



## NOVEL PREFABRICATED PANELS FOR THE REPAIR OF DAMAGED INTERIOR RC BEAM-COLUMN JOINTS

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**ABSTRACT:** A novel prefabricated panel is introduced for the repair and strengthening of damaged interior RC beam-column joints. This prefabricated hybrid composite plate (HCP) is made of a Strain Hardening Cementitious Composite (SHCC) reinforced with CFRP materials. Besides the higher durability of this system when compared to EB-FRP, thanks to the high ductility of the SHCC, anchors can be used in combination with adhesive to attach the HCP to the concrete substrate. The first section of this paper reports the methodologies to apply HCP for the repair of two severely damaged interior RC beam-column systems. To evaluate the performance of this rehabilitation technique, the repaired specimens were subjected to the same loading pattern as it was imposed to their virgin states. Since both repaired specimens showed a higher lateral load and energy dissipation capacities than the corresponding values in their undamaged state, the effectiveness of the HCP for the repair of damaged interior beam-column joints is proved.

### 1. Introduction

There is a high possibility of occurring severe damages in the components of the gravity load designed (GLD) structures during an earthquake event. However, there are many structures whose social and cultural relevance recommend restoring and enhancing their performance after an earthquake occurrence (if they have not collapsed); such is the case of hospitals, bridges, museums and monuments.

Studies made during last decades, demonstrated the deficiencies of the beam-column joints of GLD structures against lateral loads (Fernandes et al., 2013, Pampanin et al., 2002). Among different strengthening and rehabilitation techniques proposed for these elements, the use of Fiber Reinforced Polymers (FRPs) has been widely accepted (Engindeniz et al., 2008, Esmaeeli and Danesh, 2008). However, these systems still susceptible to vandalism acts, high temperatures, detrimental environmental conditions, and quality of the substrate (Benmokrane and Mohamad, 2013), since they can debond prematurely.

To overcome these deficiencies, a Prefabricated Hybrid Composite Plate (HCP) was developed, which is composed of a thin Strain Hardening Cementitious Composite (SHCC) plate reinforced with CFRP (Esmaeeli et al., 2013a). The CFRP can be used as externally bonded, HCP<sup>(s)</sup>, or near surface mounted, HCP<sup>(L)</sup>, to reinforce the face of the HCP that will be in contact with the substrate. The SHCC is a mortar reinforced with discrete fibers able of developing a post-cracking tensile resistance higher than its stress at crack initiation and a tensile strain at macro-crack localization that generally exceeds 1.5%. The SHCC is designed to be an effective medium for the transference of the tensile stresses through the CFRP material to the concrete substrate, especially when chemical anchors are used in combination with the adhesive to attach the HCP to the substrate. The high post-cracking ductility of SHCC assures diffuse crack propagation around the anchoring regions, preventing stress localization and premature fracture of the plate.

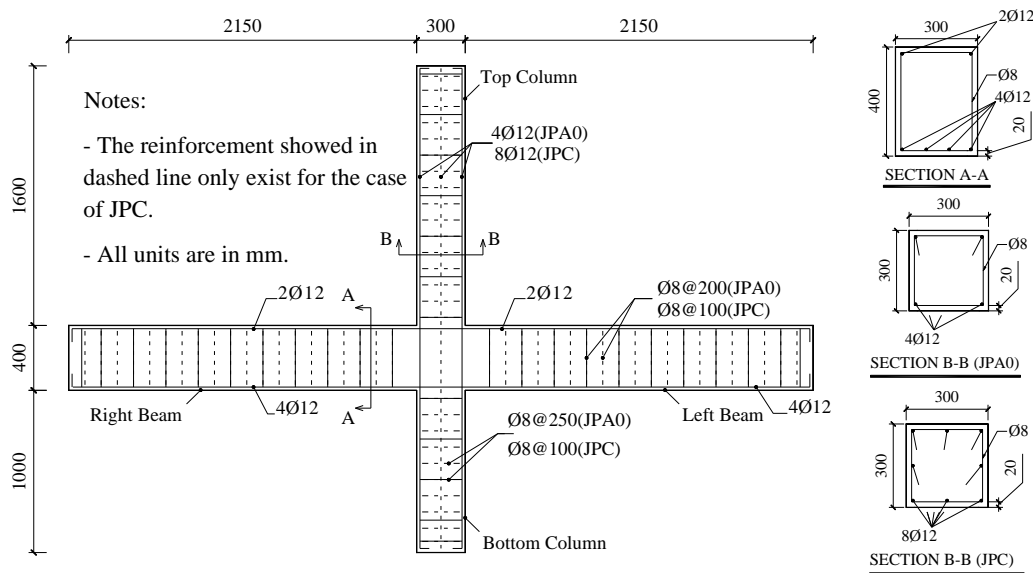
This paper reports the performance of the HCP, as a novel system, on the retrofitting of severely damaged interior RC beam-column systems. Two different configurations of the HCP system were applied to two damaged full-scale beam-column joints; each one represents framed elements of GLD buildings. The damages in these specimens were consequence of the lateral cycles of displacements imposed to the top of their upper column in a previous experimental program (Fernandes et al., 2013).

Both the repair methodologies and the performance of the repaired specimens are presented and discussed.

## 2. Background and Details of Damaged Specimens

Two damaged interior RC beam-column joints, namely JPA0 and JPC, are selected between a series of already tested specimens (Fernandes et al., 2013). Full-scale interior beam-column joints were reinforced with plain steel bars to be representative of the reinforcement generally found at construction practices before the 1970s. No transverse reinforcement was placed in the joint region and the stirrups of the beams and columns had 90° hooks.

The details of the geometry and configurations of the specimens are shown in Fig. 1. For JPC more four longitudinal bars for the column and also closer spacing for beams stirrups was adopted as compared to JPA0.



**Fig. 1 - Details of Adopted Configurations for the Interior Beam-Column Joints**

An average compressive strength of 23.8 MPa was obtained in cubes of 150 mm edge made with the same concrete used to build the specimens. These specimens were subjected to the cycles of the lateral displacements imposed to the extremity of the upper column at the presence of a constant gravity load at the same point. The lateral loading history, with maximum drift of 4%, was composed of 48 incremental displacement-controlled cycles. The constant axial load at the top of the column was 450 kN to simulate a gravity load of 20% of the nominal compressive capacity of the column. Details of specimens, materials characterization, test setup and loading history can be found elsewhere (Fernandes et al., 2013).

At the end of the test, the relevant damages were localized at the beams at vicinity of connecting zones to the columns (Fig. 2). Also cracks along the interfaces of the columns with the joint region, with minor importance, were observed. The premature loss in beams bending resistance, as a consequence of deficient bond between smooth longitudinal bars and surrounding concrete was reported as the failure mode for both specimens.

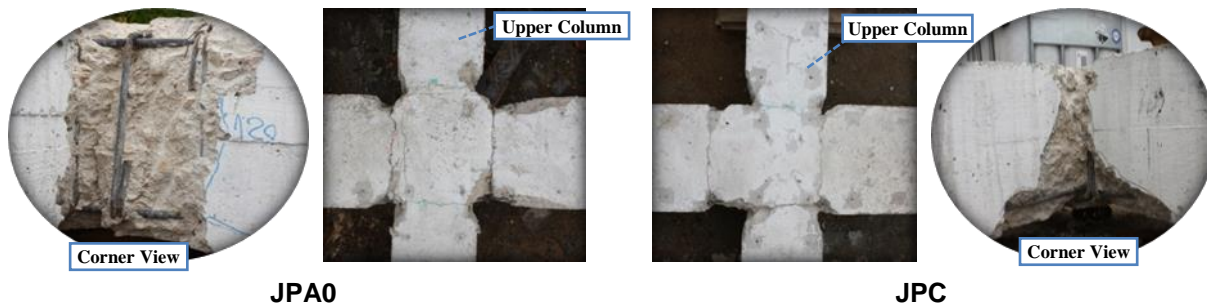


Fig. 2 - Damage Extent and Distribution before Repairing

### 3. HCP Fabrication and Retrofitting Configuration

The schematic 3D views of both specimens after repair are shown in Fig. 3a and Fig. 3b. For both specimens, a cross-shape HCP<sup>(L)</sup> was attached to their front and back faces by means of epoxy resin and mechanical anchors. For the case of JPC, also L-shape HCP<sup>(S)</sup> was attached to the lateral faces of the beams and the columns in the joint region. For the repaired JPA0 and JPC specimens the designation of JPA0-R and JPC-R was assumed, respectively.

The cross-shape plate and the components of the L-shape HCP were casted inside wooden molds. The SHCC material was composed of Cement, Fly ash, Fine Silica Sand, Chemical Admixtures, Water and 2% in volume PVA fibers. Details of SHCC composition, adopted mixing and curing procedures, and properties at fresh and hardened states can be found in (Esmaeeli et al., 2013a, Esmaeeli et al., 2013b). For the case of cross-shape HCP, the longitudinal and transverse grooves, of approximately 5 mm width and with two different depths, as depicted in Fig. 3c, were cut into the top face of the cross-shape plate. After filling the grooves partially with a high viscosity epoxy resin (S&P 220), CFRP laminates, with cross section of 10×1.4 mm<sup>2</sup>, were placed in their positions following the common procedure known for the NSM technique. According to the results of the tensile tests on the CFRP laminates, the average values of 2689 MPa, 1.62% and 165 GPa were determined for their tensile strength, tensile strain at fibers fracture and modulus of elasticity, respectively.

According to the details of L-HCP<sup>(S)</sup>, illustrated in Fig. 3d, unidirectional carbon fabric was externally bonded along the length of the plates to offer additional flexural strengthening for the beams and the columns of JPC-R. In addition, SHCC plates have high potential for the shear strengthening of RC elements (Esmaeeli et al., 2013a). The bonding procedure of carbon fabric to the SHCC plates followed the common EB-FRP technique. However, only the contact face of carbon sheet and the top face of SHCC plate were impregnated with low viscose resin epoxy (S&P 50/55). The relevant properties of carbon fabric and resin epoxy are reported in (Esmaeeli et al., 2013a).

### 4. Retrofitting Methodology

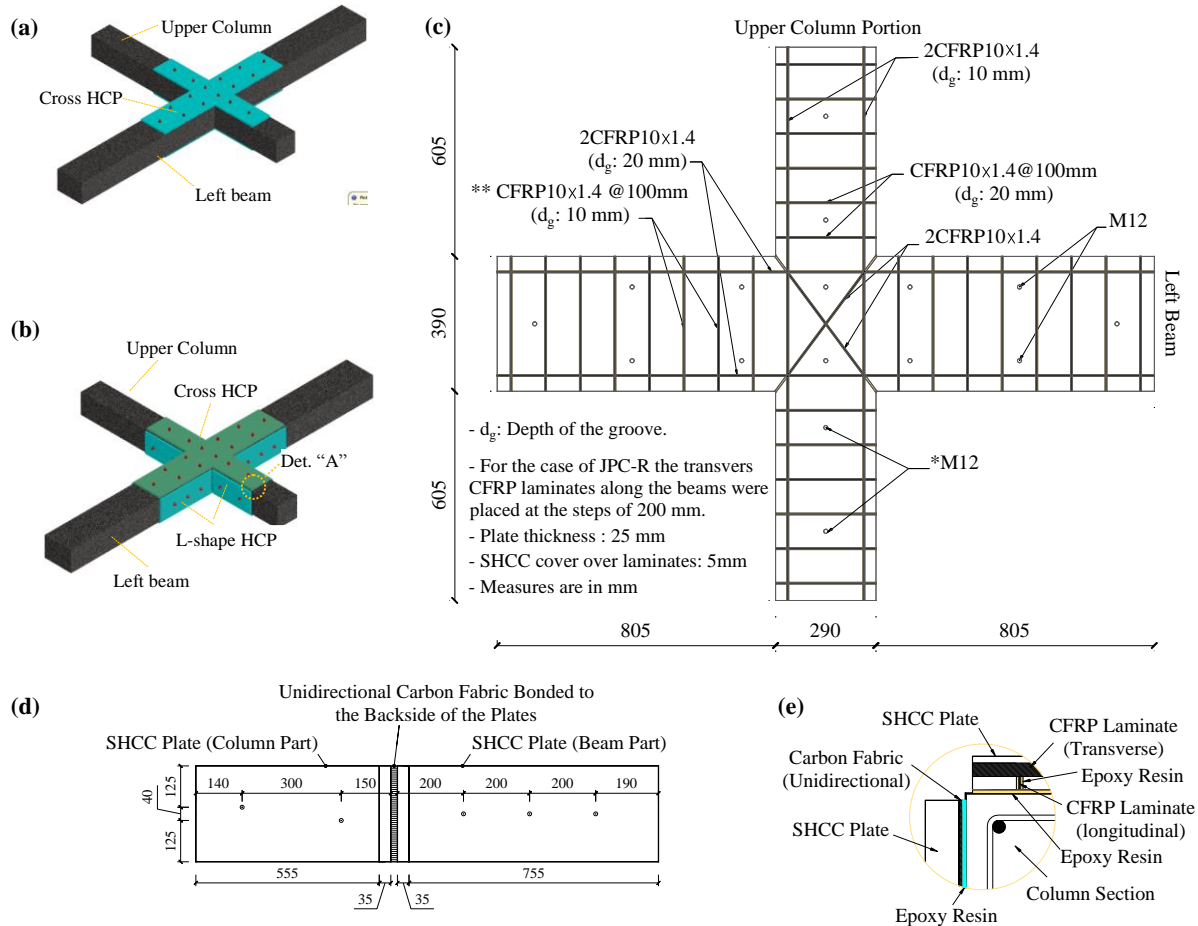
All the repairing procedures were applied to the horizontally placed specimens. For both specimens, the damaged concrete at the corners was removed, and then air pressure was used to clean the surfaces. The visible cracks were sealed by injecting a low viscosity high strength epoxy resin (Sikadur®-52N). To reconstruct the corners at the joint regions a premixed cementitious grout was used (SikaGrout-213).

Utilizing a hand-held scabblers, the concrete substrate was slightly roughened to improve the bond between HCP panel and substrate.

To install the chemical anchors, holes of 12 mm diameter and 120 mm depth were drilled at their predesigned positions in the beams, columns and joint region. These holes were carefully cleaned by air pressure before injecting a fast curing bonding agent. Just after injecting the bonding adhesive (Hilti HIT-HY 200-A), metallic anchor rods (steel grade 8.8) of 10 mm diameter were mounted inside the holes.

The same type of high viscosity epoxy resin, used to bond CFRP laminates into the grooves of HCP, was used to bond HCPs to the specimens. The HCP was then placed on the specimens, and after inserting

the washers the nuts were tightened slowly. This allowed a uniform flow of adhesive between the contact faces, also filling the existing gap between the holes of HCP and the anchors. All these procedures were done during working time of the epoxy adhesive. After curing period of epoxy resin, a torque of 40 N-m was applied to the nuts to increase the confinement of the core concrete and minimize any possible sliding between the HCP and the concrete. To attach L-shape HCP<sup>(s)</sup> to the lateral faces of the beam and column, low viscosity epoxy resin (the same type used to impregnate and bond FRP fabric to the SHCC plates) was applied to the both contact faces at each intersecting corner of the elements. The procedure for tightening the nuts of the anchors adopted in the cross-shape HCP was also followed.

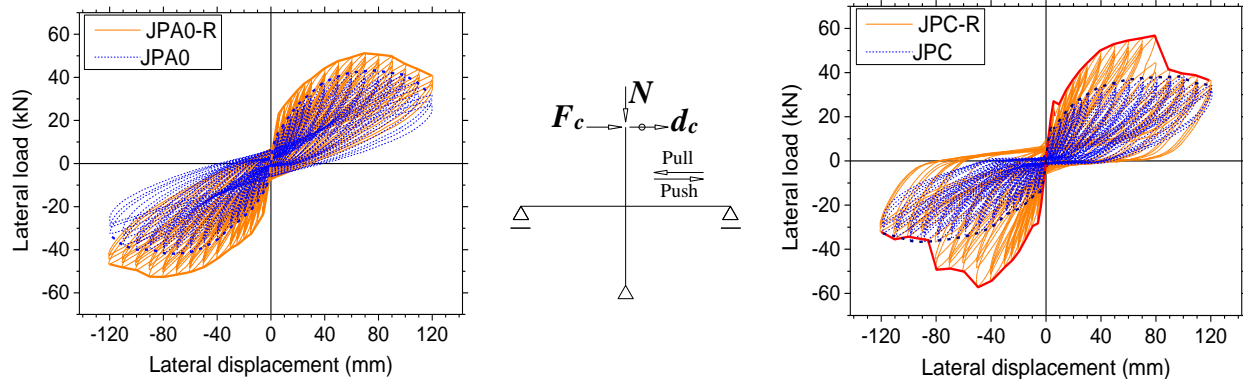


**Fig. 3 - Repair Configurations and Details of HCP a) Schematic 3D View of JPA0-R b) Schematic 3D View of JPC-R c) Plan View of the Contact Face of Cross-Shape HCP<sup>(L)</sup> d) Details of L-shape HCP<sup>(s)</sup> Shown in Plan Expanded View e) Det. "A" According to 3D View Shown in (b)**

## 5. Performance of Repaired Specimens

Both repaired specimens were subjected to the same test setup and loading history that were used to characterize the response in their virgin state. For the virgin and corresponding repaired specimens, the hysteresis response in terms of lateral load versus column-tip displacement and its envelope are shown in Fig. 4. According to this figure both repaired solutions showed a higher lateral load carrying capacity than their virgin specimens. In addition, JPC-R presented lower pinching effect when compared to JPC.

The peak load of JPA0-R has increased 25.5% and 18.2% in the pull and push loading directions, respectively; while in JPC-R the values of 54.5% and 48.3% were obtained.

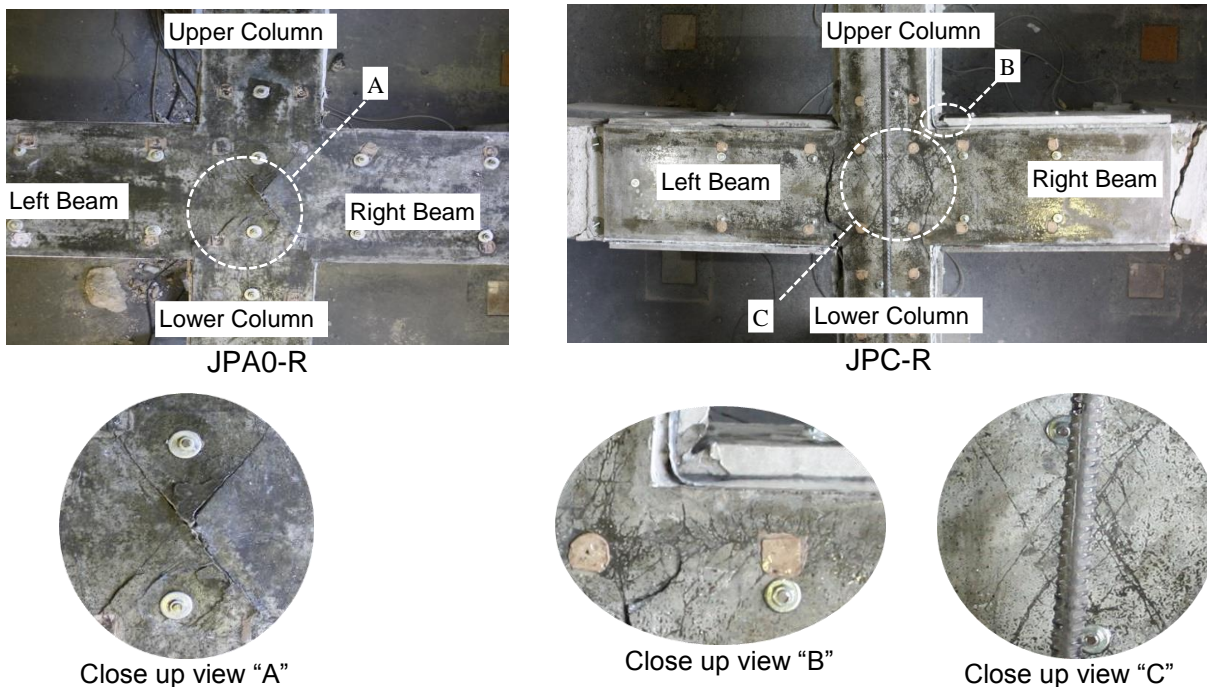


**Fig. 4 - Hysteretic and Enveloped Responses of the Repaired and Virgin Specimens**

The addition of the lateral panels has provided an increase of 22% in initial secant stiffness of JPC-R while in JPA0-R the property registered in its virgin state was restored.

At the end of the test (last cycle of 120 mm lateral displacement) of JPA0-R an increase of 23% on the accumulated dissipated energy with an absolute value of 52.3 kN.m was determined, while in the JPC-R this property was 54.03 kN.m, corresponding to an increase of 84%.

The governing failure mode of JPA0-R was based on the reduction of the shear capacity of the joint panel due to the formation of diagonal, horizontal and vertical cracks, and crushing the core concrete in this zone (Figure 5). For the case of JPC-R, the damages were mainly restricted to flexural cracks, formed initially out of the repaired regions of both beams, followed by further cracks at the vicinity of the framing section of left and right beams into the column. Therefore, JPC-R has reached its maximum lateral load carrying capacity after the formation of plastic hinges at the ends of the beams (Figure 5).



**Fig. 5 - Damage Distribution and Close-Up Views at the End of Testing the Specimens**



## 6. Conclusions

A methodology based on using the HCP to repair damaged interior beam-column joints is introduced. The high ductility of the SHCC prevented crack localization at the bearing regions of the anchors, allowing an effective mobilization of HCP strengthening capacity.

Both repairing solutions used in this research provided to the repaired specimens a superior performance than the corresponding specimens in virgin states. Higher load carrying capacity, higher energy dissipation capacity and higher initial stiffness (in the case of JPC-R) can be considered as the main mechanical achievements after applying the repair solutions.

## 7. Acknowledgements

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