Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 2863-2874

ECCOMAS Proceedia

COMPDYN 2021
8th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Streamed from Athens, Greece, 28 - 30 June 2021

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF FRP STRENGTHENED R/C BEAM-TO-COLUMN JOINTS SUBJECTED TO CYCLIC SEISMIC-TYPE LOADING

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Abstract

The behaviour of R/C beam-to-columns joints is experimentally and numerically investigated here. A 1:3 scaled specimen is constructed and tested under cyclic seismic type loading at the Laboratory of Strength of Materials and Structures (Aristotle University of Thessaloniki). The reinforcing details prohibit the appearance of shear failure modes. Thus, this study focuses on the bending behavior of the structural members forming the R/C joint as built and strengthened with FRP jacketing. The main focus of this study is the effectiveness of the strengthening system adopted here. The FRP layers are mechanically anchored using steel sections in the joint region in order to prevent the premature delamination of the FRP layers and the proper distribution of stresses through the anchoring system to the structural members. The observed at the laboratory behaviour is portrayed in terms of horizontal load versus horizontal displacement cyclic response as well as bending moment cyclic response that develops at the beams and columns forming this R/C joint. Apart from the observations of this R/C joint behaviour based on the laboratory measurements this R/C subassembly was numerically simulated. The used numerical models include detailed modeling of all material used assigned with nonlinear constitutive laws derived by material testing. By comparing the numerical results with the corresponding experimental measurements, the validity of the employed numerical simulation is validated. Both experimental and numerical results demonstrate the satisfactorily behavior of the strengthening system used here.

Keywords: R/C beam-to-column joints, Flexural behaviour, FRP strengthening, FRP jackets mechanical anchored

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ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi: 10.7712/120121.8680.19494

1 INTRODUCTION

The behavior of RC beam to column joints subjected to seismic type cyclic loading is studied here ([2], [7], [9]). For this purpose, a 1:3 scaled 3-D reinforced concrete (RC) joint specimen was constructed and tested at the laboratory of Strength of Materials and Structures of Aristotle University ([4], [5], [6]. [10], [11]), shown in figure 1. The experimental campaign included testing of the joint specimen at 3 stages. Firstly, the virgin joint, following the same specimen with retrofitted beams applying FRP sheets and the retrofitted specimens with both beams and columns strengthened using FRP sheets. In order to achieve the desired flexural strengthening of the structural members an anchoring system, formed by steel angles and bars around the joint core, is used to mechanically anchor the FRPS sheets.

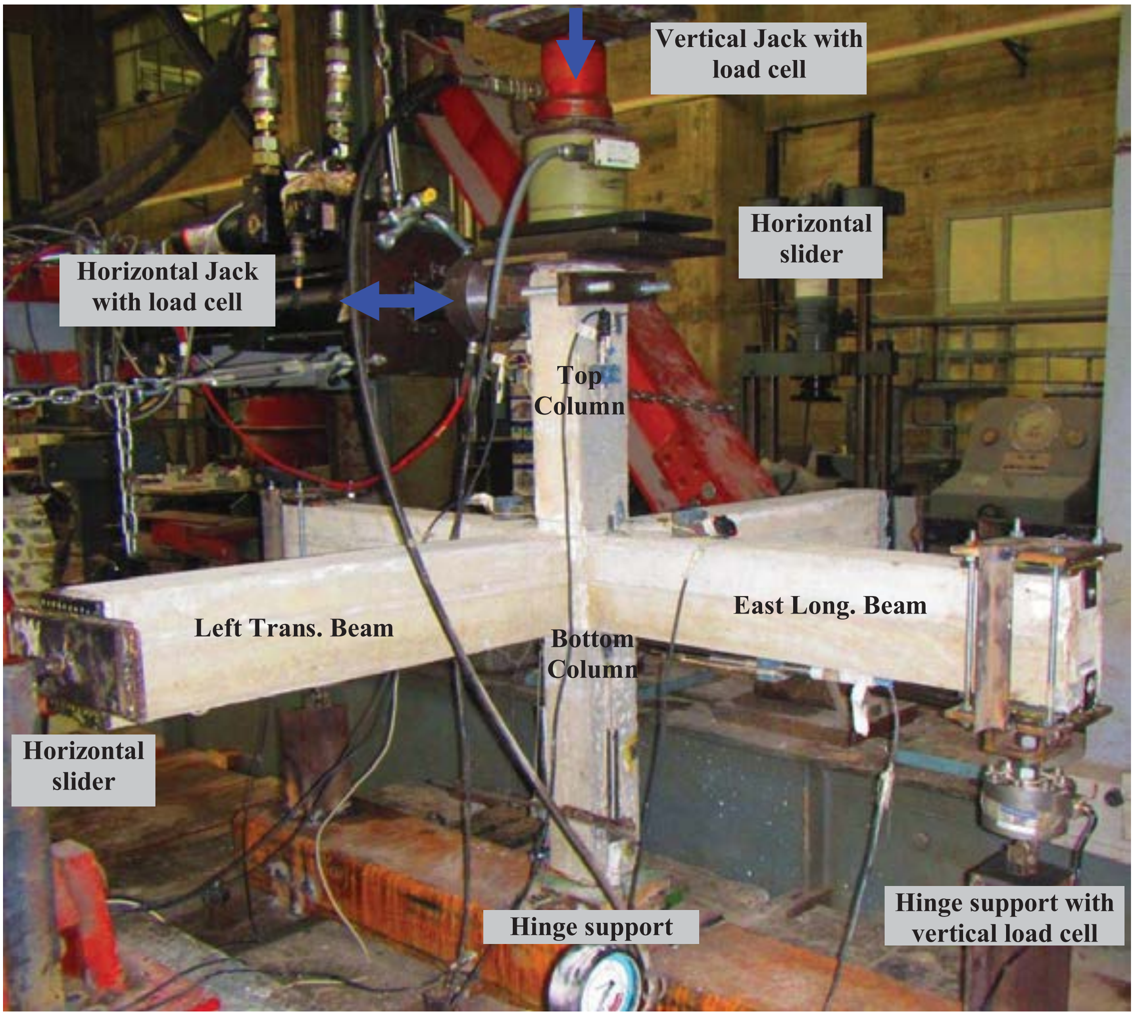

Figure 1. Interior RC joint model at Aristotle University – Experimental set-up.

In addition, 3-D numerical simulations of the tested specimens are also formed. These numerical models were subjected to monotonic loading instead of the cyclic loading sequence adopted at the experimental procedure resembling the envelope curve measured during testing. The reinforcing detailing of the tested specimen was such as to prohibit the development of any shear mode of failure. Therefore, this study focuses on numerically simulating the flexural response and mode of failures of the structural members that form this 3-D joint and not on the failure of the joint core. The numerical models follow a micro-modeling approach. The concrete volume is represented together with the embedded longitudinal and transverse reinforcement in an explicit way. Both materials are governed by nonlinear material laws which have been derived by material testing. For the strengthened models the FRPs sheets are simulated by shell elements given an elastic constitutive law, as the predominant mode of failure of the FPP sheets is the debonding from the structural member's surface and not the FRP's rupture. Thus, the debonding failure is predicted by the non-linear interface assigned between the FRP sheets and the concrete's surfaces given a tensile and shear stress limit. Nonlinear Static analysis (pushover analysis) is next conducted to determine ultimate load, deflection capability and failure mechanisms. By comparing the measured behaviour with the corresponding numerical predictions an attempt is made to check the validity of the employed numerical simulations.

2 FEATURES OF THE EXPERIMENTA SEQUENCE

In what follows a brief description of a 1:3 scaled specimen of RC beam-to-column joint is presented. This scaled model was constructed and tested at the Laboratory of Strength of Materials of Aristotle University. The specimens tested at Aristotle University did not include an RC slab. Details of this specimen are shown in figures 1 and 2. Further details are included in the published works by Manos et al. ([4], [5], and [6]). The East (E) and West (W) longitudinal beams have at their ends a hinge support which is also provided with a load cell capable of recording the vertical (upwards or downwards) reaction at these supports. The transverse beam North (N) and South (S) ends are free to deflect vertically as well as to slide horizontally at the E-W direction of the cyclic horizontal load (as is shown in figure 1) being in contact with a sliding surface at these locations. The horizontal movement of these transverse beam ends at the N-S directions is restrained. The end of the bottom column is restrained in the two horizontal as well as at the vertical direction though a hinged support.

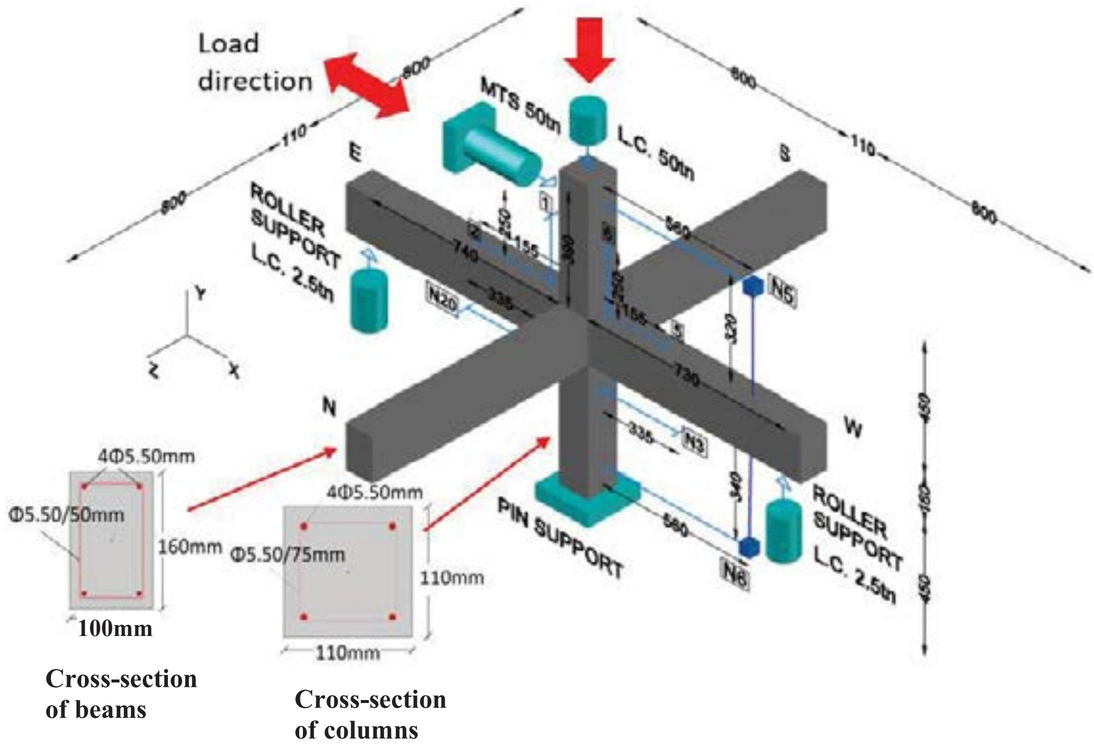

Figure 2. Interior RC joint model at Aristotle University – Experimental set-up and instrumentation scheme.

The top of the column is attached to the horizontal dynamic actuator capable of applying an imposed cyclic horizontal displacement in the E-W directions, as depicted in figures 1 and 2. The corresponding horizontal load is measured in this location by a horizontal load cell. Before any horizontal displacement is applied at the top of the column, a vertical load of 5.0tnf is applied through a jack and kept constant throughout each test. This load is monitored through a vertical load cell. These vertical load cell and jack were supported on top of the column through a set of sliders in such a way as not to restrict the horizontal movement of the top of the column (figure 1).
Apart from the load cells described before a number of displacement transducers were also provided in order to monitor the horizontal displacement of the top of the column at the point of horizontal cyclic load application as well as the horizontal displacement of the axis of the longitudinal beam. In addition, for both left and right longitudinal beams as well as top and bottom columns displacement transducers were provided capable of recording the relative extension or contraction of their top and bottom fiber near the joint in an effort to measure directly the rotation of each part of these structural elements during the flexural response of the whole RC joint. The geometry of the cross-sections of the beams and columns of this specimen are shown in figures 1 and 2 together with the details of the used reinforcing arrangement (see also table 1). The mechanical properties of the concrete and the steel used to build this specimen are listed in table 2 from axial compression and tensile tests with coupons taken during the construction. All RC beams and columns were provided with steel stirrups spaced in a way to prohibit the development of any form of shear failure. Both the longitudinal and transverse reinforcement was formed by smooth small diameter reinforcing bars according to similitude requirements ([4], [5], and [6]).

Columns		Longitudinal beams		Transverse beams	
width b (mm)	height h (mm)	width b (mm)	height h (mm)	width b (mm)	height h (mm)
110	110	100	160	100	160
Longitudinal Reinforcing bars Number / diameter (mm)					
4 / Ø5.5mm	2 / Ø5.5mm + 2 / Ø5.5mm				

Table 1. Details of RC joints (figure 1)

Steel reinforcing bars	Yield stress f_y (MPa)	Yield strain ε_y	Ultimate stress f_u (MPa)	Ultimate strain ε_u
Diameter Φ5.50mm longitudinal	311	0.08	425	0.22
Diameter Φ5.50mm (stirrups)	360	0.06	542	0.20

Table 2. Mechanical properties of used reinforcing bars (figure 1)

3 RESULTS AND OBSERVATION FROM THE MEASURED BEHAVIOUR

Figure 3a depicts the variation of the applied horizontal cyclic load versus the corresponding horizontal dislacement of the tested RC beam-to-column joint that develops either at the top of the column or at the axis of the longidudinal beam (approximately at the mid-height of the specimen). The maximum load measured was equal to 8.69KN. The observed damage at the East beam cross-section is depicted in figure 3b.

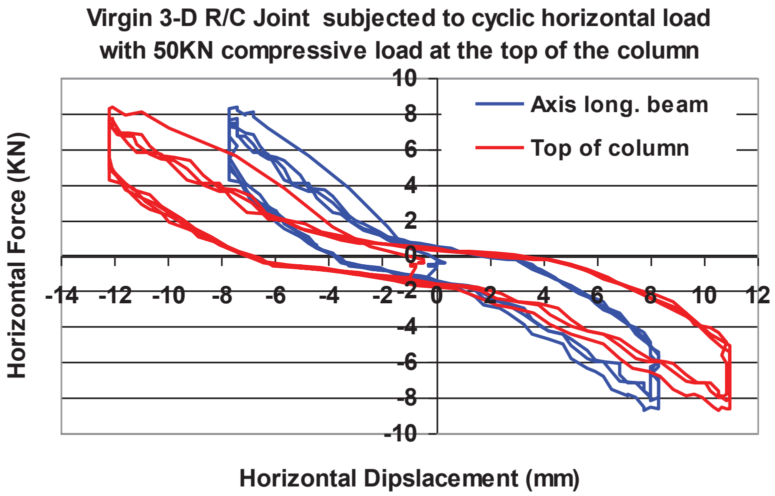

Figure 3. a) Cyclic load versus the corresponding horizontal dislacement response of the RC beam-to-column interior joint model tested at Aristotle University. b) observed cracking at the East beam cross-section

Following, a strengthening technique was adopted only for the longitudinal beams. In these members two CFRP sheets were bonded in both faces. Near the joint core steel angles were placed together with circular bars in order to support mechanically the FRP layers and prohibit the premature delamination as depicted in figure 4. The response of the specimen with strengthened beams in terms of applied load versus the horizontal displacement at the top of the column is given in figure 5 together with the observed damage pattern. In this case, the cracking occurs at the bottom column's cross-section near the joint core. The maximum load meassured was equal to 12.54KN.

Figure 4. The examined strengthening method: The anchoring system consisting of steel parts is placed around the joint area and the CFRP sheets are bonded to the longitudinal beam faces.

Next, the same strengthening techinque was used for the column sections as well. Three CFRP sheets were bonded at each face of the column members. Again the specimen was subjected to cyclic horizontal loading. The variation of the applied horizontal cyclic load versus the corresponding horizontal dislacement of the tested RC beam-to-column joint that develops at the top of the column is shown in figure 6. The maximum load observed was equal to 16.63KN.

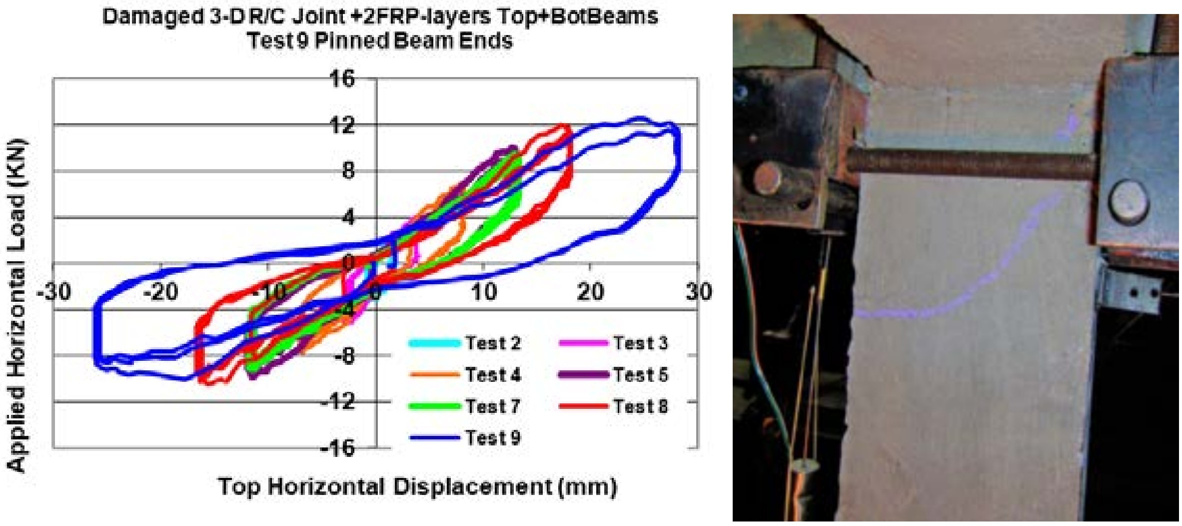

Figure 5. a) Cyclic load versus the corresponding horizontal dislacement response of the RC beam-to-column joint with FRP strengthened beams. b) observed cracking at the East beam cross-section

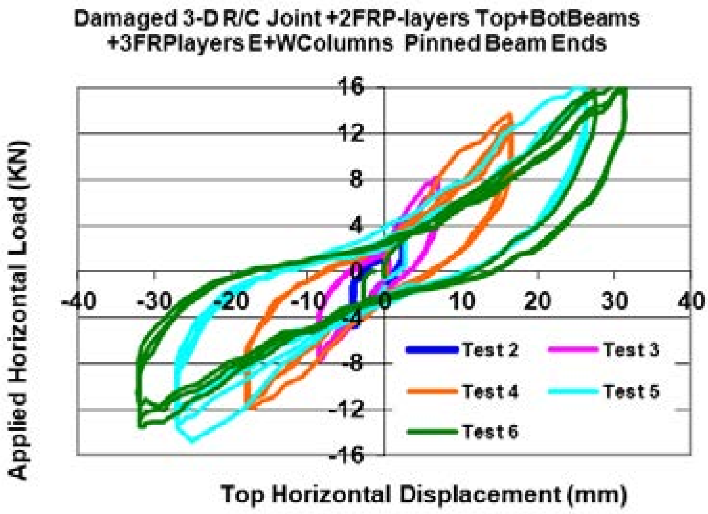

Figure 6. a) Cyclic load versus the corresponding horizontal dislacement response of the RC beam-to-column joint with FRP strengthened beams and columns. b) observed cracking at the East beam cross-section

4 NUMERICAL SIMULATIONS OF THE OBSERVED BEHAVIOUR

The numerical models discussed here utilize solid elements for the concrete volume as shown in figure 7a, together with wire elements for the numerical representation of the reinforcing bars as shown in figure 7b. Reinforcing bars were added within the concrete volume representing the actual reinforcing bars. The reinforcing bars were in full contact with the surrounding concrete through the relevant option (embedded region) provided in the software [1].

Non-linear constitutive laws were adopted in this numerical simulation for either the concrete or the steel elements. These stress-strain constitutive laws are based on the corresponding measured axial compression or tension tests performed with specimens taken during the construction of the RC beam-to-column mock-up at the laboratory of Strength of Materials and Structures of Aristotle University. The vertical load of 5.0tnf was initially applied and kept constant, while the horizontal force at the top of the column was applied in a gradually increasing manner, following a step-by-step time history pushover analysis. The response of the virgin joint model is given in figure 8 in comparison with the corresponding experimental measurements in terms of applied load versus the horizontal displacement at the top of the column. Figure 9 depicts the formation of plastic hinges at beam cross sections. As can be seen in this figure, large principal plastic strains appear to develop at the edges of the beam ends near the joint faces corresponding to areas of the concrete volume that develops flexural cracks (figure 9a). In figure 9b the reinforcing bars, at the same locations where the concrete develops high principal plastic strains, develop high tensile stress that have values larger than the yield stress of the reinforcing steel (fy=311MPa, Table 2). The yielded reinforcing longitudinal bars are marked with red color. Therefore, in this 3-D numerical simulation the plastic hinges in the beams are numerically represented explicitly in this detailed manner.

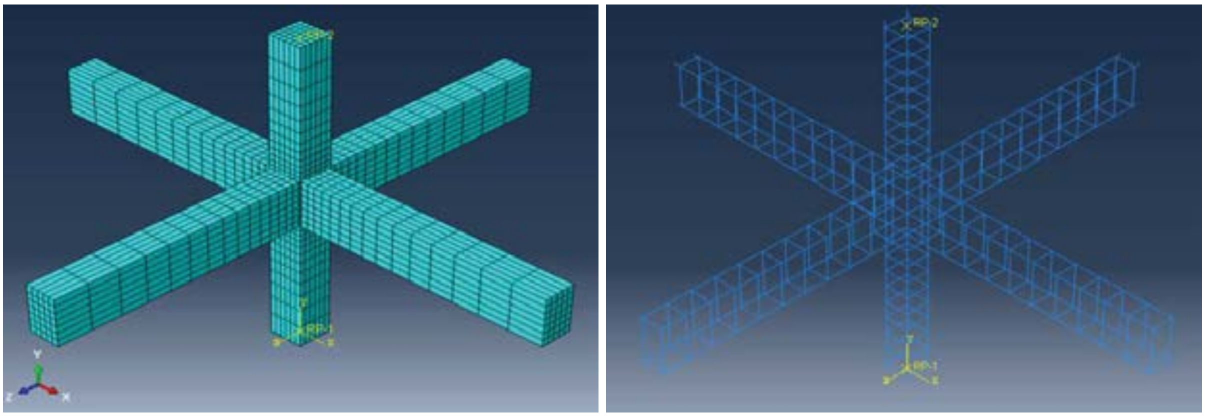

Figure 7. 3-D numerical simulation of the RC beam-to-column joint tested at the laboratory of Strength of Materials and Structures of Aristotle University. a) The numerical simulation of the concrete volume. b) The numerical simulation of the longitudinal and transverse reinforcement.

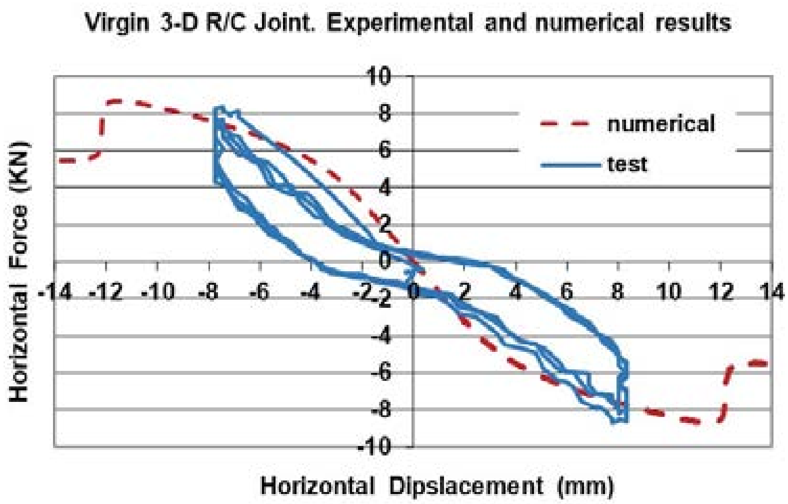

Figure 8. Comparison between the measured horizontal force versus horizontal displacement at the top for the virgin RC joint tested with the 3-D numerical predictions

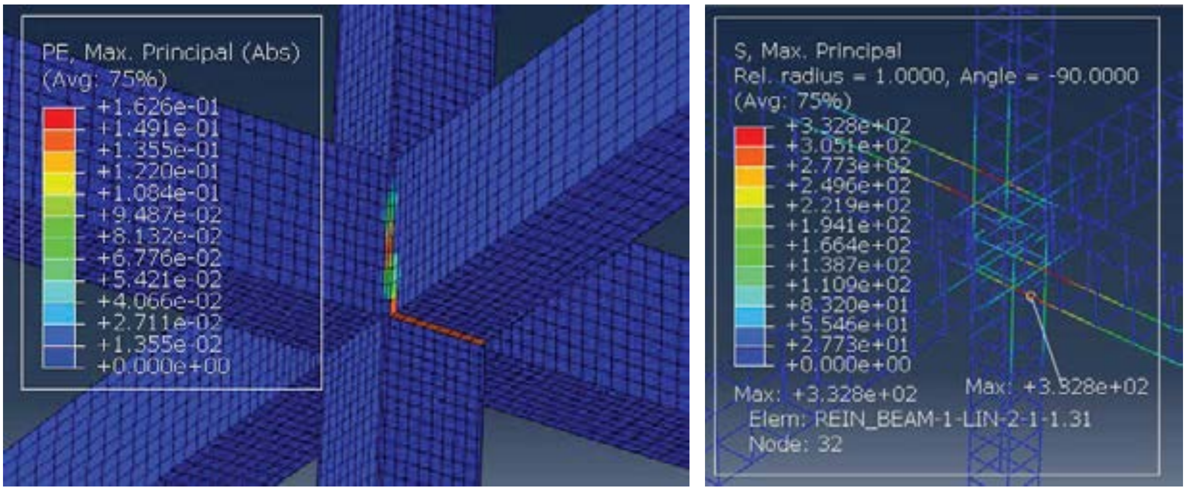

Figure 9. Virgin RC joint numerical response. a) The distribution of plastic strains at the beams near the region that they meet the RC joint. b) Distribution of axial stress at the longitudinal reinforcement of longitudinal beams. The yielded reinforcing longitudinal bars are marked with red color.

Following, the anchoring system was simulated with simple contact with the R/C joint and the FRP sheets were bonded to the beams and attached at the anchoring system (figure 10a). The response of this model in terms of applied load versus the horizontal displacement at the top column is depicted in figure 10b together with the corresponding experimental measurements. Figure 11 shows the plastic strains developed at concrete's volume. Large plastic strains develop at the column cross sections near the joint. At the same location the vertical reinforcing bars develop high tensile stresses, larger than the yield limit (table 2). Thus, plastic hinges are formed in column's cross section.

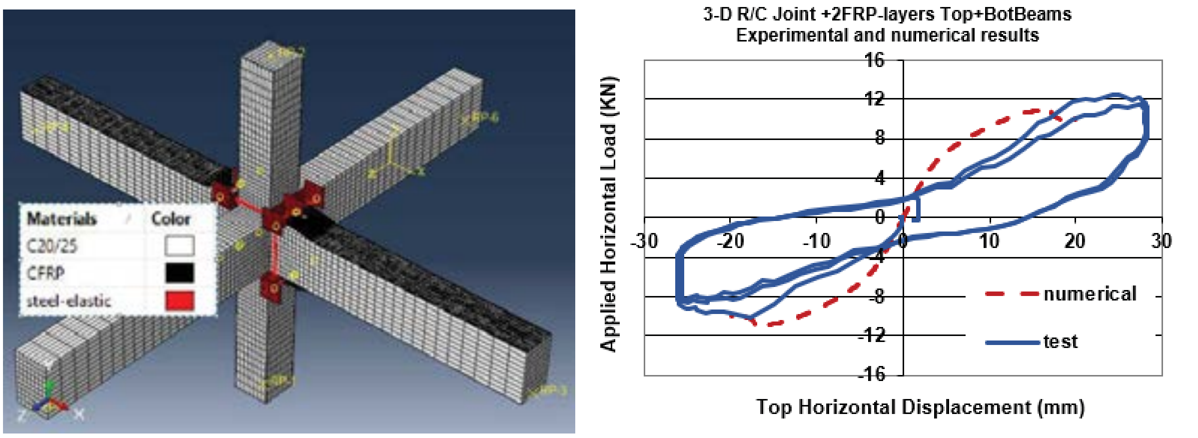

Figure 10. a) The numerical model of joint with FRP strengthened beams. b) Comparison between the measured horizontal force versus horizontal displacement at the top for the joint with FRP strengthened beams and the corresponding numerical prediction

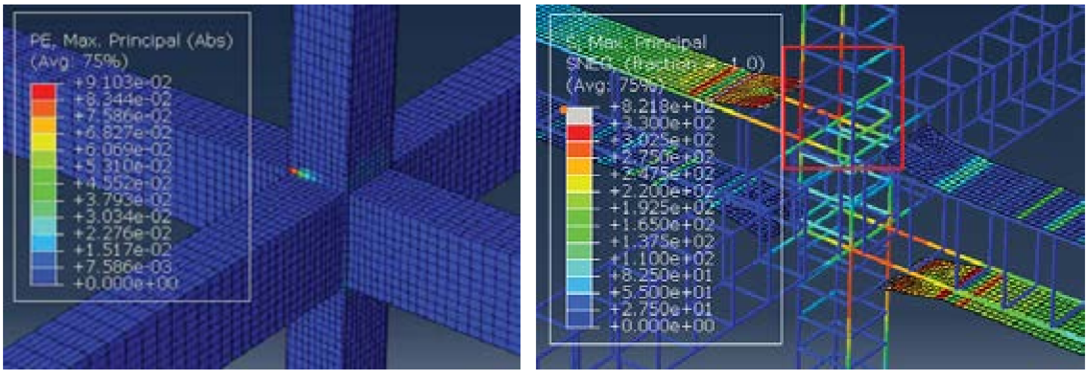

Figure 11. Joint with strengthened beams. a) The distribution of plastic strains at the column near the region that meet the RC joint. b) Distribution of axial stress at the longitudinal reinforcement and FRP sheets of longitudinal beams. The yielded reinforcing longitudinal bars are marked with red color.

Next, FRP sheets were attached at the two faces of the top and bottom column following the same methodology as previously described, 2 CFRP sheets to beams and 3 CFRP sheets to columns (figure 12a). The response of this model in terms of applied load versus the horizontal displacement at the top column is depicted in figure 12b together with the corresponding experimental measurements. Figure 13 shows the plastic strains developed at concrete's volume. Large plastic strains develop at the beam cross sections near the joint. At the same location the reinforcing bars develop high tensile stresses, larger than the yield limit (table 2). Thus, plastic hinges are formed in column's cross section.

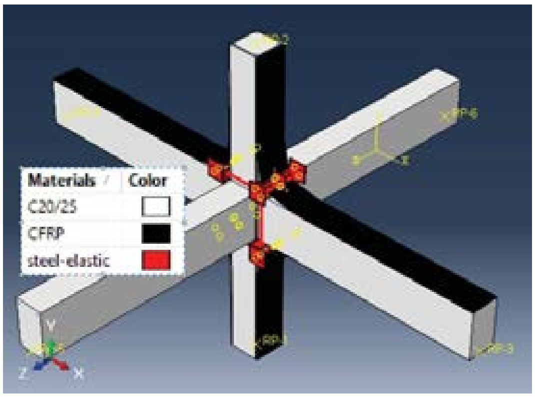

Figure 12. a) The numerical model of joint with FRP strengthened beams and columns. b) Comparison between the measured horizontal force versus horizontal displacement at the top for the joint with FRP strengthened beams and columns and the corresponding numerical prediction

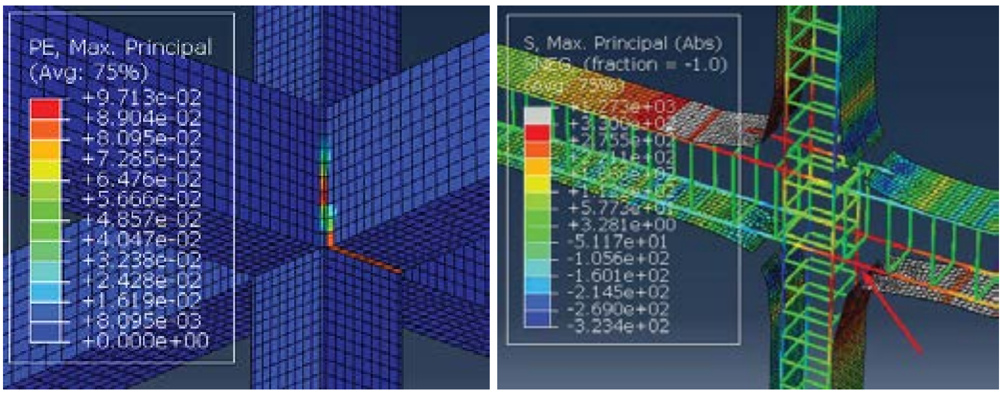

Figure 13. Joint with strengthened beams and columns. a) The distribution of plastic strains at the beam, near the region that meet the joint core. b) Distribution of axial stress at the longitudinal reinforcement and FRP sheets. The yielded reinforcing longitudinal bars are marked with red arrow.

5 DISCUSSION OF THE OBTAINED RESULTS.

In section 3 the experimental results of the tested R/C joints are given. The virgin 3D joint was tested under cyclic horizontal load with a constant vertical load equal to 50KN. Following, the damaged specimen was strengthened with 2 CFRP sheets bonded at the longitudinal beams. Subsequently, 3 FRP sheets were placed to the column as well. In all cases the FRP layers were attached to the examined anchoring system placed near the joint core region. The virgin joint exhibited a maximum load equal to 8.69KN, while cracking appeared at the beam cross sections near the joint. The beam strengthened joint exhibited greater maximum load, 12.54KN, while cracking was observed at the bottom column. Finally, the joint with both beams and columns strengthened exhibited a maximum load equal to 16.63KN.

Afterward, numerical models were developed using all the geometrical and the mechanical properties of the tested specimen. Three models are examined with correspondence with the above mentioned tests. The virgin model exhibited a maximum load equal to 8.70KN, while cracking appeared at the beam cross sections near the joint. The beam strengthened joint exhibited greater maximum load, 10.96 KN, while cracking was observed at the bottom column. Finally, the joint with both beams and columns strengthened exhibited a maximum load equal to 12.55 KN, while the beam cross section showed cracking.

	Experimental results		Numerical results	
Specimen	Maximum load (KN)	Observed mode of failure	Maximum load (KN)	Observed mode of failure
Virgin	8.69	Cracking of beam sections	8.70	Plastic strains at concrete and rebar of beams
Beams Strengthened (2 sheets)	12.54	Cracking of column sections	10.96	Plastic strains at concrete and rebar of column
Columns Strengthened (3 sheets)	16.63	Cracking of beam sections	12.55	Plastic strains at concrete and rebar of beams

Table 3 Summary experimental measurements and numerical predictions

6 CONCLUSIONS

The behavior of RC beam-to-column joints subjected to seismic type cyclic loading is studied here as built and subsequently strengthened using CFRP sheets. The strengthening methodology aims to upgrade the flexural capacity of the structural members and for this purpose an anchoring system near the joint area is used. The observed behaviour is portrayed in terms of horizontal load versus horizontal displacement cyclic response. Apart from the laboratory observations numerical simulations were conducted. The main conclusions are enlisted below:

- The anchoring system employed in the discussed experimental campaign successfully prohibited the delamination of FRP sheets near the joint core and ensured the stresses distribution. Thus, the structural subassembly bearing capacity is increased by 44% and 91% for the beam strengthened specimen and the both beams and columns FRP strengthened specimen.
- The used 3-D numerical simulations of the tested RC joint successfully represented the observed flexural non-linear response of this RC structural sub-assembly, as for each case satisfactorily captured the mode of failure.

- Regarding the bearing capacity predicted by these numerical models again the numerical simulation can be considered successful up to point. The strengthened models exhibited an increase of maximum load by 27% and 44% for the beam strengthened specimen and the both beams and columns FRP strengthened models, which are smaller than the corresponding laboratory measurements. This can be explained by the fact that during the analysis damage on the interface between FRP sheets and R/C members was observed, while the experimental procedure did not exhibit such a failure. Thus, the bearing capacity's increase is limited. Therefore, the properties of these interfaces should be further investigated.

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