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Anchoring FRP laminates for the seismic strengthening of RC columns

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ABSTRACT: This paper aims to examine the effectiveness of seismic strengthening of reinforced concrete (RC) columns by externally bonded Fibre Reinforced Polymer (FRP). Particularly, a novel strengthening system, designed for the flexural strengthening of columns is studied. This flexural strengthening is achieved by FRP plates bonded longitudinally and anchored at the column-stub junction. The proposed system is validated through an experimental campaign carried out on full-scale RC columns. Different strengthening configurations have been applied on columns, which were tested under combined constant axial and reversed cyclic lateral load. The experimental results demonstrate that bonded FRP enhance the bending moment capacity and flexural deformation capacity of strengthened columns. Those tests helped us to analyze the behaviour of columns depending on the FRP confinement (FRP jacket) and the coupling of the confinement with the anchored flexural strengthening. It was then found that the proposed anchoring system is a promising constructive disposition for the seismic strengthening of columns, but this system needs to be improved.

1 INTRODUCTION

Modern seismic design of reinforced concrete (RC) structures is generally based on the principles of capacity design and relies on yielding of steel, moderate concrete damage and formation of plastic hinges for the earthquake energy dissipation. However existing under-designed buildings or bridges may be not resistant enough and may collapse if any earthquake occurs. Considering that the major cause of constructions collapse is column failure, specific retrofitting techniques have to be established for such structural element. Within this context, the use of Fibre Reinforced Polymer (FRP) has significantly increased in construction and civil engineering fields. Indeed, bonding of external FRP reinforcements is now recognized as an effective technique for the strengthening of RC structures and it can be particularly useful for seismic retrofitting. Most research studies conducted to date on strengthening of existing RC columns using externally bonded FRP have mainly been focused on confinement efficiency (for example Iacobucci *et al.* (2003), Harries *et al.* (2006), Mohamed & Dagher (2008), Promis *et al.* (2009), Gu *et al.* (2010)). However, columns can be strengthened by associating a confinement by wrapping with a flexural strengthening achieved either by FRP plates bonded longitudinally (Quiertant & Clément (2010)) or by near-surface-mounted FRP rebars (El-Maaddawy & El-Dieb (2011)). Such retrofitting scheme seems particularly appropriate for seismic strengthening or more generally for the strengthening of structural RC columns that are rarely perfectly axially compressed. The specific contribution of bonded FRP flexural reinforcement was studied by Hadi (Hadi (2006)) and was found to be effective when applied to small plain concrete columns eccentrically loaded. Nevertheless experimental investigations conducted on full-scale RC columns (Sadone *et al.* (2012)) showed contradictory results: in the tested configuration, the FRP longitudinal reinforcement coupled with confinement does not noticeably change the behaviour of the columns in terms of ductility, strength, or dissipated energy when compared to simply confined columns (columns without longitudinal FRP). Bonded longitudinal reinforcement was then considered ineffective. It was observed that the behaviour of the strengthened columns was mainly controlled by the rotation at the plastic hinge leading to a large crack opening at the column-stub junction. At that location, FRP plates bonded for longitudinal strengthening were not connected to the stub and then were not efficient to oppose the hinge rotation.

Considering this results, an innovative anchoring system for FRP laminates has then been proposed and tested under monotonic and low cycle fatigue loading (Sadone *et al.* (2010)). It appeared that those anchors could increase the ultimate capacity and ductility of bonded plates when tested on small concrete blocks, but they still have to be tested on representative-scale structures. It must be emphasized that other anchorage devices for FRP laminates were applied to the flexural strengthening of columns (for example Ascione & Berardi (2011)). The originality of the proposed anchoring system is that it is not an additional device but the extension of the Carbon FRP (CFRP) laminate bonded to achieve the flexural strengthening. This will be detailed latter.

This study aims to evaluate the strength and ductility enhancement resulting from longitudinally bonded FRP laminates anchored at the column-stub junction. To reach this goal, real scale RC columns were tested under a quasi-static loading path intended to be representative of a seismic solicitation: reversed lateral cyclic loading and constant axial load. The main experimental parameter was the FRP configuration. Those tests helped us to analyze the behavior of RC columns depending on the FRP configuration and allowed us to determine the influence of these parameters mainly on the ultimate strength and on ductility, and then to conclude about the effectiveness of the proposed anchoring system.

2 EXPERIMENTAL INVESTIGATIONS

2.1 *Test specimens*

A total of 6 representative scale RC column specimens were constructed. Specimens consisted of 0.25 x 0.37 x 2.50m^3 columns connected to 1.25 x 1.00 x 1.00m^3 RC stubs. Specimen dimensions and internal reinforcement details are shown on Figure 1. The reinforcing cage was made of two parts: one for the column and one for the stub, with the column longitudinal rebars extending through the stub. Reinforcement of the columns was achieved by 6 steel deformed rebars of 10mm in diameter used for longitudinal reinforcement and ties of 6mm in diameter spaced at 150mm used for transverse reinforcement. These design details produce a longitudinal reinforcement ratio of 0.5 %.

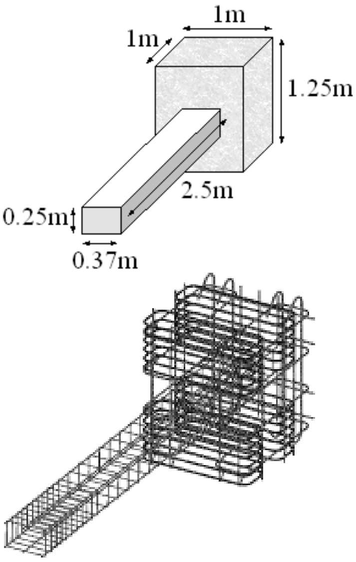


Figure 1. Column dimensions and reinforcing cage.

2.2 *Materials*

RC column specimens were vertically cast. From each batch of concrete it was possible to cast two or three specimens at the same time. The concrete strength of each specimen was determined by averaging the values obtained using three standards 11cm by 22cm concrete cylinders. Mechanical properties of concrete, for each column, are summarized in Table 1. Tensile strength was determined by splitting tensile test.

Table 1. Mechanical properties of concrete

	Compressive strength	Tensile strength
	[MPa]	[MPa]
PRef1	46.23	3.55
PRef2	47.43	3.49
PCL1	34.70	2.88
PCL2	40.30	3.74
PCLA1	38.00	2.90
PCLA2	41.30	3.70

The CFRP confining jacket was made using the wet-lay up process. Saturated carbon fibre sheets were wrapped around the column while flexural reinforcement was achieved by bonding pultruded CFRP plates. Characteristics of FRP reinforcements are summarized in Table 2. Presented characteristics are those reported by the manufacturer. Before strengthening, corners of the columns were rounded at a radius approximately equal to 25mm to avoid premature failure of CFRP and to enhance the confining effect of the wrap. Confining sheets were applied one day after the laminates have been installed.

Table 2. Manufacturers reported CFRP reinforcement (Freyssinet products)

	CFRP sheets (TFC©)		
Thickness	Width	Young’s modulus	Ultimate strain
0.48mm	300mm	105 000MPa	0,01
	Pultruded plates		
Thickness	Width	Young’s modulus	Ultimate strain
1.2mm	50mm	160 000MPa	0,007

To characterize internal reinforcement of RC columns, tensile tests were realized on 6mm and 10mm-diameter steel rebars. Results of the tests are presented in Table 3.

Table 3. Certified mechanical properties of steel rebars

	Nominal diameter of the rebar	
	6mm	10mm
Tensile strength (MPa)	613.7	603.5
Ultimate strain (µdef)	20820	37340
Yielding strain (µdef)	3106	2785
Young’s modulus (MPa)	185417	195000

2.3 *Anchoring system*

The anchored strengthening system was fabricated with a pultruded carbon plate (a commercially available CFRP strengthening system of Freyssinet), from which the end has been modified; the anchorage system and the CFRP strengthening system (the plate) were then a single continuous element (see Fig. 2). Previous work (Sadone *et al.* (2010)) showed that the proposed system could be an interesting constructive disposition. The system was adapted to facilitate its installation in real structures, by creating a 15° angle between the straight part of the plate and its end with a modified shape (Fig. 2); Such angle makes the drilling of the anchoring holes easier (Fig. 3). After been drilled, the holes were cleaned carefully by pressurized air and filled with an epoxy-based adhesive. Then the anchored part of the CFRP was inserted into the hole.

Figure 2. Anchoring system.

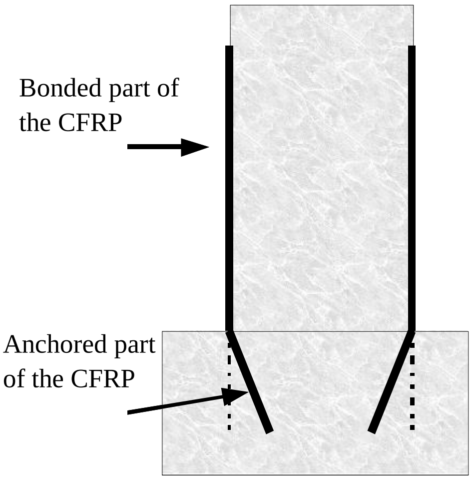


Figure 3. Scheme of the anchoring principle of the flexural strengthening.

2.4 *Instrumentation*

Extensive instrumentation was used to collect data during tests: concrete, FRP and steel strains at different locations, deflections along the specimen length, and axial and lateral load were recorded. 15 strain gauges were attached to longitudinal rebars and 2 strain gauges on ties; 18 strain gauges measured either concrete (for non reinforced columns) or FRP (for reinforced columns) strains, and 5 LVDT measured transverse displacements of test specimens. Displacements and loading applied by hydraulic jacks were recorded thanks to displacement sensors and load cells located in front of the jacks.

2.5 *Strengthening configurations*

For the 6 columns, the main studied parameter is the FRP configuration. As established in Sadone *et al.* (2012), there is no noticeable difference between the behaviour of a confined column, and a column reinforced with confinement and un-anchored laminates for flexural reinforcement. From this conclusion, the 3 studied strengthening configurations are then:

- no strengthening (reference specimens PRef1 and PRef2),
- a combination of confinement and laminates (the confinement being the only efficient strengthening system) for specimens PCL1 and PCL2
- and a combination of confinement and anchored laminates (PCLA1 and PCLA2).

Those strengthening configurations are summarized in Figure 4 and should allow quantification of anchored laminates efficiency. Two specimens of each series were tested. Repeating the experiments twice was an experimental choice to increase the confidence level in the results.

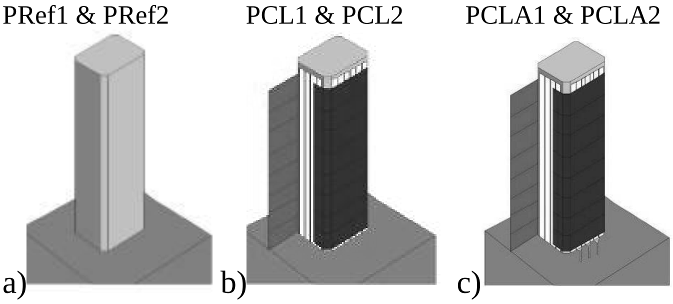


Figure 4. FRP strengthening configurations. a) no strengthening b) confinement and un-anchored flexural reinforcement c) confinement and anchored flexural reinforcement

The detailed scheme of the anchored configuration is provided on Figure 5

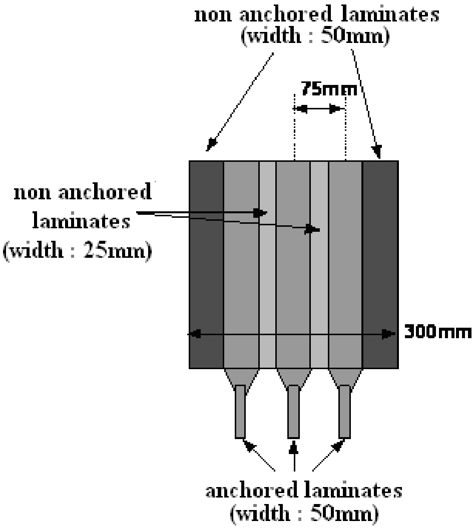


Figure 5. Detailed anchored configuration.

Anchored laminates are only applied on upper and lower faces, these faces being the most solicited faces (under flexion), and an alternation of anchored and non-anchored laminates has been used, to avoid weakening the concrete of the anchoring zone.

2.6 *Test setup and loading procedure*

Testing was carried out in the Structures Laboratory of IFSTTAR, located in Paris. The specimens were tested horizontally as shown on Figure 6. Seismic load was simulated by applying cyclic lateral displacements gradually increasing (representative of a seismic loading), while the column was simultaneously subjected to a constant axial load (simulating gravity load). The constant axial load of 700kN, corresponding approximately to 20% of the axial load carrying capacity of the column, was applied through a pair of hydraulic jacks (capacity 1100kN, 220mm) linked to prestressing tendons. The displacement controlled lateral load was applied thanks to another hydraulic jack (capacity 2000kN, +/- 250mm).

At the beginning of each test, axial load was applied thanks to 6 prestressing tendons, three on each side of the column, linked to an anchored plate at the top of the column, and to the jacks behind the stub. After the application of the axial load, the specimen was subjected to progressively increasing lateral displacement cycles. Two fully reversed cycles were applied for each displacement step. Those displacement steps, referred here as “drift ratio”, were defined as a ratio of the column height: 0.25%; 0.5%; 1%; 2%; 4%; etc. until failure. The column was considered to have reached its ultimate condition when the specimen is unable to sustain an applied lateral load inferior to 50% of the maximum lateral capacity observed during the test.

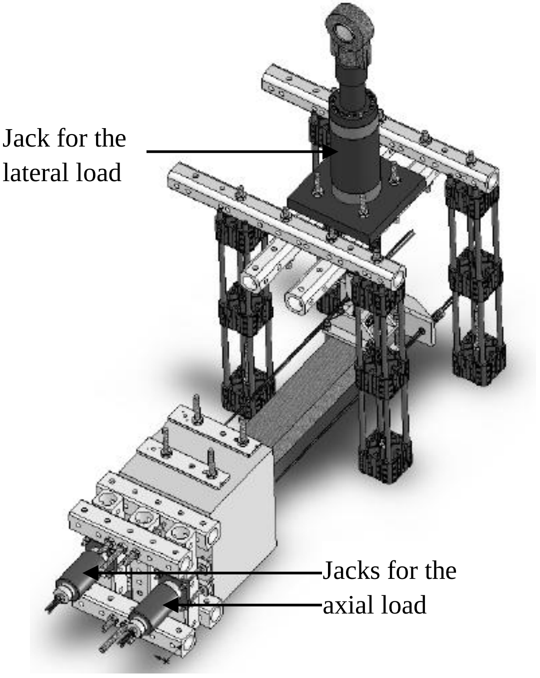


Figure 6. Test setup.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

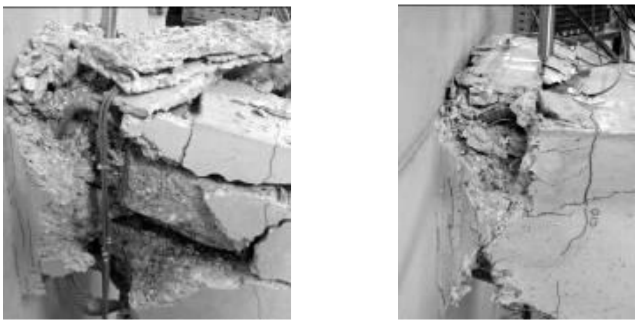
3.1 *General observations*

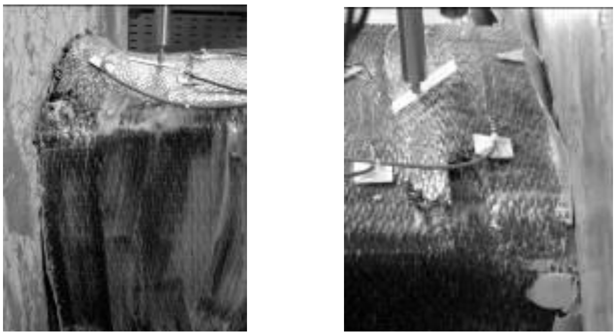
For reference specimens (PRef1 and PRef2), a buckling of the longitudinal rebars and a huge spalling of cover concrete (Fig. 7) occurred during lateral displacement cycles corresponding to a drift ratio of 4%. Cracks formed at or near the footing column interface. Then, at the end of the second cycle at the drift ratio of 6%, an important loss of axial resistance appeared: the column was not able to resist the applied load anymore and the test was stopped. Specimens PRef1 and PRef2 reached, respectively, maximum lateral loads of +57.2/-42.7kN and +54.7/-41.8kN (the minus sign referring to cycles downwards, and the plus sign to cycles upwards), at drifts of +70/-58.7mm and +58/-58.5mm (during the first cycle at a 4 %drift ratio).

Retrofitted specimens produced sporadic popping sounds at the beginning of tests as the composite jackets and laminates were stressed. For all specimens, steel longitudinal reinforcements started buckling for a drift ratio of 2%. Then, from the lateral displacement corresponding to the drift ratio of 6% until the end of the test, it was possible to hear the tensile rupture of the different longitudinal rebars. The first confinement strip ruptured at welded corner (Fig. 7) during loading cycle at a 6% drift ratio for specimen PCL1 and at a 10% drift ratio for specimen PCL2. PCLA1 and PCLA2 showed the same failure process as PCL1 and PCL2 (quick debonding of laminates, buckling and tensile rupture of longitudinal rebars, etc.), but a premature failure of anchorages also appeared for these two specimens. Indeed, when the anchored plates were loaded in compression (for example, the anchored plates on the upper face, when the specimen was applied cycles upwards) during the first cycles, a crushing of end-anchored parts happened.

PCL1 reached maximum loads of +54.1/-43.8kN at drifts of +40.6/-41.5mm (during the first cycle at a drift ratio of 2%) and PCL-2 reached maximum loads of +57.1/-45.3kN at drifts of +76.1/-42mm (during the first cycle at a drift ratio of 4%). PCLA1 reached maximum loads of +60.8/-59.8kN at drifts of +36.5/-41.4kN, and PCLA2 reached maximum loads of +59.8/-59.3kN at drifts of +33.9/-39.7mm.

For reference specimens PRef1 and PRef2, the test was terminated after successfully completing the loading cycles corresponding to a peak drift ratio of 6%, whereas retrofitted specimens were tested until a drift ratio of 10%. The ultimate drift displacement is defined as the displacement recorded at failure.


PRef1 PRef2


PCL1 PCL2


PCLA1 PCLA2

Figure 7. Specimens after testing

3.2 *Strength – lateral displacement hysteretic response*

Figures 8-10, show the load-lateral displacements curves obtained for the different specimens. In these figures, the legend “lateral displacement” refers to the lateral deflections of the specimen measured at the height of 2142.5mm. Considering that a good reproducibility of tests was obtained for each strengthening configuration, and for a better legibility of the graph, results of only one specimen by series are plotted on Figure 11, which shows the applied lateral force versus displacement drift ratio envelope curves for three specimens.

On Figure 11 it can be observed that the ultimate lateral displacement of PCL2 and PCLA2 is about twice the ultimate displacement of reference specimen. From this result, it can be concluded that the two strengthening configurations are efficient to enhance structural ductility. However, considering that PCL2 and PCLA2 exhibit similar post-peak behaviour, it can be then concluded that the confinement seems to be here the main strengthening system to enhance the ductility of specimens.

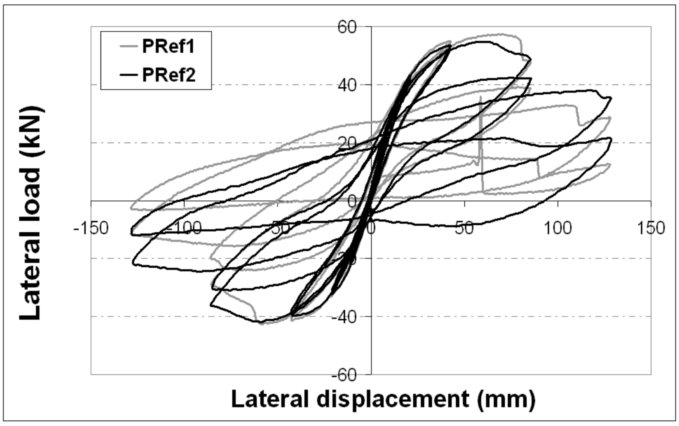


Figure 8. Load-lateral displacements curves for reference specimens.

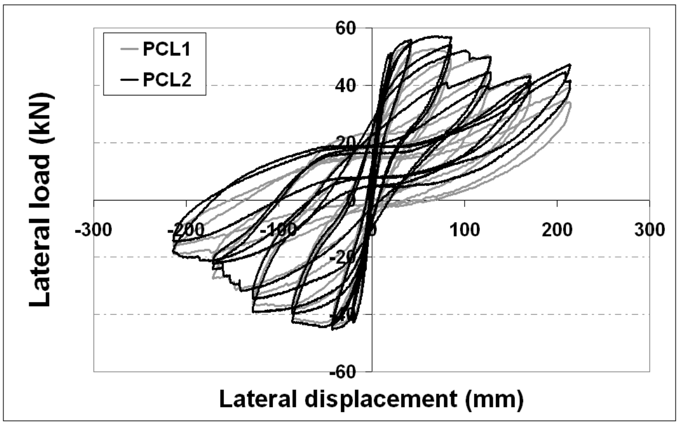


Figure 9. Load-lateral displacements curves for specimens PCL1 and PCL2.

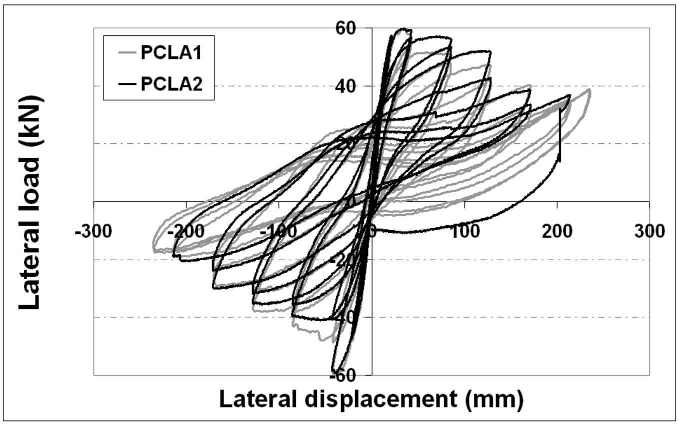


Figure 10. Load-lateral displacements curves for specimens PCLA1 and PCLA2.

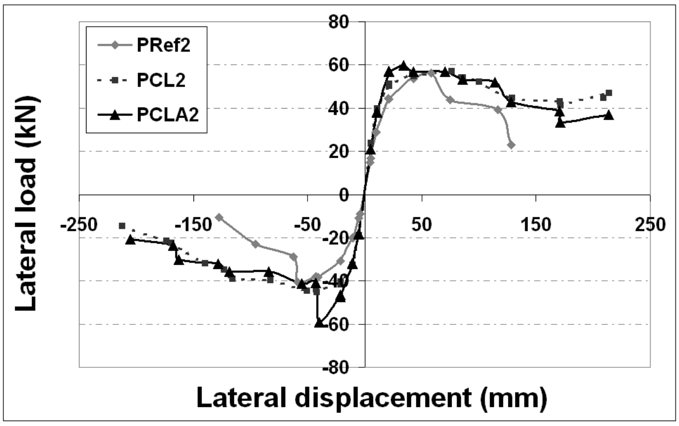


Figure 11. Load-lateral displacements envelope curves

Concerning the strength enhancement, Figure 11 reveals that PCLA2 exhibits a maximum lateral load about 40% higher than the maximum load obtained for PCL2 or PRef2 (considering downwards deflection). However, as described previously, a premature failure of the CFRP anchoring was observed on specimens PCLA1 and PCLA2 resulting in a instantaneous inefficiency of the flexural strengthening. Thus, even if PCLA2 could withstand higher lateral loads, the anchor failure leads to similar post-peak behaviour between all strengthened column, whatever the strengthening configuration. Then, envelope curve of PCLA2 became similar to that of PCL2 after a few cycles (after crushing of anchors).

4 CONCLUSIONS AND PERSPECTIVES

The behaviour of RC columns strengthened with externally bonded FRP and subjected to a seismic loading was investigated. The effectiveness of flexural strengthening achieved by FRP plates bonded longitudinally and anchored at the column-stub junction was particularly studied. 6 realistically sized RC columns were constructed in the laboratory. Two strengthening configurations were tested (2 specimen for each configuration and 2 reference specimens without any strengthening): columns combining CFRP confinement with bonded longitudinal CFRP plates for the flexural reinforcement, and columns strengthened with the same configuration, but the CFRP plates being anchored. The specimens were tested under constant axial load representing the expected gravity service load and lateral reversed cyclic load simulating earthquake force. Finally, within the conditions and the limits of this study, the following conclusions were drawn:

- in terms of ductility better performances are observed for strengthened columns compared to reference specimens, the confinement being the major strengthening system,
- the damaged zone is concentrated at the junction footing-column, with a plastic hinge located in this zone
- the anchored plates can provide an increase of the lateral load carrying capacity of 40% to strengthened columns. But this benefits is limited due the premature failure of the anchorages by crushing.

Considering these conclusions, it appears that the proposed anchoring system for FRP laminates is a promising constructive disposition for the seismic strengthening of columns. However it still needs to be improved. in order to avoid any premature failure of the anchorages and allowing then to provide larger bending moment capacity to strengthened columns.

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