91.85	2.35	29030	8.69	Ext1- 2573.5	0.167
								Ext2- 3269.1	0.212
Unconfined concrete	-	0		40.0 (f_c)	1.0	3323 (ε_{cp})	1.0	-	
W60S3	3	3	4.01E-01	65.87	1.65	27640	8.32	11203.0	0.727
		5	6.68E-01	79.28	1.98	27778	8.36	6300.9	0.409
		7	9.35E-01	83.72	2.09	29243	8.80	6016.5	0.394
Unconfined concrete	-	0		36.7 (f_c)	1.0	3518 (ε_{cp})	1.0	-	
W300S1	-	3	6.68E-01	83.33	2.27	25960	7.38	-	-
		5	1.11E00	95.98	2.62	25720	7.31	4948	0.321
		7	1.56E00	99.58	2.72	26320	7.48	3428	0.222

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