DEVELOPMENT OF HYBRID COMPOSITE PLATE (HCP) FOR THE REPAIR AND STRENGTHENING OF RC ELEMENTS

Esmaeel Esmaeeli, Joaquim A.O. Barros, Hadi Baghi and José Sena-Cruz

ISISE, Dept. of Civil Engineering, University of Minho, Guimarães, Portugal

Abstract

Hybrid Composite Plates (HCPs) made of a Strain Hardening Cementitious Composite (SHCC) and reinforced with Carbon Fiber Reinforced Polymer (CFRP) materials are developed by taking the synergetic advantages of SHCC and CFRP for the retrofitting of reinforced concrete (RC) structures. Thanks to the high ductile character of SHCC, this prefabricated plate can be attached to the substrate using a combination of adhesive and chemical anchors to assure an effective transference of forces between these elements, leading to a high mobilization of the tensile capacity of the CFRP. This paper reports the most relevant results of a series of experimental tests performed to assess the effectiveness of this innovative technique for the repair/strengthening of RC elements. Enhancements obtained in both shear and flexural capacity of strengthened RC beams, in shear capacity of a repaired RC beam, as well as in the repair of a severely damaged interior RC beam-column joint, have demonstrated the high effectiveness of this technique.

1. INTRODUCTION

The deterioration or deficient functioning of reinforced concrete (RC) structures can be caused by ageing effects on its intervening materials, design and/or construction inaccuracies or abnormal loading conditions not considered in the design phase or of unexpected intensity like those from seismic events. To restore, or even to increase the aimed working performance for this type of structures, fiber reinforced polymer (FRP) systems have been used with appreciable success during the last 25 years, mainly due to the well-known advantages of these materials (e.g., lightness and high tensile strength) and the associated strengthening techniques (easy and fast application, small interference on the dimensions of the structure to be retrofitted). However, FRP systems are susceptible to vandalism acts, and their properties can be negatively affected by high temperatures and some environmental conditions [1]. Furthermore, the strengthening effectiveness of FRP-based techniques also depends on the quality of the concrete substrate. Recently Esmaeeli et al. [2] demonstrated the efficacy of an innovative technique based on the use of Hybrid Composite Plates (HCP) for the retrofitting of short-span shear critical RC beams. This thin panel was composed of strain hardening cement composite (SHCC) reinforced with carbon fiber reinforced polymer (CFRP) sheet that was bonded to its inner face. This face of the HCP was then bonded to the lateral surfaces of the retrofitted beams by using an epoxy adhesive. Apart the favorable contribution of the SHCC for a more effective mobilization of the tensile capacity of the CFRP sheet, due to its strain hardening character, the SHCC also assures protection to the CFRP against high temperatures, environmental aggressiveness conditions and vandalism acts. Moreover, the SHCC contributed to the main load transfer mechanism, inclined compressive struts, in these short-span beams.

A new version of a HCP is proposed in the present work where the CFRP sheet is replaced by CFRP laminates that are introduced into thin grooves open on the SHCC layer and bonded with epoxy adhesive. CFRP laminates used to produce this system have a section of 10×1.4 mm^2. Due to a high sectional aspect ratio of these CFRP laminates, their high tensile capacity can be mobilized to the surrounding SHCC more efficient through the interface bond. This new hybrid prefabricated panel, herein designated as $HCP^{(L)}$, was used to explore its potentialities for the shear and flexural strengthening of RC beams, for the repair of a RC beam failed in shear and finally, the repair of a severely damaged interior RC beam-column joint. The main results of these experimental tests are presented and discussed.

2. MATERIAL PROPERTIES

In the following sections of this paper, unless specifically indicated, material properties are those herein reported. The self-compacting SHCC used to produce $HCP^{(L)}$ is a cement based mortar reinforced with 2% in volume of 8mm PVA fibers . The average tensile stress at crack initiation and the average tensile strength of the SHCC was 2.43 MPa and 3.35 MPa, respectively, with a tensile strain capacity higher than 1.3%. Details on mix development and tensile characteristics of the SHCC can be found in [3]. S&P 220 epoxy resin used to bond CFRP laminates into the grooves open on the SHCC and also to bond $HCP^{(L)}$ to the substrate, had an average tensile strength of 18 MPa with an average modulus of elasticity of 6.8 GPa measured on seven days cured of six dumbbell-shaped specimens. Average values of 2689 MPa, 1.6% and 165 GPa were obtained for the tensile strength, strain at rupture and modulus of elasticity of CFRP laminates (cross section of 1.4×10 mm^2), respectively.

3. STRESS TRANSFER MECHANISM IN $HCP^{(L)}$

Figure 1 shows the structure of two different types of $HCP^{(L)}$: (i) with only one layer of CFRP laminates; and (ii) with two layers of CFRP laminates. Basically, in a $HCP^{(L)}$ system the SHCC acts as a medium able to mobilize the high tensile capacity of the CFRP laminates and transfer effectively the stresses between the substrate and the $HCP^{(L)}$ by using anchors/adhesive or a combination of them. The high tensile strain capacity of SHCC proportionates a strain compatibility with CFRP laminate up to its rupture. This property of SHCC, together with its high post-cracking resistance up to quite high tensile strain, which is followed by the formation of diffused crack patterns allows the use of anchors for the installation of the $HCP^{(L)}$ without the occurrence of its premature failure at the bearing zones.

To assess the potential retrofitting capacity of this prefabricated panel, pullout tests on HCP$^{(L)}$ attached to RC blocks were executed. These RC blocks were fixed to a steel frame at their bottom face by constraining their longitudinal steel bars. Three sets of specimens were tested, by differing on their attaching configuration to the RC block. Details of these specimens along with the idealized test setups are shown in Figure 2.

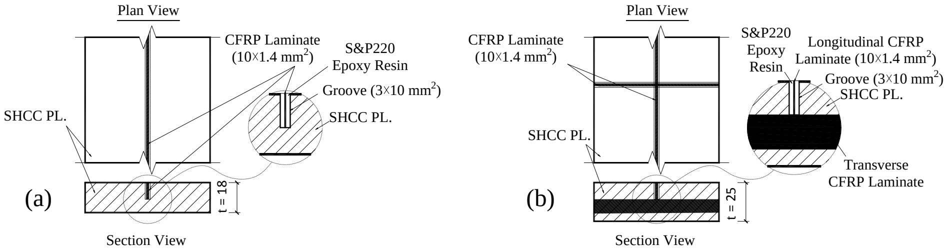


Figure 1 : Structure of HCP$^{(L)}$, (a) one layer of CFRP and (b) two layers of CFRP

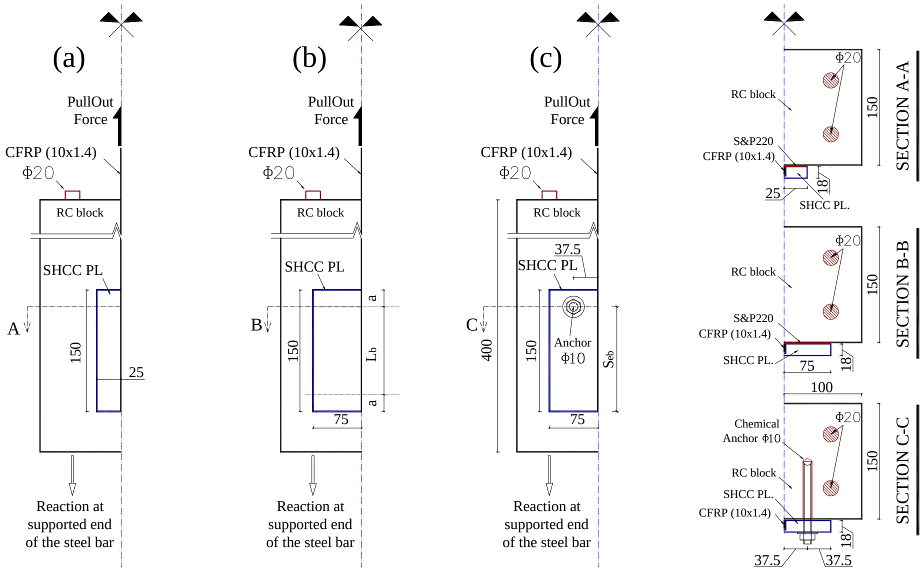


Figure 2 : Idealized test setup and details of the specimens for the pull tests ("L_b" is the bonded length of CFRP laminate into the groove of SHCC and "a" is the unbonded part; $f_c' = 38.2\ MPa$).

According to the results of these tests, an average shear strength of 2.39 MPa was obtained for the panel/substrate interface, with the occurrence of an inter-laminar shear failure in SHCC plate (**Error! Reference source not found.**a and Figure 3a). This mode of failure was expected due to the absence of coarse aggregate in SHCC, the low content of fibers oriented out of the casting plane, the high shear resistance of adhesive material, and the moderate shear strength of substrate concrete.

According to these experiments a bond length (L_b) of 90 mm for the CFRP/SHCC is sufficient to fully mobilize the tensile capacity of a CFRP laminate with a cross section area of 1.4×10 mm^2 (**Error! Reference source not found.**b and Figure 3b). When HCP$^{(L)}$ was supported on two anchors of 10 mm in diameter, installed in a distance of 90 mm and 120 mm from the bottom edge of HCP$^{(L)}$ (S_{eb} in **Error! Reference source not found.**c), tensile loads of 15 kN and 23.7 kN were mobilized, respectively. The HCP$^{(L)}$ failed with diagonal-tension cracks (**Error! Reference source not found.**c and Figure 3c).

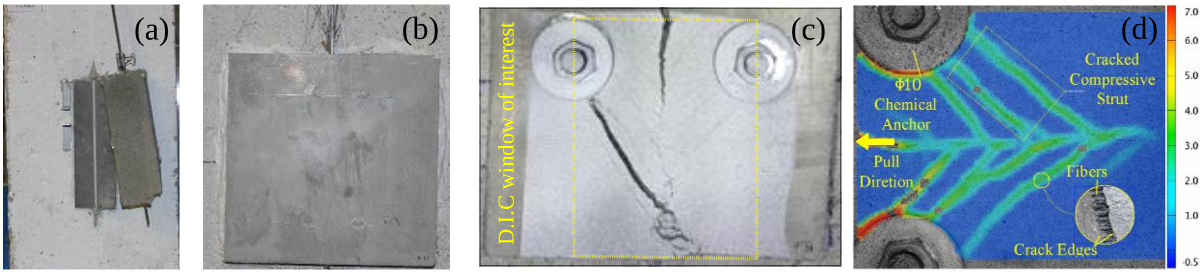


Figure 3 : Failure mechanism of HCP$^{(L)}$ under pullout tests, (a) inter-laminar shear failure inside SHCC (cohesive failure), (b) rupture of CFRP laminate, (c) diagonal-tension failure of compressive strut for HCP$^{(L)}$ (S_{eb}= 90mm), (d) major strain distribution analyzed using digital image correlation in a window of interest showed in side image (rotated 90 degrees) and the role of fibers in bridging cracks formed in compressive struts

Figure 3d shows the major strain field in the SHCC, at a load level of 94% of HCP$^{(L)}$ peak pullout load, obtained by Digital Image Correlation (DIC) analysis in a window of interest according to **Error! Reference source not found.**c and Figure 3c (S_{eb}= 90mm). According to this analysis, the presence of the chemical anchors promotes the formation of inclined compressive struts during the pullout process of the CFRP laminate. These compressive struts, of fish spine configuration, transfer the tensile force from the laminate to the anchors. This loading transference process is followed by the formation of diagonal cracks, whose opening is arrested by the fiber reinforcement mechanisms that promote the formation of several cracks, which contributes for the maintaining of the integrity of this zone up to a high loaded end slip.

4. RETROFITTING OF RC ELEMENTS

The assessment of the effectiveness of HCP$^{(L)}$ for the retrofitting of RC elements was followed by executing a series of experimental tests on some specimens. A summary of these experiments and their corresponding results are presented in this section.

4.1 Shear strengthening of short-span beams

Three point bending tests were carried out on three small-scale beams (150×150×600 mm^3). All RC beams had similar geometry and steel reinforcement arrangement. No transverse steel reinforcement was applied in the loading span (500 mm) of these beams that have a shear span ratio less than 2.5 (the ratio of the distance between the loading point and the support to the effective depth of the beam’s cross section). This complies with the configuration of deep beams where the main load transfer mechanism is assured by the formation of compressive struts from the loading point to the supports of the beam. The reference beam (CB) did not include any strengthening scheme. The other two beams were strengthened with SHCC plates and HCP$^{(L)}$s attached to their lateral faces. Details of these strengthening schemes along with designations attributed to each of these beams are shown in Figure 4. The obtained results in terms of load *versus* mid-span deflection relationship are presented in Figure 5a. In comparison to the maximum load carrying capacity of the reference beam (CB), the SHCC plates bonded to the lateral faces of the beam (BS) provided an increase of 74%. This increase was 126% in the BH beam where HCP$^{(L)}$s were used. The CB and BS beams presented a diagonal-tension failure of the compressive strut formed between the loading point and the left support (Figure 5b and Figure 5c), while the BH beam failed by the detachment of the concrete cover of the lateral faces of the beam that was maintained bonded to the HCP$^{(L)}$ (Figure 5d).

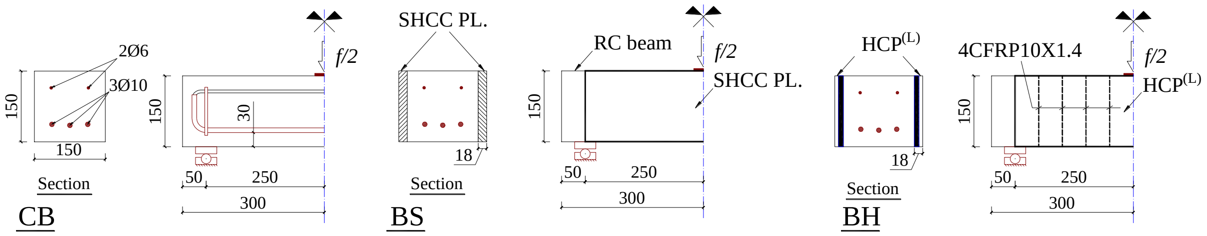


Figure 4 : Details of short-span beams (f_c': 38.2 MPa, $f_y^{\emptyset 10}$: 532 MPa).

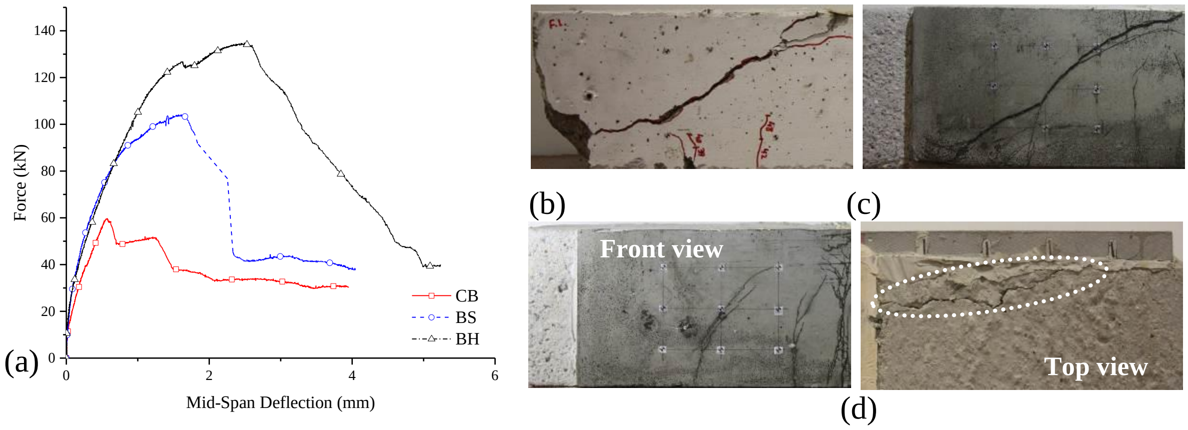


Figure 5 : Results of three-point bending tests with RC beams (a) load *versus* mid-span deflection, failure of compressive strut in (b) “CB” and (c) “BS”, and (d) lateral concrete cover detachment in “BH”

4.2 Flexural strengthening of RC beams

Two RC beams with the same geometry and steel reinforcement arrangement were subjected to a four point bending load configuration (Figure 6). The FB_R was the reference beam, while the FB_B beams was strengthened using HCP$^{(L)}$. The HCP$^{(L)}$, containing two longitudinal CFRP laminates, was attached to this beam’s soffit by means of only chemical anchors.

Test results of these beams in terms of load *versus* mid-span deflection are presented in Figure 7a. The strengthening technique assured an increment of 66% in terms of maximum load carrying capacity and an increase of 23% of the load carrying capacity corresponding to the yield initiation of the longitudinal steel bars. Although the strengthening technique did not alter the deflection corresponding to the yield initiation of the steel rebars, there was no visible crack on the surface of HCP$^{(L)}$ up to 10 mm of deflection, which corresponds to serviceability limit state. In fact, macro-cracks formed in the RC beams were transformed in a diffuse micro-crack pattern at the corresponding region on the HCP$^{(L)}$. Failure mode and crack pattern of each of the beams at the end of their tests are shown in Figure 7b and Figure 7c. According to these figures yielding of longitudinal rebars followed by compressive failure of concrete was the dominant failure of FB_R. For the case of FB_B, after yielding of longitudinal steel a splitting crack in the alignment of the anchors was formed.

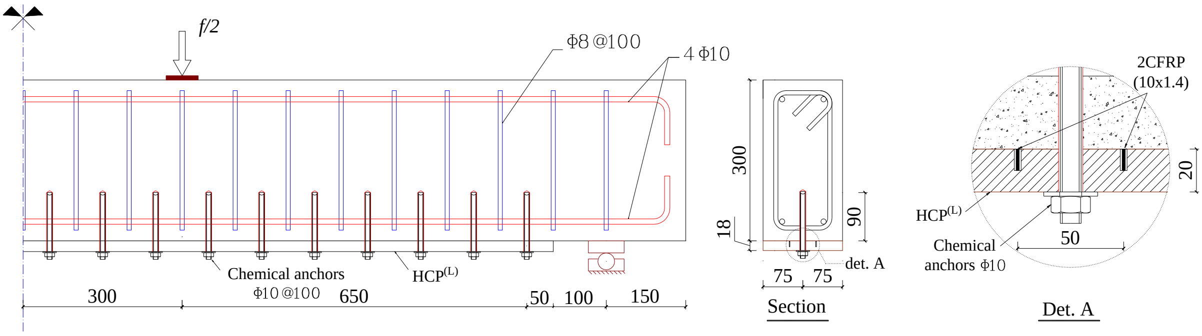
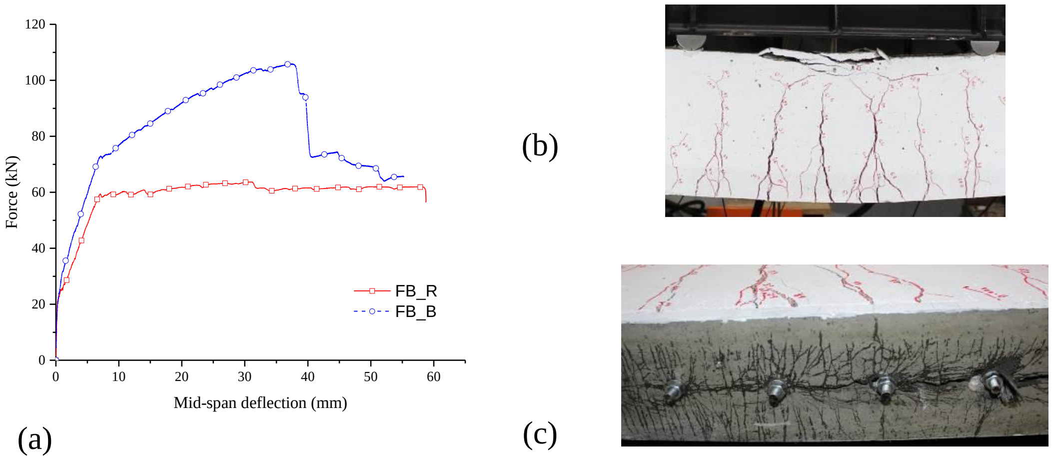


Figure 6 : Details of the beams, test setup, and the strengthening scheme (the reference beam has the same configuration but without HCP$^{(L)}$; f_c': 31.26 MPa,$f_y^{\emptyset 10}$: 529 MPa).



(a)

(b)

(c)

Figure 7 : Results of four-point bending tests (a) load versus mid-span deflection, (b) crushing of concrete of the reference beam (FB_R) and (c) splitting crack along the anchors in strengthened beam (FB_B).

4.3 Repair of shear-damaged RC beam

A repairing scheme based on attaching HCP$^{(L)}$s to the lateral faces of a shear-damaged RC beam was investigated. The virgin beam (FS_V) was subjected to a three point bending test, and after failing in shear was unloaded. Two HCP$^{(L)}$s were then attached to its lateral faces in the damaged region using a combination of epoxy adhesive and through bolts. The repaired beam, designated as FS_R, was subjected to the same test configuration adopted in its virgin state. Details of the beam, test setup and repairing scheme are shown in Figure 8. The load *versus* loaded-point deflection relationships for the virgin and repaired state are presented in Figure 9a. According to this figure the adopted repairing strategy provided an increase of 99% in terms of maximum load carrying capacity. This strengthening scheme has contributed for the recovering of 62% of the initial stiffness (measured as the slope of the initial linear portion of the load-deflection curves) of the beam in its virgin state. Failure modes of both virgin and repaired specimens are shown in Figure 9b and Figure 9c. Lateral concrete cover detachment was the governing failure mode for the repaired specimen.

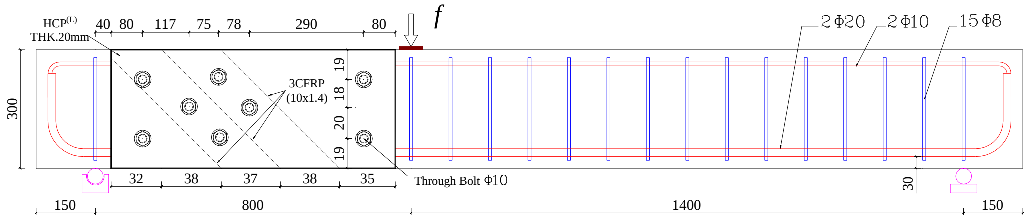


Figure 8 : Details of repaired beam (there was no transverse steel reinforcement in the critical shear span of the beam; a combination of epoxy adhesive and through bolts were used to fix the HCP$^{(L)}$ reinforced with 3 CFRP laminates; f_c' =31.26 MPa, $f_y^{\emptyset 20}$: 576MPa).

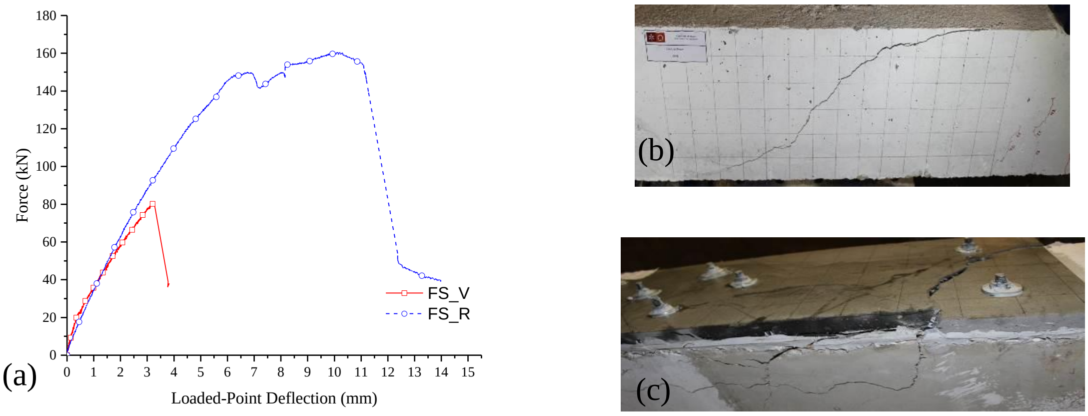


Figure 9 : Results of three-point bending tests (a) load *versus* loaded-point deflection, (b) shear failure of the virgin specimen (FS_V), (c) lateral concrete cover detachment (FS_R)

4.4 Repair of severely damaged interior RC beam-column joint

A severely damaged interior RC beam-column joint was selected between a series of damaged prototypes for assessing the effectiveness of HCP$^{(L)}$ for the repair of this type of elements. The state of the damages in this specimen, before the repair, is illustrated in Figure 10. The damage in the specimen was due to the experimental test performed using a simultaneous constant axial load and cyclic lateral displacement history applied to the top of the superior column when it was in virgin state. Pre-seismic oriented code practices were used to design this full-scale specimen, therefore only gravity loading considerations were taken into account, and the reinforcement was constituted by plain steel bars. The geometry and the steel reinforcement arrangement of this specimen are presented in Figure 11. Additional details on test setup, loading history, material properties, geometry and steel detailing can be found elsewhere [4].

For the repairing two prefabricated "Cross" shape HCP$^{(L)}$s were applied to the front and rear faces of this damaged specimen according to the scheme represented in Figure 11. The repairing procedures were executed in two steps, with the specimen placed horizontally, the first one on the front face and then, after turning the specimen, on the rear face. Before installing the HCP$^{(L)}$, the too damaged concrete at corners of the specimen was removed and replaced by a grout. The HCP$^{(L)}$ was attached to the relatively roughened surface of substrate by using a combination of epoxy adhesive and chemical anchors.

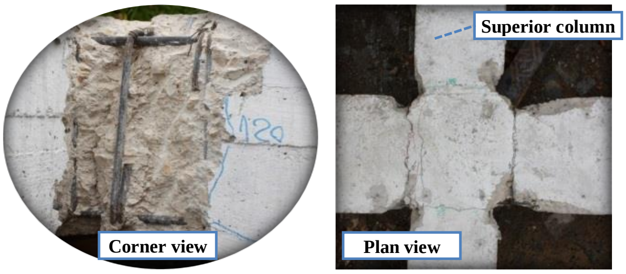
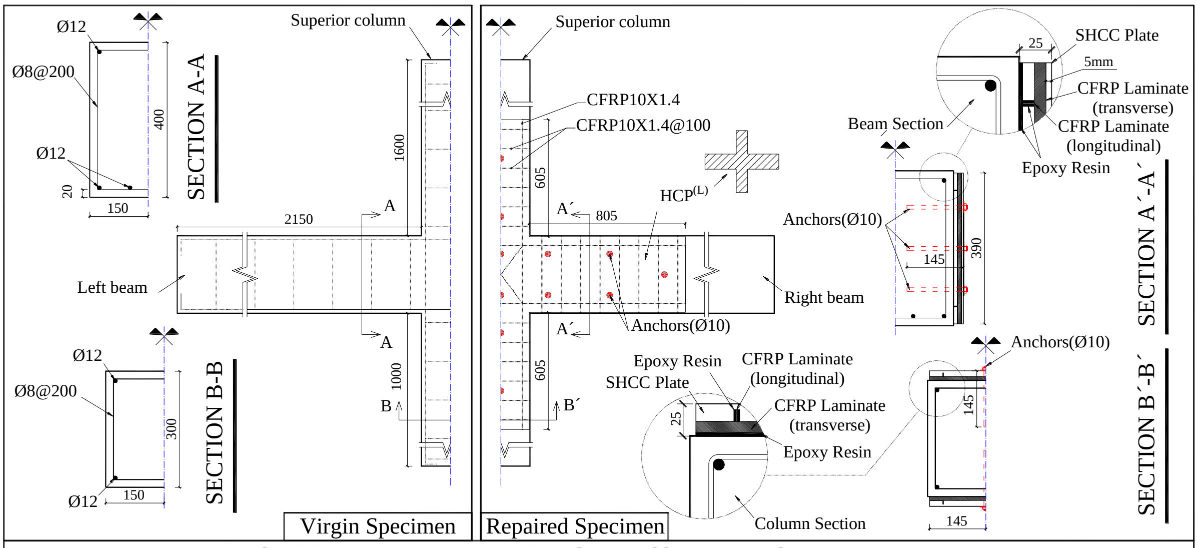


Figure 10 : Level of damage in the prototype before its repairing



(i) Drawings are not to scale; (ii) Measures are in mm; (iii) Plain steel bars are used.

Figure 11 : Configuration of the interior beam-column specimen and the repair scheme

The repaired specimen was tested using the same test setup and loading pattern used when testing it in the virgin state. The hysteresis responses and the corresponding envelope curves for the specimen in the repaired and virgin states are presented in Figure 12a. The idealized test setup is also shown in this figure. According to these results, the repaired specimen presented a superior response with an average increase of 21% in the maximum lateral load carrying capacity (considering the push and pull loading directions). When repaired, the specimen has dissipated more energy (the areas enclosed inside the hysteretic loops) than when in its virgin state. For instance, for a lateral displacement of 120mm (corresponding to a drift of 4%) the repaired specimen has dissipated 23% more energy than its virgin state. The specimen was failed with diagonal cracking and bulging of the HCP$^{(L)}$ at the joint region (Figure 12b).

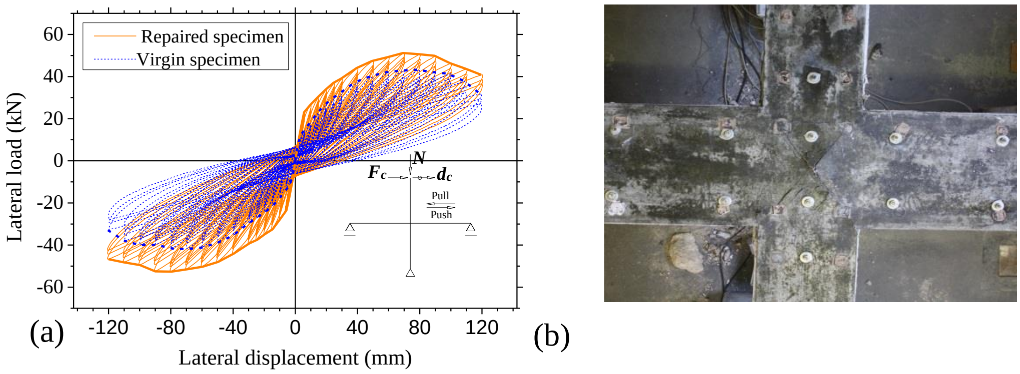


Figure 12 : Results of cyclic tests (a) Hysteretic responses and (b) damage state at the end of the test of repaired specimen

ACKNOWLEDGMENTS

The study presented in this paper is a part of the research project titled “PrePam –Pre-fabricated thin panels by using advanced materials for structural rehabilitation” with reference number of PTDC/ECM/114511/2009. The first author acknowledges the PhD scholarship SFRH/BD/65663/2009 provided by FCT. The authors also thank the collaboration of the following companies: Sika for providing the sand, Grace for the superplasticizers, Dow Chemical Co. for viscous modifying agents, SECIL for supplying the cement, ENDESA Compostilla power station for the fly ash, CiviTest for contribution in the execution of short-span beams, and Prof. Humberto Varum for supplying the beam-column joint and the corresponding results.

REFERENCES

[1] Benmokrane B, Mohamad HM. Durability Issues of FRP for Civil Infrastructure. In: Minho Uo, editor. 11th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS11). Guimaraes2013. p. 11-4.

[2] Esmaeeli E, Barros JAO, Baghi H. Hybrid Composite Plates (HCP) for Shear Strengthening of RC Beams. In: Minho Uo, editor. 11th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS11). Guimaraes2013. p. 11-4.

[3] Esmaeeli E, Barros J, Mastali M. Effects of curing conditions on crack bridging response of PVA reinforced cementitious matrix. 8th RILEM international symposium on fibre reinforced concrete: challenges and opportunities (BEFIB2012). Guimaraes, Portugal2012.
[4] Fernandes C, Melo J, Varum H, Costa A. Cyclic Behavior of Substandard Reinforced Concrete Beam-Column Joints with Plain Bars. ACI Structural Journal. 2013;110(1):11.