RETROFIT TECHNICS FOR CYCLIC BEHAVIOR IMPROVEMENT OF RC COLUMNS

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ABSTRACT :

The main purpose of this paper is to present an experimental and numerical study concerning retrofit techniques on cyclic behavior of RC columns. The Laboratory for Earthquake and Structural Engineering (LESE) of the Faculty of Engineering of University of Porto (FEUP) is performing an experimental campaign on RC columns representative of typical buildings designed prior to 1980. Cyclic loading tests under constant axial load were carried out on specimens as built and after retrofit in order to assess the available capacity during seismic events and to define retrofit strategies compatible with actual safety levels. All studied specimens were retrofitted by different techniques based on either CFRP sheets or steel plates, bearing in mind the behavior and failure type obtained from the "as built" previous test. The description of retrofit design methodologies and application details are presented, highlighting for each case the main important aspects to achieve optimized retrofit strategies. The application of retrofit techniques was deliberately based on common practices as used on building rehabilitation. Some details are also given concerning the adopted testing setup in order to evidence the inherent advantages and limitations. In addition the adopted specimen instrumentation is described, showing that the result discussion is not only based on force and displacement response but also on dissipated energy.

KEYWORDS: RC Columns, non-linear cyclic behavior, experimental tests, RC retrofitting, numerical simulations

1 INTRODUCTION

This paper presents the results of the first set of tested specimens, before and after their retrofit with steel plates and with Carbon Fiber Reinforced Polymers (CFRP) sheets.
In order to analyze and assess different strategies for the seismic retrofit of RC columns, an experimental campaign is presently underway at the Laboratory of Earthquake and Structural Engineering (LESE) of the Faculty of Engineering of the University of Porto (FEUP). Four RC columns full scale models were designed to reproduce some columns of the ICONS frame. The specimens have 200 mm by 400 mm rectangular cross-section and are 1720 mm high from the top to the footing, the later with 1300 mm x 1300 mm x 500 mm and heavily reinforced to avoid any premature failure during testing. The specimens have been chosen aiming at reproducing some columns of a RC frame studied within the ICONS project framework developed at the European Laboratory for Safety Assessment (ELSA) of the Joint Research Centre (JRC) at Ispra (Italy), where the frame experimental tests took place [Pinho, 2000] and [Varum, 2003]. In total, eight full-scale RC columns will be tested, both in the original undamaged state and after retrofit interventions according to different techniques.
The test setup, as illustrated in Fig. 1 (left), is suitable to apply lateral loads using a hydraulic actuator attached to a reaction steel frame. Constant axial load of 170 kN was applied to the column supported on another independent steel portal frame. The specimen footing is bolted to the strong floor (600 mm thick). A special device was designed to apply a constant axial load in the column, while allowing lateral displacements and top-end rotations.

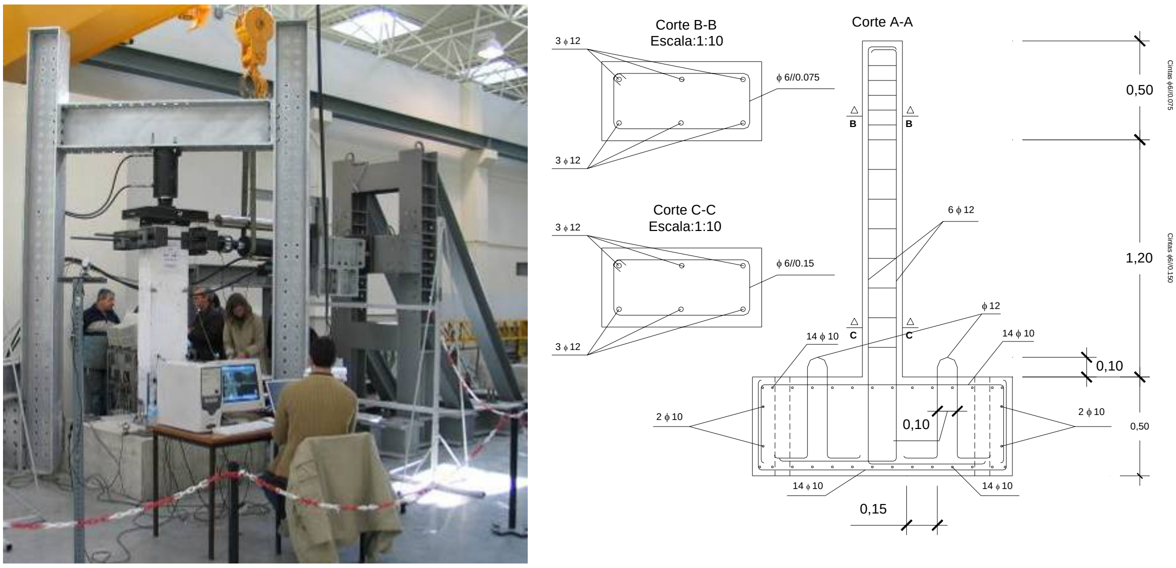


Figure 1: View of the test setup at LESE Lab and specimen PA1.

As also shown in Fig. 1 (right), the column specimen PA1 has six 12 mm diameter longitudinal rebars of A400 steel grade with average yield strength of 460 MPa; it is transversely reinforced with 6 mm diameter rebars, with 150 mm spacing, made of A500 steel grade with average yield strength of 750 MPa. The footing reinforcement is also shown and made with A400 steel grade. The average concrete compressive strength is 43 MPa, as obtained from tests performed on concrete cubes. The specimens were named PA1-Nx, were PA1 is the model reference and x referees to the specimen number.

2 CYCLIC TEST OF THE “AS BUILD” SPECIMENS

For all the column specimens, three repetitive cycles were applied (fig. 2) for several peak drift ratios, Δ/L, where Δ is the lateral displacement and L is the clear length of the column model measured between the bottom and the application point of the lateral force. Thus, the following drift ratios were considered: 0.19% (3 mm), 0.31% (5 mm), 0.63% (10 mm), 0.75% (12 mm), 0.94% (15 mm), 0.47% (7 mm), 1.25% (20 mm), 1.88% (30 mm), 2.50% (40 mm), 0.94% (15 mm), 3.13% (50 mm), 3.75% (60 mm), 4.38% (70 mm) and 5.00% (80 mm).

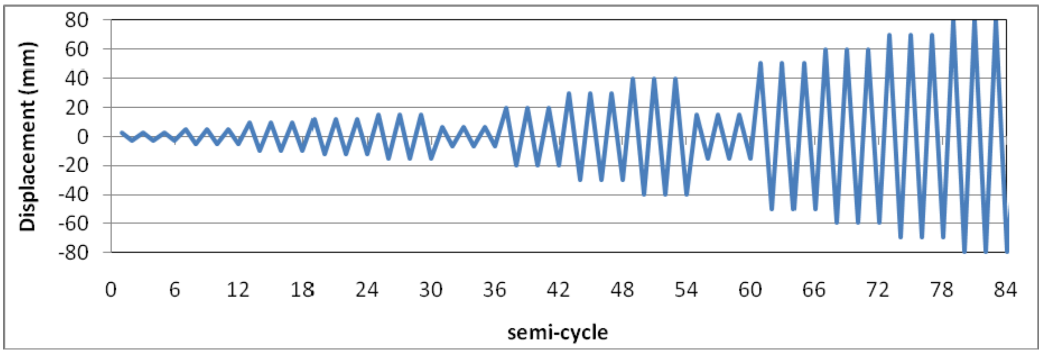
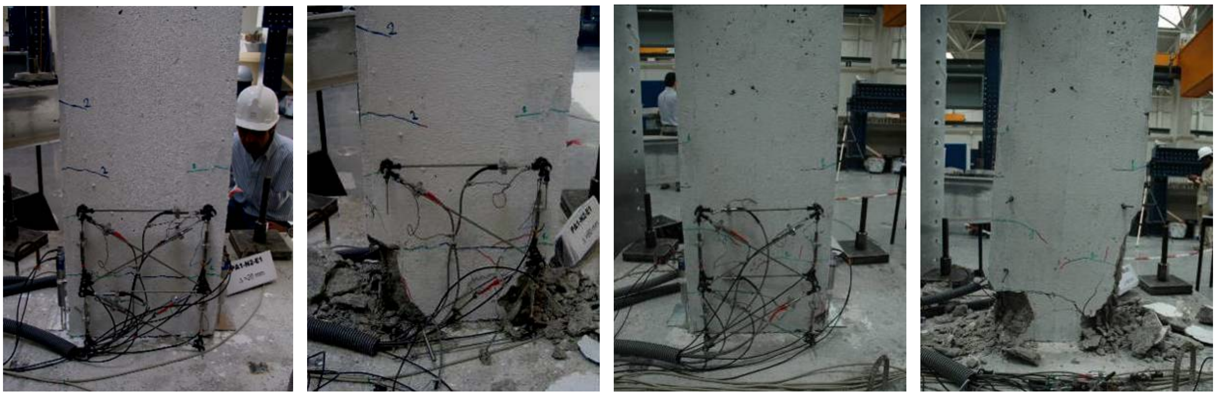


Figure 2: Target top-displacements during the tests

However, the experimental test of the column PA1-N2 was stopped after the 60mm cycle, due to an unexpected rotation of the column on the transversal direction of analysis – perpendicular direction of the actuator which coincides with the less stiff column direction.



(a) (b) (c) (d)

Figure 3: Damage patterns in the column PA1-N2 (a and b) and PA1-N3 (c and d).

Fig. 3 shows the damage reached during the test for columns PA1-N2 (3a and 3b), PA1-N3 (3c and 3d). For both columns, before 20 mm, little damage was achieved at the first cycles, where only small cracks are visible (Fig. 3a and 3c), and severe damage was found at the end of the tests, Fig. 3b and 3d, exhibiting buckling and rupture of the four corner reinforcement bars as well as significant degradation of the concrete.
In Fig. 4 the comparison between the experimental cyclic results of the two referred columns is presented. As can be seen the results are quite close for the maximum forces achieved and globally for all the cyclic behavior. As seen during the tests and also after analyzing the results, the buckling of the longitudinal reinforcement between the critical section (at the column base) and the first hoop affects drastically the column behavior, which leads the quickly degradation on strengthening.
During the tests performed to date, an undesired problem occurred with the hydraulic system used to apply the axial load: the pressure that should been remain constant has in fact increased. Actually, the hydraulic system was designed to keep constant the oil pressure, in order to maintain constant the axial force, but a deficient performance of the circuit has blocked the return of the oil from the vertical actuator; therefore, the axial load increased during the cyclic displacement history, because the axial actuator was forced to remain in the same position when the top-end pier section was rotating and displacing. A preliminary test to calibrate all the setup was carried out by the same authors (Delgado, et. al 2006).

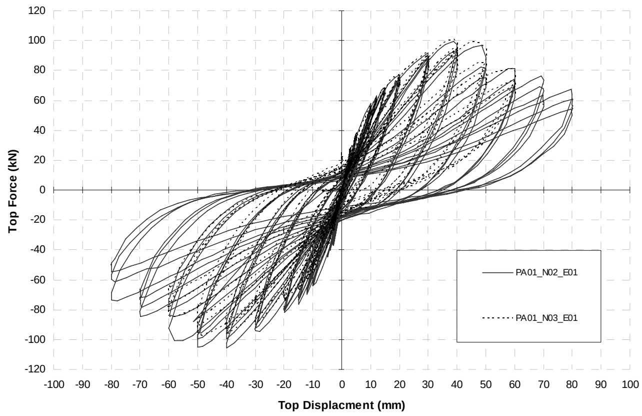


Figure 4: Experimental cyclic results of columns - PA1-N2 and PA1-N3 ("as built")

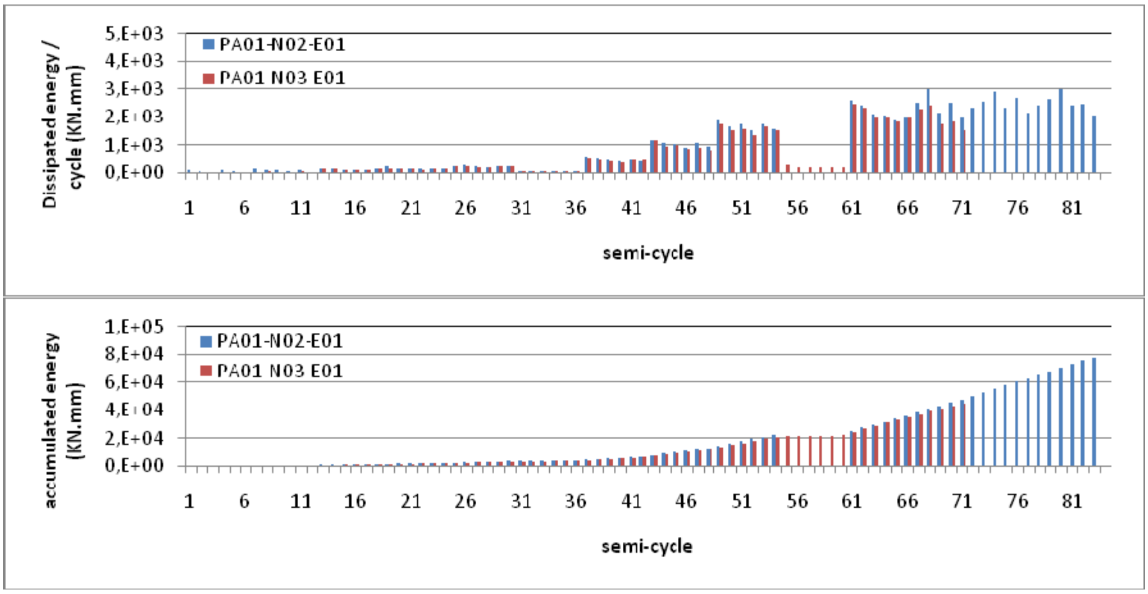


Figure 5: Dissipated and accumulated energy - PA1-N2 and PA1-N3 ("as built")

As can be seen in fig. 5, until near the end of each test, the dissipated energy was similar on booth cases. The accumulated energy in columns PA1-N3-E1 is a little bit lower than it was in PA1-N2-E1. This difference may be justified by the displacement history (15 mm cycle between 40 and 50 mm on PA1-N3-E1 to evaluate the behavior, particularly the stiffness, for smaller cycles after having incursions in non-linear) and the different axial load. Besides this, it is possible that the different cover concrete observed in two specimens can contribute in capacity of the pillar, especially on greater amplitude cycles.

3 RETROFIT

After the cyclic test of the "as built" specimens took place up to failure, they were repaired and retrofitted with three different techniques: CFRP jacket; steel plates; and steel plates connected by equal legs angles steel profiles. Before performing the retrofit all specimens were prepared according to the following steps:

1) Delimitation of the repairing area (the critical section at the plastic hinge region taking out all the damaged concrete - from the footing up to 30 cm above the column height);
2) Removal and cleaning of the damaged concrete (Fig. 6a);

(a) (b) (c) (d)

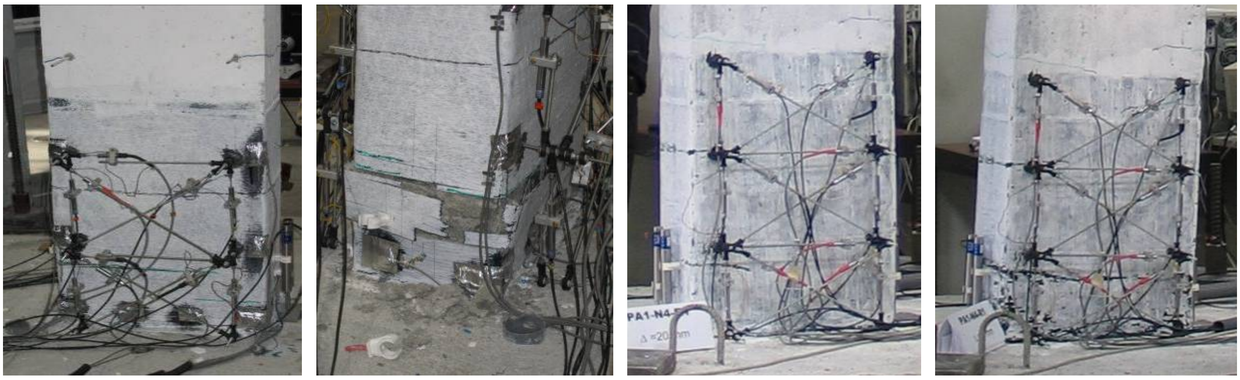
Figure 6: Lap spliced zone (a); retrofitted column with CFRP sheet jacket (b); steel plates (c); and steel plates connected by equal leg angle steel profiles (d).

3) Alignment and replacement of the longitudinal reinforcement bars (it was needed to cut 2 to 4 cm of the corner bars that had buckled and failed in order to ensure the alignment. The additional bars were bonded in the footing within 20 to 25 cm depth with epoxy resin and lap spliced along 20 cm);
4) Application of formwork and new concrete (Microbeton, a pre-mixed micro concrete, modified with special additives to reduce shrinkage in the plastic and hydraulic phase);

To have an idea of the damaged column, the following pictures illustrate the column during repairing and after retrofitted with the three techniques used in this project (Fig. 6). In order to design the retrofit jackets (Fig. 6b), the authors used the Priestley et al. approach (Priestley et al., 1996) to calculate the thickness of the jacket for rectangular column to achieve a target displacement of $\Delta = 50$ mm at the point of horizontal force application, i.e. 1600 mm above the footing, keeping the initial conditions (without upgrade of ductility and strength). Inelastic deformation capacity of flexural plastic hinge regions can be increased by recourse to confinement of the column concrete with an advanced composite fiber jacketing system. The steel jacketing wore calculated based on the same proposal only changed the material characteristics (Rocha, et. al 2006).

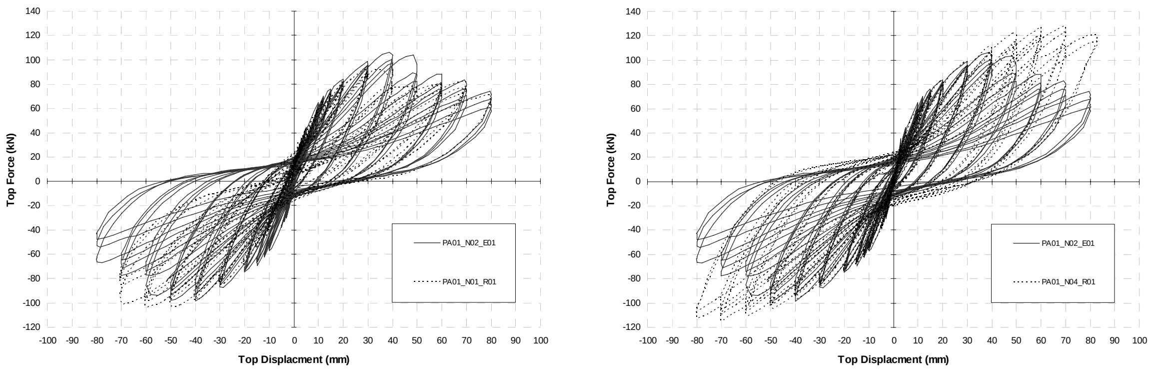
4 CYCLIC TEST OF THE RETROFITTED SPECIMENS

The retrofitted column PA1-N1 was tested following the same cyclic displacement history of the "as built". As can be seen in the Fig. 14, the retrofitted specimen showed a good behavior in comparison with the "as built", exhibiting flexural cracking along the CFRP jacket (Fig. 7a and 7b), very distributed and reaching the region above the jacket for both lateral displacement direction. The CFRP jacket failure took place at 65 mm (drift = 4.0%) lateral displacement preceded by the noise of the fiber rupture (Fig. 7b).



(a) b) (c) (d)

Figure 7: Damage on the CFRP retrofitted specimen: flexural cracking (a and c) and failure (b and d).



a) PA1-N2 "as built" and PA1-N1-R1 b) PA1-N2 "as built" and PA1-N4-R1

Figure 8: Experimental cycle results – Comparison between CFRP retrofit solutions.

During this test some unexpected displacements occurred on the steel portal that supports the vertical hydraulic jack. This incident affected the obtained results on the load cell connected to the upper steel plate. However, as expected, this retrofit solution applied to an “as build” specimen shows an excellent behaviour in both ductility and strength capacity as can be seen in Figs. 7c, 7d and 8b. The energy evaluation between both CFRP retrofitting (fig. 9) show the substantial gain of capacity of the specimen retrofitted as build when compared with other retrofitted after one previous analog test.

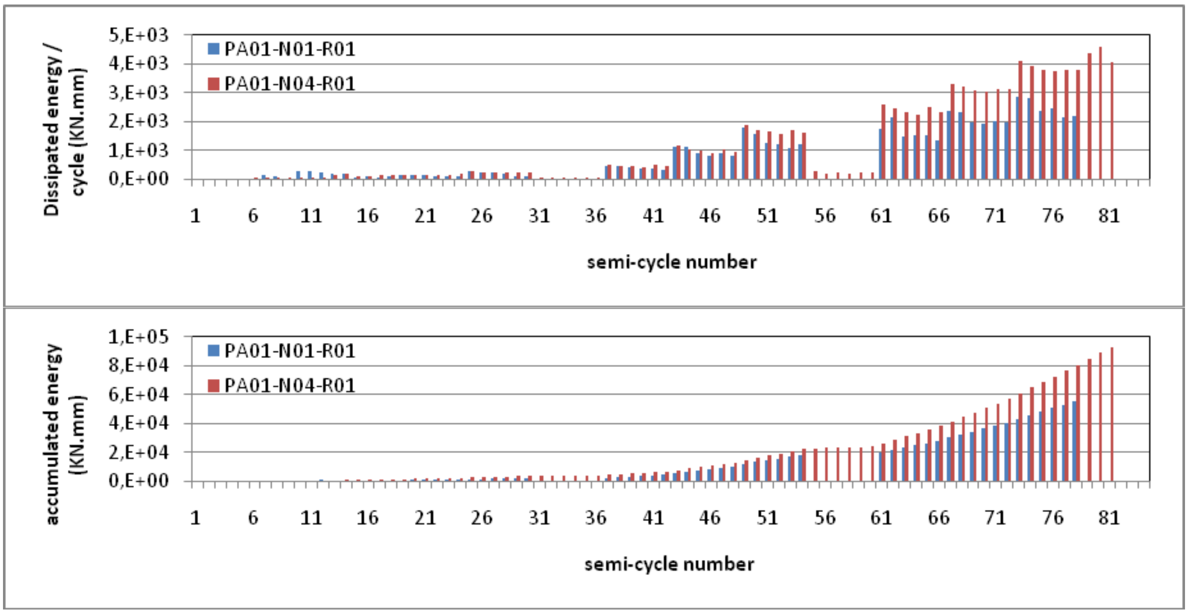
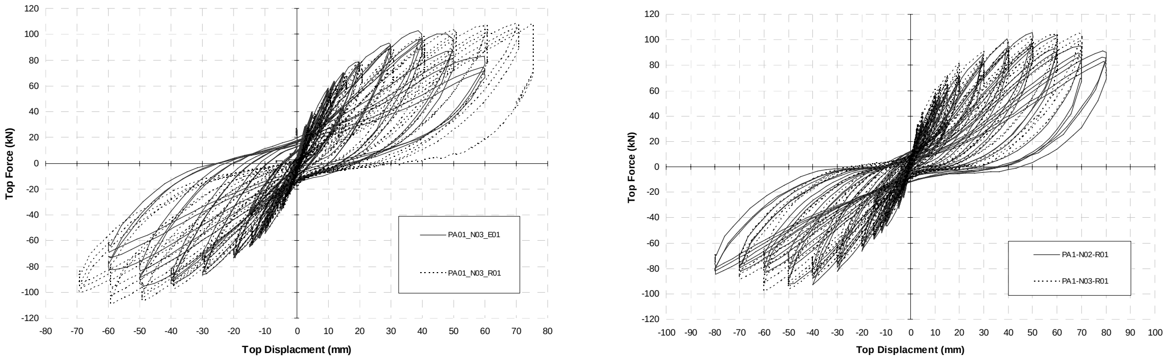


Figure 9: Dissipated and accumulated energy - Comparison between CFRP retrofit solutions

The test of the retrofit solution applied on PA1-N2-R1 column – steel plates - is illustrated in the Fig. 10 (a and b). Very small and distributed flexural cracking was achieved during the first cycles, about 20 mm (Fig. 10a). For the maximum displacements cycles (Fig.10b) the retrofitted specimen showed a quite good behavior in comparison with the “as built”, with only local damage below the lower steel plate.
In Fig. 10 (c and d) the experimental test carried out on column PA1-N3-R1 retrofitted with steel plates connected by equal leg angle steel profiles is illustrated sowed e very similar behaviour.

(a) (b) c) (d)

Figure 10: Damage on the retrofitted specimen PA1-N3: flexural cracking (a and c) and failure (b and d).



a) PA1-N3 "as built" and PA1-N3-R1 b) PA1-N2-R1 and PA1-N3-R1

Figure 11: Experimental cycle results - Comparison between steel retrofit techniques.

The results obtained from the two retrofit techniques with steel are almost similar, although the specimen PA1-N3 showed an improved behavior in terms of strength degradation (Fig.11a). This small improvement can be justified by the steel angles profiles added to the strips at the corners of this specimen; even without being connected to the footing, the steel angles profiles avoided the cover concrete spalling, particularly close to the critical zone, which improves the strength capacity of the compressive zone.
The last considerations can be confirmed by observation of Fig. 12, where is represented the dissipated and accumulated energy. Based on same reasons, it is possible to observe the small improvement of the solution with steel plates connected by equal leg angle steel profiles on dissipation energy capacity.

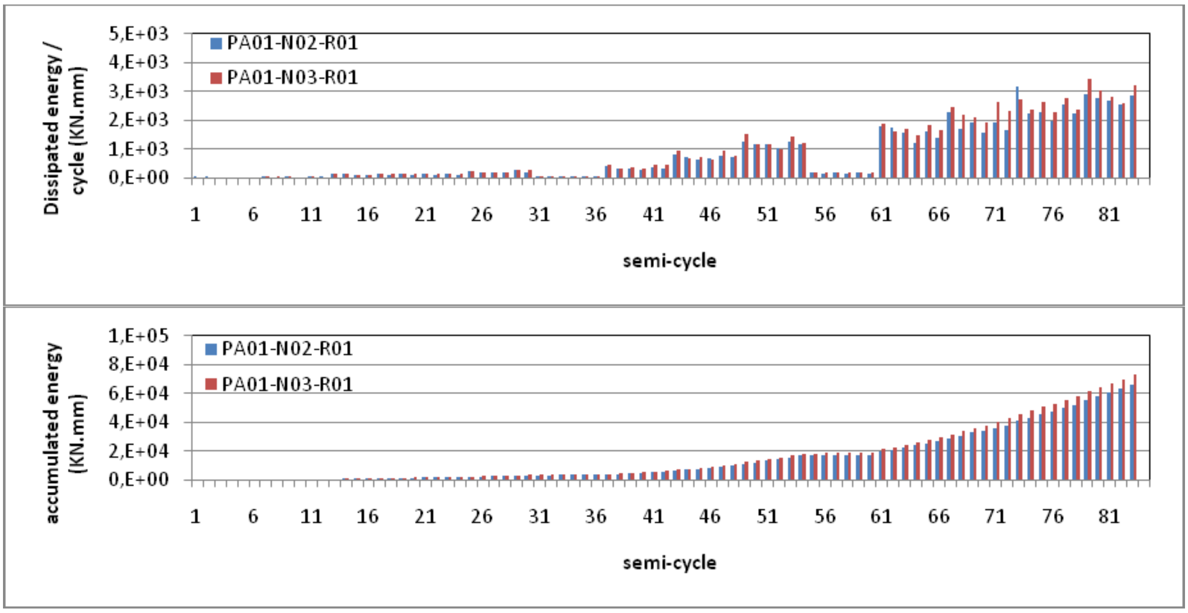


Figure 12: Dissipated and accumulated energy - Comparison between steel retrofit techniques

5 CONCLUSIONS

The setup used within this framework shows a very good performance to carry out bending tests with axial load. The slide device, a steel plate system for the axial force transmission that allows the top displacements of the column, performed satisfactorily and showed low values of friction forces.

Since the retrofit objective was basically the reestablishment of the original conditions, no strength and ductility increase was observed, as expected. Furthermore, the experimental strain at the failure stage was close to the numerical prediction strain obtained using Priestley approach. From the observation of the experimental tests and their results it is possible to conclude that restraining the longitudinal reinforcement buckling by transversal retrofit have significant benefit in behavior and particularly leading to lower strength degradation.
As expected the CFRP retrofit solution applied to an "as build" specimen shows an excellent behavior in both ductility and strength capacity, also clear on observation of energy graphics.
The two steel retrofit techniques showed a satisfactory solution to the buckling problem and brought a significant strength increase in the final cycles of displacement, doubling the residual strength of the "as built" specimen.
The comparison between the two retrofit techniques with steel showed an almost similar behavior with a very small improvement of strength degradation on steel plates connected by equal leg angle profiles, cause by better cover concrete spalling which improves the strength capacity of the compressive zone.
Any of the proposed retrofit led to strong concentration of deformation and the concrete degradation at the critical section (base) of the specimens reducing significantly the plastic hinge length.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the "João da Silva Santos, Lda" company, for the construction of the tested columns. Final acknowledgements to the laboratory staff, mainly Mr. Valdemar Luís, for all the care on the test preparation. This study was partially performed with the financial support of the FCT through the Project PTDC/ECM/72596/2006, "Seismic Safety Assessment and Retrofitting of Bridges".

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