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HYBRID CFRP-BASED STRENGTHENING TECHNIQUE TO INCREASE THE FLEXURAL RESISTANCE AND CONCRETE CONFINEMENT OF RC COLUMNS SUBMITTED TO AXIAL AND CYCLIC LATERAL LOADING

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Summary: *A strengthening technique that combines carbon fibre reinforced polymer (CFRP) laminates and strips of wet lay-up CFRP sheet was used to increase the flexural resistance and the energy dissipation capacity of square cross-section columns of very low concrete strength submitted to constant axial compressive force and cyclic lateral loading. The laminates, applied according to the Near Surface Mounted (NSM) technique, have the purpose of increasing the flexural resistance of the columns, while the CFRP sheet installed as a localized jacket in the plastic hinge has the aim of increasing the concrete confinement and avoid the buckling and the debonding of the laminates. In spite of the 8 MPa of average concrete compressive strength used to manufacture the columns, the hybrid strategy provided an average increase of about 46 % in terms of load carrying capacity, even when applied in columns that had already been tested and presented intensives damages. The experimental program is described and the main results are presented and analyzed.*

Keywords: Near surface mounted technique; CFRP laminates and sheets, concrete confinement; flexural resistance; cyclic loading

1 INTRODUCTION

Previous research revealed that carbon fibre reinforced polymer (CFRP) pre-cured laminates, applied according to the Near Surface Mounted (NSM) technique, are very effective to increase the flexural resistance of reinforced concrete (RC) columns [1]. However, this strategy is not able to provide a significant increase in the energy dissipation capacity of this type of structural elements [2], which is a serious deficiency if the purpose is the upgrading of RC columns of buildings located in zones of high seismic risk. This drawback can be overcome using FRP systems wrapping the RC column [3]. Since existing RC columns have always a certain percentage of steel hoops, even if this percentage does not accomplish the actual code standards, applying strips in between existing steel hoops has proved to be an efficient technique to increase the concrete confinement [3]. Combining CFRP pre-cured laminates for the flexural resistance, applied in the faces of the columns submitted to tensile stresses, with strips of wet lay-up CFRP sheets located in between existing steel hoops (Figure 1), a high effective technique can be obtained, which is herein designated as hybrid CFRP-based strengthening technique. Apart the confinement they provide to the concrete, the strips of CFRP sheets contribute to avoid the buckling of the laminates and to increase the shear resistance of the RC columns.

Within the ambit of a research program, five groups of columns strengthened according to the hybrid technique were tested to assess the influence of the percentage of existing longitudinal steel reinforcement, the concrete strength class and the number of layers per each strip of CFRP sheet, on the effectiveness of this technique when applied to columns subjected to axial and cyclic lateral loading. Due to space limitation, only the influence of the longitudinal reinforcement was considered in the present paper, but the discussion of the full experimental program was presented elsewhere [4].

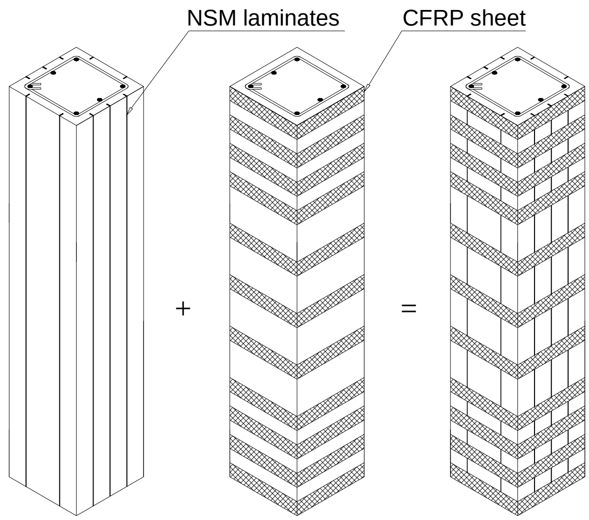


Fig. 1 – Strengthening strategy to increase the flexural and shear resistance of RC columns, and their confinement.

2 TEST SERIES

Figures 2a and 2c show the typical specimen of the experimental program. It is composed of a RC column monolithically connected to a RC footing. The column was cast in a second phase, 3 days after the corresponding footing has been cast, in order to reproduce the real practice as much as possible. With the same purpose, starter longitudinal steel bars were used to connect the reinforcement system of the column to the corresponding foot (see Figure 2a). The lap splice of the starter bars had a length of 260 mm.

The research program had the purpose of evaluating the influence of concrete compressive strength, reinforcement ratio of longitudinal steel bars (ρ_{sl}) and number and width of strips of CFRP sheet, on the load carrying and energy dissipation capacities of RC columns strengthened according to the hybrid technique. The full experimental program is described in Table 1. Due to space limitation, only the tests of G1 group are treated in the present paper, but a detailed analysis of the full experimental program can be found elsewhere [4]. The arrangement of the CFRP strips of wet lay-up sheets in the G1 group of tests is represented in Figure 2b. The denomination used to identify the columns has the format F***a***_S***b***_W***c***L***d_t***, where "***a***" represents the diameter of the longitudinal steel bars, in mm (10, 12 and 16), "***b***" is the number of CFRP laminates applied in each face of the column subjected to cyclic tension/compression, in order to increase the column flexural resistance (2, 3 and 4), "***c***" is the width of the strips, in mm, of wet lay-up CFRP sheets applied to increase the concrete confinement (100 and 150), "***d***" represents the number of layers in each strip (2 and 3) and "***t***" is the type of series (NON, PRE and POS). The NON term means a reference column, PRE is a column that was strengthened before have been tested and POS means a column that, after have been tested and strengthened, it was tested again.

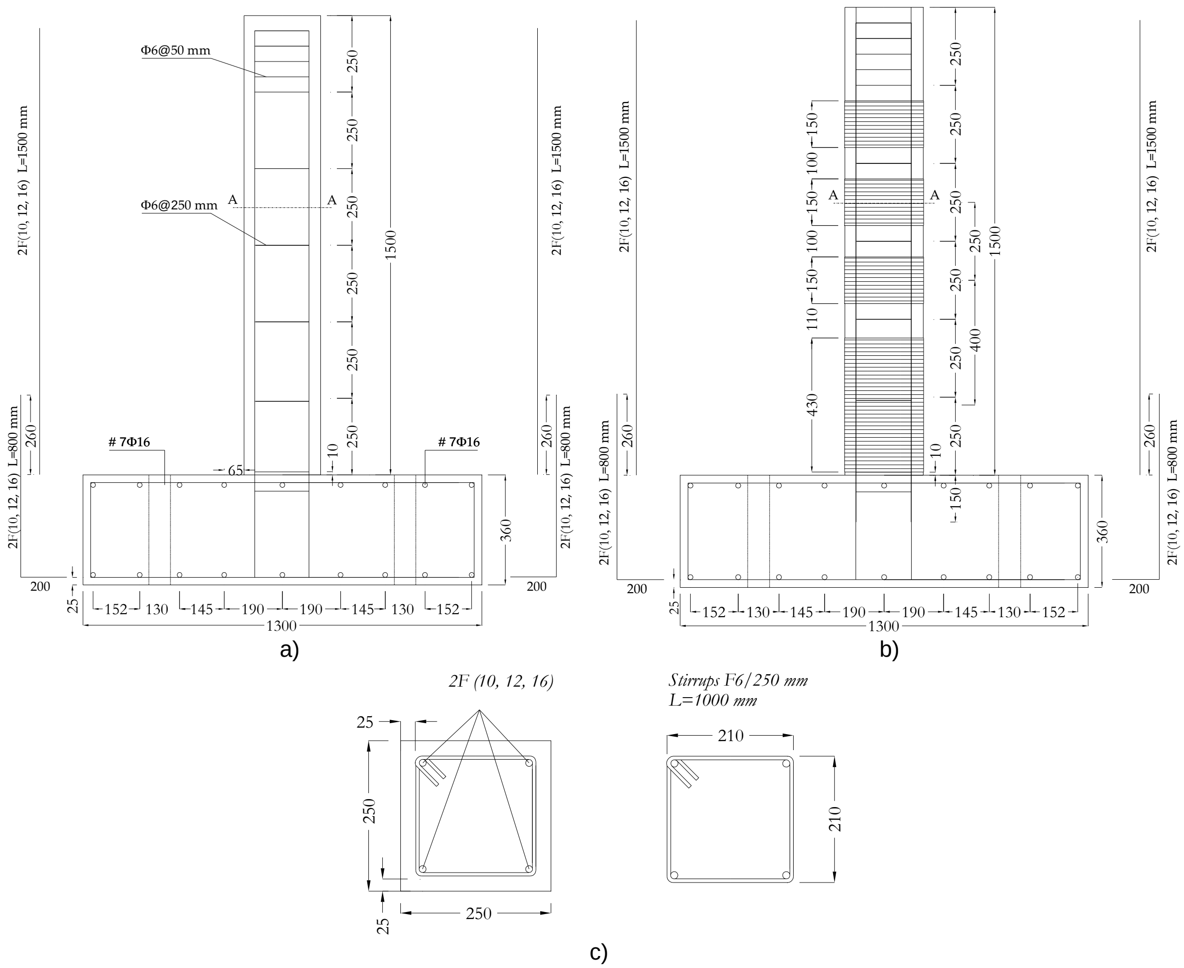


Figure 2 – Geometry of the specimens and column cross section.

Table 1 – Groups of tests.

Group n.	Symbol	Specimen reference
1	G1	F10_NON F12_NON F16_NON F10_S2_W150l2_POS F12_S3_W150l2_POS F16_S4_W150l2_POS
2	G2	F10_S2_W150L2_PRE F12_S3_W150L2_PRE F16_S4_W150L2_PRE
3	G3	F12_S3_W150L3_PRE
4	G4	F12_S3_W100L3_PRE
5	G5	F12_S3_W150L2_PRE_C25/30

3 STRENGTHENING TECHNIQUE

The strengthening technique is composed by CFRP laminates of 9.37x1.4 mm^2 of cross section (CFK 150/2000 of S&P), fixed by epoxy adhesive (S&P Resin 220) into pre-cut slits opened on the concrete cover of faces of the column that will be subjected to cyclic compression/tension stresses (faces A and C in Figure 11), and strips of CFRP wet lay-up sheet, the first one applied at the bottom of the column, with a width (430 mm) similar to the pre-evaluated [4] length of the plastic hinge, and the remaining strips, of a width of 100 mm, applied in between the existing steel hoops. Figure 3 shows the positions of the laminates for the columns reinforced with distinct percentage of longitudinal steel bars. The number of CFRP laminates was evaluated in order to provide an increase of 50% to the load carrying capacity of its corresponding reference column, when the strengthening intervention is applied on untested specimen (PRE columns) [4]. To anchor the laminates to the column's foundation, holes were executed with a depth that ranged between 120 mm and 150mm mm, and with an almost rectangular cross section of approximately 20x30 mm^2 (Figure 4). These holes were filled with the same epoxy adhesive used to bond the laminates to the concrete column.

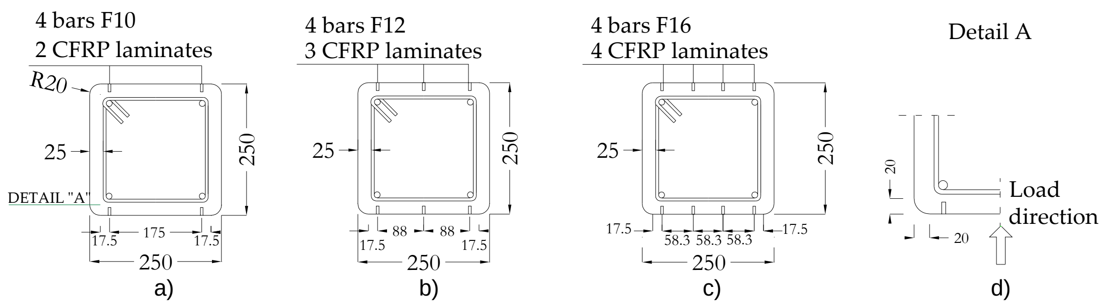


Figure 3 – Reinforced sections of the column specimens (dimensions in mm).

To install the laminates the following procedures were adopted: using a diamond cutter, slits of 4 to 5 mm width and 12 to 15 mm depth were opened on two concrete surfaces of the column; the slits were cleaned by compressed air; the laminates were cleaned by acetone; the epoxy adhesive was produced according to supplier recommendations; the slits were filled with the epoxy adhesive; the epoxy adhesive was applied on the faces of the laminates; the laminates were introduced into the slits and the epoxy adhesive in excess was removed. Before bonding the strips of CFRP sheet used to increase the concrete confinement, the corners of the columns were rounded according to the scheme represented in Fig. 3d. To bond the first strip layer to concrete and to bond consecutive layers, the epoxy adhesive S&P Resin 50 was used. The strips were applied one day after the laminates have been installed. The arrangement of the CFRP strips is represented in Figure 2b. The curing/hardening process of the epoxy adhesive lasted for, at least, seven days prior testing the strengthened columns. In the POS columns the hybrid strengthening technique was applied after have repaired the most damaged zones, localized at the concrete cover of the plastic hinge. The concrete of these zones were replaced by an epoxy mortar. Figure 5 shows the typical appearance of the POS columns before have been submitted to the restoration process, and also illustrates this process.

Figure 4 – Opening of the pre-cut slits in a column and holes in the corresponding foundation

1. The too damaged concrete cover was removed
2. The damaged concrete cover was replaced by epoxy mortar
3. application of the epoxy resin to bond CFRP strips

Figure 5 – Treatment of damaged zones of a POS column

4 MATERIAL PROPERTIES

4.1 Concrete

To assess the performance of the developed hybrid strengthening technique for columns of extremely low concrete strength class, that can be found in buildings of South Europe, a part one column, the remaining columns of the experimental program were built with a concrete of an average compressive strength of 8.1 MPa at 28 days, evaluated in cylinders of 150 mm diameter and 300 mm height. The concrete mix composition is presented elsewhere [4]. Since the columns were tested at the age that ranged from 41 days to 80 days, the concrete average compressive strength at these ages varied from 8.4 to 8.8 MPa.

4.2 Steel bars

To characterize the steel bars, uniaxial tensile tests were conducted according to the standard procedures found in NP-EN 10 002-1 [5]. The obtained results are presented in Table 2.

Table 2 – Values of the tensile properties of the tested steel bars.

Diameter	E_s (GPa)	f_y (MPa)	f_{su} (MPa)	ε_{sy} (mm/m)	ε_{su} (mm/m)
6	169.0	537.0	597.7	3.4	20.0
10	204.5	445.0	564.0	2.2	168.0
12	201.0	455.0	563.0	2.4	133.0
16	210.0	450.0	580.5	2.2	268.0

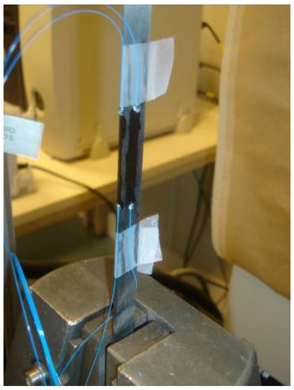
4.3 CFRP composites

With the purpose of assessing the possibility of measuring accurate strains from optical fibre (OF) sensors installed on the shortest edge of the CFRP laminate cross section (width of 1.4 mm), uniaxial tensile tests were carried out according to the ISO 527-5 recommendations [6], with OF installed on the shortest and the largest edge of the laminate, for comparison purposes (see Figure 6a). The obtained results showed that both sensors measured similar results, see Figure 6b. Placing optical fibre (OF) sensors on the shortest edge of the laminate cross section is a very favourable monitoring arrangement, since the sensors do not interfere with the NSM-concrete bond conditions, and smaller probability of rupture of the sensor occur when installed into the slit. From the five tests carried out, the following results were obtained: elasticity modulus, E_f, of 164.11 GPa with a coefficient of variation

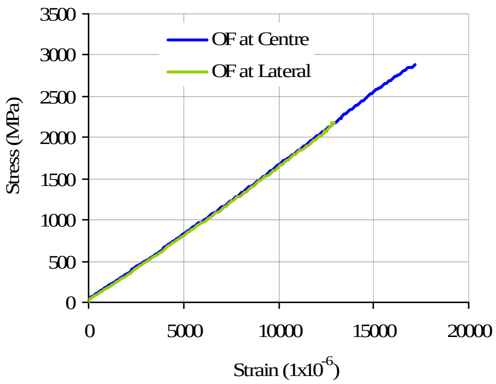
(Cov) of 2.7%; tensile strength, f_{fu}, of 2704.2 MPa with Cov=4.2%; ultimate tensile strain, ε_{fu}, of 16.464 mm/m with a Cov=2.1%.

According to the supplier, the CFRP wet lay-up sheet, with the trade name S&P C-Sheet 240 of fibre weight of 300 g/m^2 in the fibres direction and a weight per unit area of sheet of 330 g/m^2, has a thickness, t_f, of 0.176 mm, an elasticity modulus and an ultimate strain in the fiber direction of 240 GPa and 1.55% %, respectively, and a tensile strength higher than 3800 MPa.

The epoxy mortar used to replace the damaged concrete cover in zones of the nonlinear hinge was made of one part of epoxy resin (type S&P Resin 50) and three parts of previously washed and dried fine sand (parts measured in weight). From nine compression tests with cube specimens of 50 mm edge, an average compressive strength of 45.69 MPa, with a Cov of 2.79% and a standard deviation of 1.28 MPa were obtained.



a)



b)

Figure 6 – Optical fibre (OF) sensors to measure the strains in the laminates: a) tensile test set up and positions of the OF; b) obtained stress-strain relationships.

5 TEST SET UP AND MONITORING SYSTEM

The test set-up is illustrated in Figure 7. A constant vertical load of approximately 120 kN was applied to the column, inducing an axial compressive stress of about 1.92 N/mm^2. Linear variable displacement transducers (LVDTs) were used to record the horizontal displacements of the column, as well as any horizontal movement of the footing, see Figure 8. The positions of the strain-gauges (SG) glued on steel bars are represented in Figure 9, while the positions of the SG installed on CFRP laminates and wet lay-up sheets are indicated in Figure 10. The tests were carried out with a closed loop servo-controlled equipment. A history of displacements was imposed for the internal LVDT of the actuator (LVDT/ACTUATOR in Fig. 8)) that applies the lateral force. The history of horizontal displacements for the G1 group of tests included eight load cycles between ±2.5 mm and ±20.0 mm, in increments of ±2.5 mm, with a displacement rate of 50 μm/s for the first set of cycles, 75 μm/s for the second set of cycles, and 100 μm/s for the remaining set of cycles.

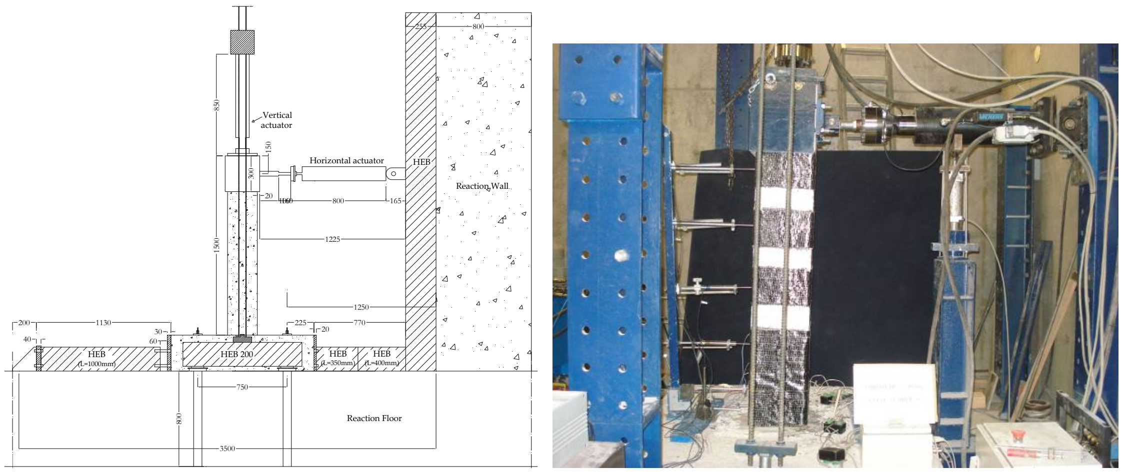
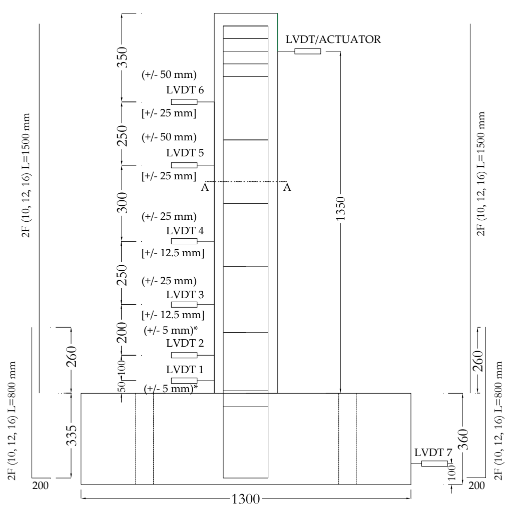


Figure 7 – Test setup



[…] For NON columns;
(…) For PRE and POS columns
(…)* For NON, PRE and POS columns.

Figure 8 – Position of the LVDTs (all dimensions in mm)

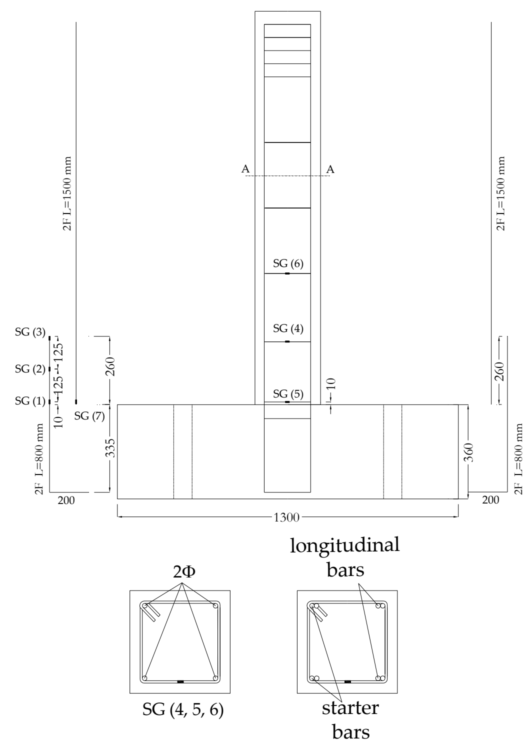


Figure 9 – Position of the strain gauges installed on steel bars (all dimensions in mm)

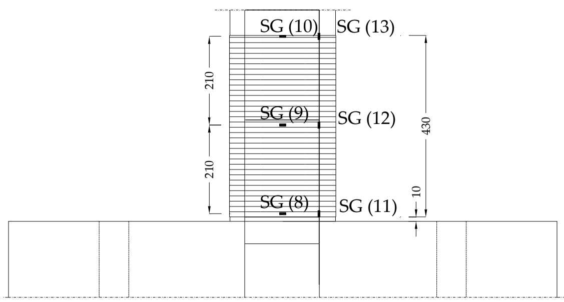


Figure 10 – Positions of the SG on the CFRP sheet (SG8 to SG10) and laminate (SG11 to SG13) (dimensions in mm)

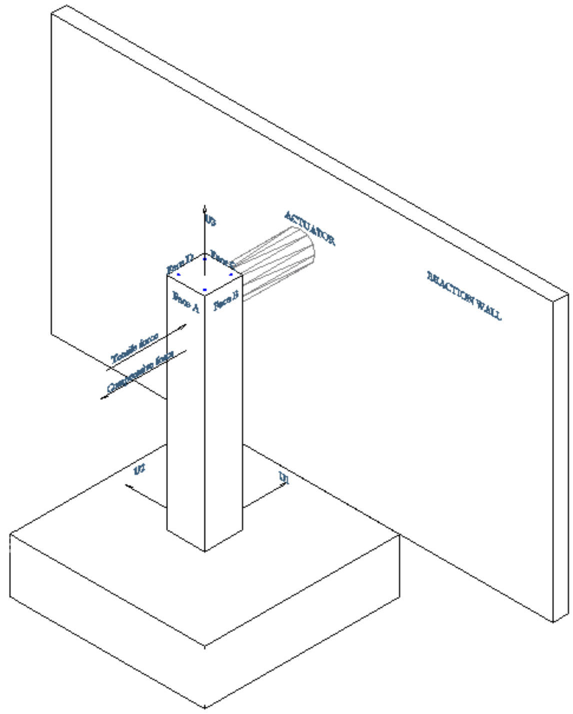
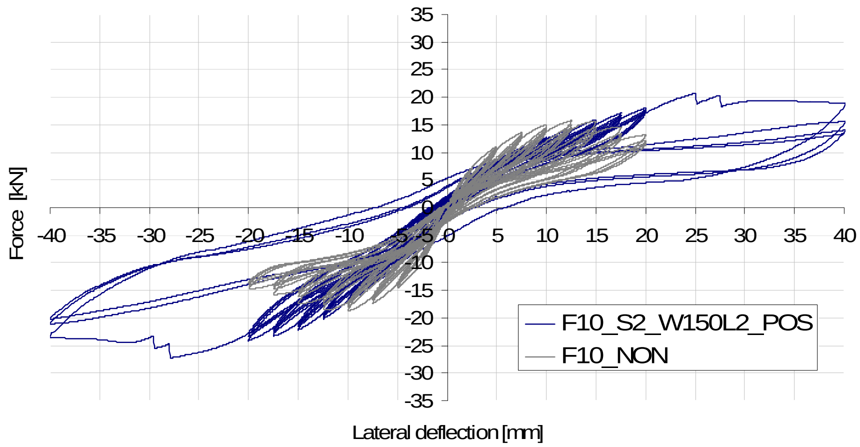


Figure 11 – Axonometric representation of the test set-up

6 RESULTS AND DISCUSSION

Figure 12 represents the force-lateral deflection, F-u_{Act}, (measured by the internal LVDT of the actuator, LVDT/ACTUATOR in Figure 8) for the columns of the G1 group of tests. In each graph the F-u_{Act} curves of the reference column and its corresponding post-strengthened column are superimposed in order to highlight the most relevant features provided by the proposed technique. The relationship between the dissipated energy and the accumulated lateral deflection (at LVDT/ACTUATOR) for the tested columns is represented in Figure 13. The main results are presented in Table 3. The convention signals for tensile/compressive forces and positive/negative lateral displacement are represented in Figure 11.

From the obtained results it is verified that the hybrid post-strengthening technique has provided an increase of the column load carrying capacity that ranged from 31% to 55%. Due to the too low compressive strength of the concrete of these columns, the maximum tensile strain recorded in the longitudinal bars was lower than their yield strain. Figure 14 shows a typical relationship between the applied cyclic lateral force and the strain measured by the strain gauge SG1 installed in the starter steel bar (see Fig. 9). It is observed that, for a certain strain value, the force installed in the POS column was higher than the force supported by the NON column, due to the contribution of the composite materials.



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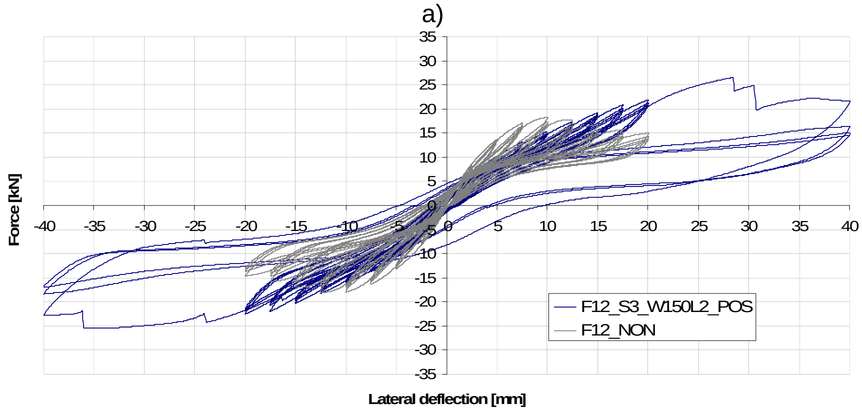

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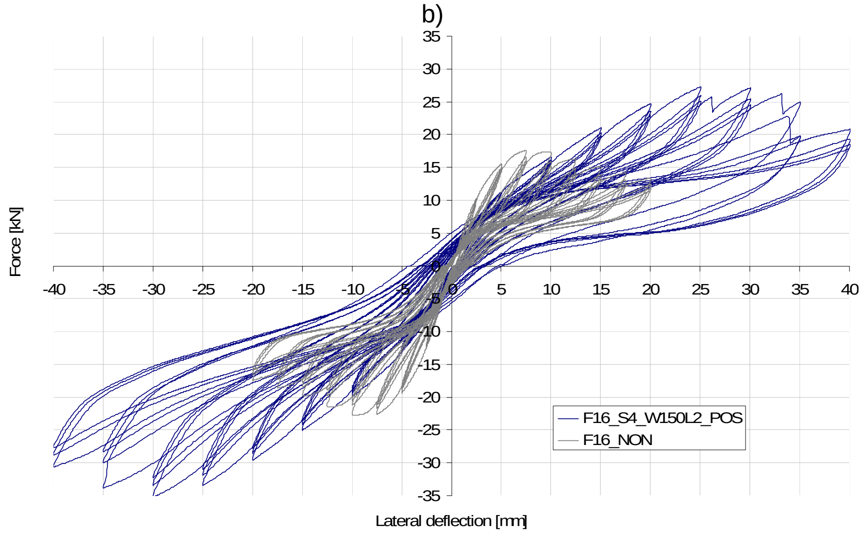
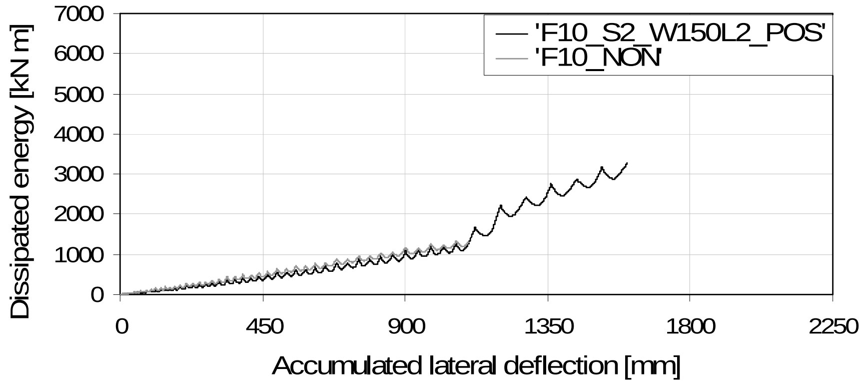


c)

Figure 12 – Force-lateral deflection for the: a) F10_NON and F10_S2_W150L2_POS columns; b) F12_NON and F12_S3_W150L2_POS columns; F16_NON and F16_S4_W150L2_POS columns.



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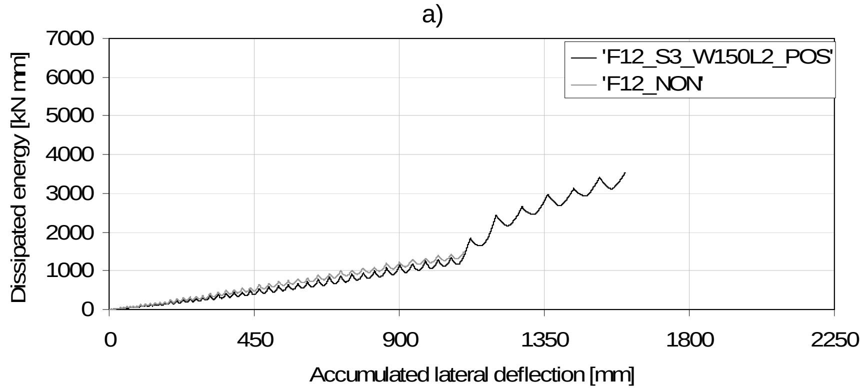

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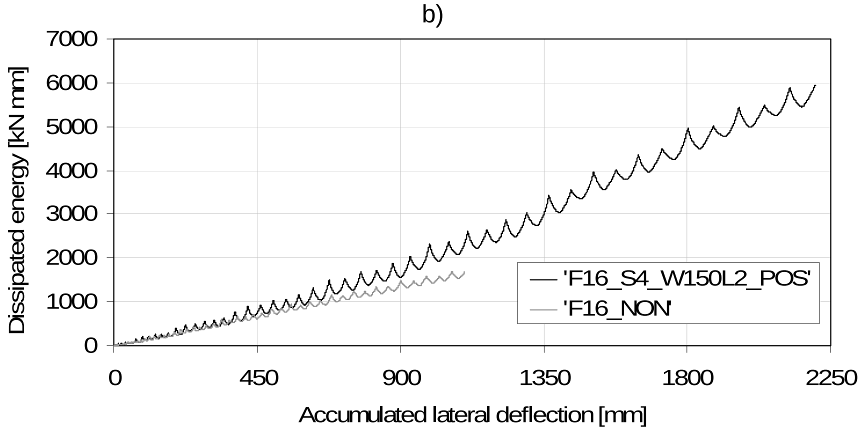

c)

Figure 13 – Dissipated energy vs. accumulated lateral deflection for the: a) F10_NON and F10_S2_W150L2_POS columns; b) F12_NON and F12_S3_W150L2_POS columns; F16_NON and F16_S4_W150L2_POS columns.

Apart F16_S4_W150L2_POS column, the hybrid technique had no benefit in terms of energy dissipation capacity of the column up to the maximum accumulated lateral deflection of the reference columns, since the poor quality of the materials does not allow the strengthening technique to be effective. However, after this deflection, Fig. 13 reveals that an increase of the ratio between the dissipated energy and the accumulated lateral deflection occurred, indicating that for larger lateral deflections the contribution of the CFRP materials become more effective, due to the dilation of the concrete in the confined nonlinear hinge (column bottom zone). In fact, Figure 12 shows that, above a lateral deflection of +/-20 mm, the hysteretic cycles of the strengthened columns presented a significant level of energy dissipation. For instance, in the F16_S4_W150L2_POS the dissipated energy at the end of the test (for an accumulated lateral deflection of 2201 mm) was 5947 kN.mm. Figs 12 and 15 show that, due to the damages accumulated up to the end of the tests of the NON columns, the POS columns presented lower initial stiffness than their corresponding NON columns. However, after a lateral deflection of about 12 mm, the stiffness of the POS columns became higher than the stiffness of the corresponding NON column. The stiffness was obtained dividing the lateral force by the corresponding lateral deflection.

Table 3 – Main results from the G1 group of tests

Specimen designation	$F^{exp}_{c,max}$ (kN)	$F^{exp}_{t,max}$ (kN)	$\varepsilon^{Lam}_{f,max}$ (‰)	$\varepsilon^{She}_{f,max}$ (‰)	$\varepsilon^{F^{exp}_{max}}_{s,max}$ (‰)	$U_{ald=1100}$ (kN.mm)	$U_{ald,max}$ (kN.mm)
F10_NON (41)	-18.80	15.78	-	-	2.243	1312	1312
F10_S2_W150L2_POS (80)	-27.27 [45%]	20.68 [31%]	3.372	4.3	2.177	1282 [-]	3280 (1601)*
F12_NON (46)	-18.00	18.23	-	-	1.403	1490	1490
F12_S3_W150L2_POS (76)	-25.47 [42%]	26.44 [45%]	9.65	3.27	1.430	1384.2 [-]	3539 (1601)*
F16_NON(48)	-22.73	17.65	-	-	1.538	1678	1678
F16_S4_W150L2_POS (74)	-35.24 [55%]	27.38 [55%]	NA	0.88	1.326	2643 [58%]	3811 (1601)*

$F^{exp}_{c,max}$ =maximum compressive force; $F^{exp}_{t,max}$ =maximum tensile force; $\varepsilon^{Lam}_{f,max}$ =maximum tensile strain in laminates (SG11); $\varepsilon^{F^{exp}_{max}}_{s,max}$ =strain in the longitudinal bars at maximum lateral force (SG1); $\varepsilon^{She}_{f,max}$ =maximum tensile strain in sheet (SG8); $U_{ald=1100}$ =dissipated energy up to accumulated deflection of 1100 mm; $U_{ald,max}$ =maximum dissipated energy; * dissipated energy up to 1601 mm of accumulated deflection; () age, in days, at testing; [] increase provided by the strengthening technique;

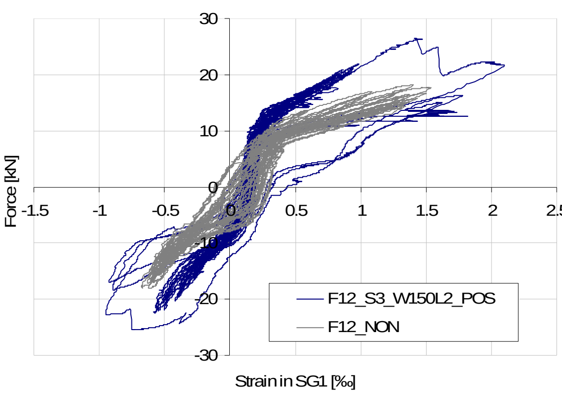

Figure 14 – Force versus the strain in the SG1 (Fig. 9) for the F12_NON and F12_S3_W150L2_POS columns.

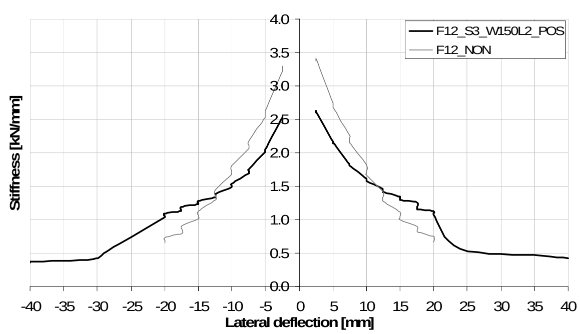

Figure 15 – Evolution of the stiffness of F12_NON and F12_S3_W150L2_POS columns.

7 CONCLUSIONS

The effectiveness of a hybrid strengthening strategy to increase the flexural resistance and energy dissipation capabilities of reinforced concrete columns (RC) of rectangular cross section was analyzed in the present paper. This strategy is composed by CFRP laminates applied according to the near surface mounted (NSM) technique, and CFRP wet lay-up sheets confining the plastic hinge of the RC columns. This strategy was applied to a group of columns of a concrete average compressive strength, f_{cm}, of 8 MPa, in order to explore its capability for columns of very low strength concrete. The tested group of columns was composed by three reference RC columns of distinct longitudinal steel reinforcement ratio (NON tests), that after have been tested, were strengthened according to the hybrid technique and were again tested (POS tests). The columns were subjected to a constant compressive load of 120 kN (1.92 MPa that corresponds to 24% of the f_{cm}) an cyclic lateral loading.

In terms of column load carrying capacity, the hybrid technique provided an average increment of 46% in columns that presented intensive damages when submitted to the rehabilitation process (at the end of the NON tests). Since the number of CFRP laminates was evaluated to assure an increment of 50% for the load carrying capacity of virgin columns (the hybrid technique is applied on untested columns), the obtained results indicate that this technique is also very effective for columns with significant damages. However, due to the too low concrete strength, the longitudinal steel bars did not yield, which only guarantied an appreciable increase in terms of dissipated energy in the columns with the highest percentage of longitudinal reinforcement ratio (58% up to the accumulated lateral deflection when the corresponding NON test ended). Therefore, if the purpose is also increasing the energy dissipation capacity of columns of very low concrete strength, subjected to cyclic lateral load, the effectiveness of the technique based on wrapping the column critical zones with passive CFRP wet lay-up sheets is questionable. Applying the CFRP sheets with a certain pos-tension is an alternative that should be explored.

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