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Full scale tests of RC joints with minor to moderate seismic damage repaired using C-FRP sheets

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Abstract. After earthquakes FRP sheets are often used for the rehabilitation of damaged Reinforced Concrete (RC) beam-column connections. Connections with minor to moderate damage are often dealt with by applying FRP sheets after a superficial repair of the cracks using resin paste or high strength mortar but without infusion of thin resin solution under pressure into the cracking system. This technique is usually adopted in these cases due to the fast and easy-to-apply procedure. The experimental investigation reported herein aims at evaluating the effectiveness of repairing the damaged beam-column connections using FRP sheets after a meticulous but superficial repair of their cracking system using resin paste. The investigation comprises experimental results of 10 full scale beam-column joint specimens; five original joints and the corresponding retrofitted ones. The repair technique has been applied to RC joints with different joint reinforcement arrangements with minor to severe damage brought about by cyclic loading for the purposes of this work. Aiming at quantitative concluding remarks about the effectiveness of the repair technique, data concerning response loads, loading stiffness and energy absorption values have been acquired and commented upon. Furthermore, comparisons of damage index values and values of equivalent viscous damping, as obtained during the test of the original specimens, with the corresponding ones observed in the loading of the repaired ones have also been evaluated and commented. Based on these comparisons, it is deduced that the technique under investigation can be considered to be a rather satisfactory repair technique for joints with minor to moderate damage taking into account the rapid, convenient and easy-to-apply character of its application.

Keywords: retrofit/repair; earthquake damage; reinforced concrete; beam-column joints; FRP sheets

1. Introduction

The study of the repairing and strengthening techniques of the RC elements damaged during earthquake excitations constitutes a research field of vital importance for the seismic-prone regions around the globe. It is also worth mentioning that the financial impact of the research in this area is also very significant. Throughout the last decades, Fiber Reinforced Plastics (FRP) sheets have been used in many cases as confining jackets or external supplementary shear reinforcement for the repairing or the upgrading of damaged or underdesigned RC members, respectively. They are usually applied to existing reinforced concrete columns with insufficient shear reinforcement or poor seismic reinforcement detailing. In these cases the application of the FRP sheets as a jacketing system is particularly effective and it also substantially improves the ductile behavior of the potential plastic hinge areas.

In situ research of the observed damage after major earthquakes in Greece (Alkyonides-Korinth 1981, Kalamata 1986, Aegion 1995, Athens 1999) has shown that, in many cases, the initial damage was brought about in beam-column joints. In addition, old fashioned design of RC structures constructed seismically deficient beam-column joints (Adibi *et al*. 2017, Devi and Ramanjaneyulu 2017, Ramezanpour *et al*. 2018). Moreover, there are cases in which the damaged areas were observed in the body of beam-column connections and remained there throughout the seismic excitation. On the other hand, it is obvious and commonly accepted that failure of joint bodies may quickly lead to structural failure (Park and Paulay 1975). Therefore, the significant issue of the efficient repair or enhancement of beam-column joints damaged by seismic actions has arisen. Furthermore, it is emphasized that the philosophy behind the modern seismic design codes (Eurocode 8) is based on the idea that a specific acceptable level of structural damage can be allowed even in the event of the design earthquake. Therefore, repairing structures designed to these codes and subsequently damaged during seismic excitations constitutes a requisite part of the conceptual target of the entire design process for seismic safety.

A well known repair technique commonly used after earthquake excitations is based on the infusion of thin resin under pressure in the cracking system of the damaged body. This technique is also called "resin injections" (Karayannis *et al*. 1998) and it has been extensively applied after all major earthquakes in Greece. The infusion of thin resin solution into the cracks has also been used for the repair of beam-column connections. The efficiency of this procedure has been experimentally investigated by Karayannis *et al*. (1998, 2002). In particular Karayannis *et al*. (1998) have

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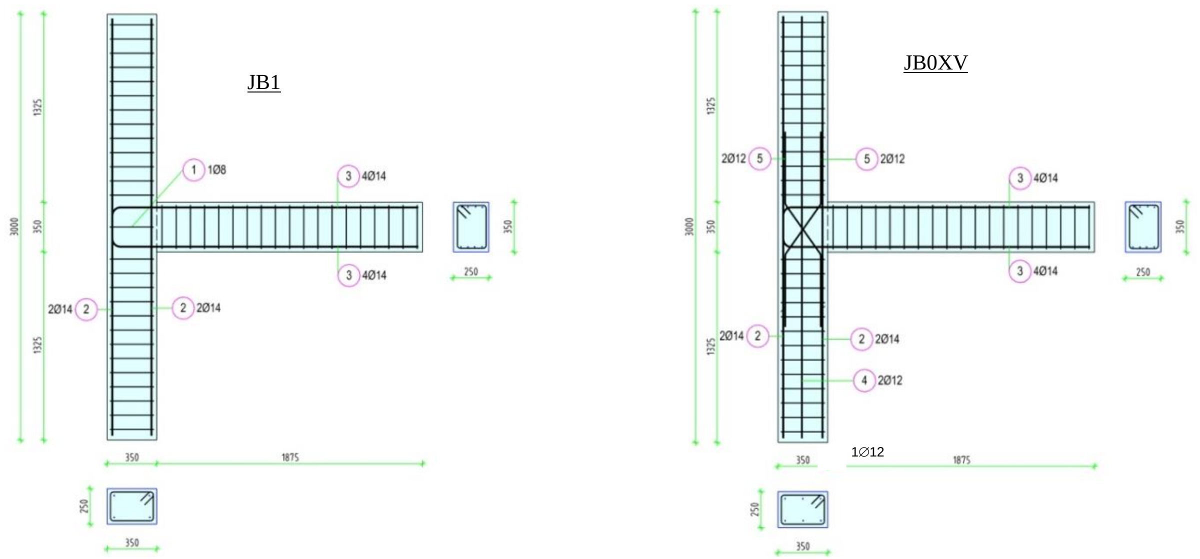


Reinforcements	Specimen JA1	Specimen JB0	Specimen JB1	Specimen JB1V	Specimen JB0VX
1	1∅8	-	1∅8	1∅8	-
2	2∅14	2∅14	2∅14	2∅14	2∅14
3	4∅12	4∅14	4∅14	4∅14	4∅14
4	-	-	-	1∅12	2∅12
5	-	-	-	-	2∅12

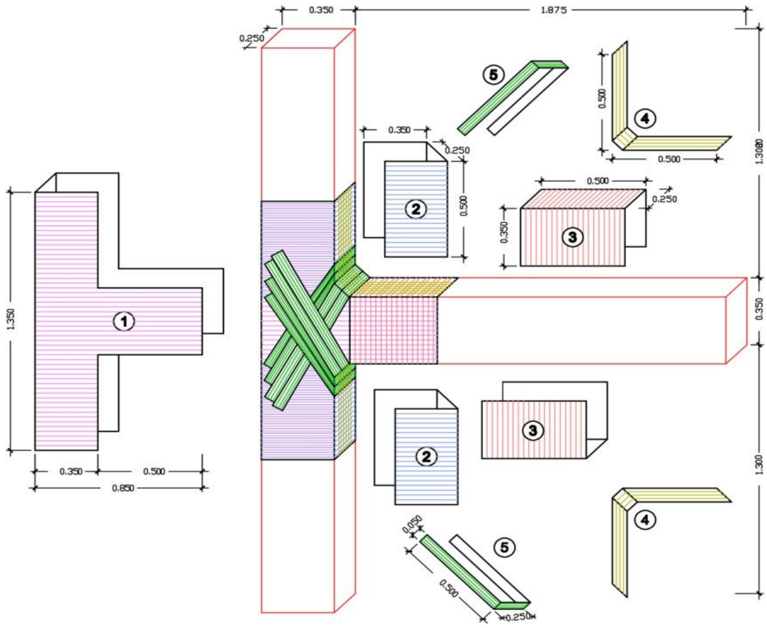
Fig. 1 Geometry and reinforcement arrangement of the original joint specimens

presented an extensive experimental program of 17 exterior joints with different reinforcement arrangements covering many commonly applied reinforcement practices and have concluded that this repair technique has been proved to be satisfactory since in all examined cases presented in this work the overall capacity of the tested specimens in terms of strength, stiffness and energy absorption had been completely restored. Many researchers have recently published valuable research on the pre-earthquake and the post-earthquake retrofitting of poorly detailed reinforced concrete structural members, too (Li *et al*. 2015, Kalogeropoulos and Tsonos 2016, Tsonos 2017, Fahmy *et al*. 2018, Adibi *et al*. 2018). Modeling of damaged joints as well as modeling of the rehabilitated ones and the influence of their degradation on the overall response of reinforced structures is also an important issue (Mathong *et al*. 2016, Lima *et al*. 2017, Fan *et al*. 2018).

Further, the effectiveness of the use of FRP for the strengthening of beam-column connections has also been the subject of some experimental investigations. Karayannis and Sirkelis (2008) presented an effort to use Carbon-Fiber Reinforced Plastic (C-FRP) sheets in combination with the application of resin injections in the cracking system of the damage for the improvement of the overall seismic capacity of damaged RC exterior beam-column connections. The increasing interest in the use of these materials, due to the immediate and easy-to-apply nature of the required intervention, was the main motive behind this effort. Furthermore the combination of the use of resin injections with the application of FRP has been proven to be a very effective strengthening technique (Karayannis and Sirkelis 2008, Tsonos *et al*. 2017).

Nevertheless, in many cases after earthquakes, FRP sheets are applied to the body of reinforced concrete members with minor to moderate damage after a superficial repair of it using resin paste or high strength mortar, but without a prior application of resin injections under pressure into the cracking system (Karayannis *et al*. 2018). This technique is usually adopted in these cases due to the fast and easy-to-apply required procedure. This superficial treatment of the damage has been mainly based on the advanced capacities of the FRP as a repair material and on the general concept that in all reported cases the application of FRP sheets has been rather successful. To help in this direction, the experimental investigation reported herein is aimed at evaluating the effectiveness of damaged beam-column connections repaired using FRP sheets after a meticulous but superficial repair of their cracking system using resin paste. The investigation comprises experimental results of 10 specimens; five original specimens and five retrofitted ones. Further, in order to draw conclusions regarding the influence of the shear reinforcement of the joint area on the effectiveness of the examined technique, beam-column joints with various joint reinforcement design practices were tested. Moreover aiming at quantitative concluding remarks, data concerning response loads, loading stiffness and energy absorption values are also acquired and commented upon.

Research in this area is essential, since engineers in seismic regions often face the problem of applying repair or strengthening techniques without established efficiency or even without having quantitative guidance (Karayannis and Sirkelis 2008, Tsonos 2008). The applied nature and the financial importance of this research field is therefore apparent and its application immediate.



Main behavior characteristics of the used C-FRP sheet:

S&P C-Sheets 240−t_f=0.168 mm
tensile strength f_f=4300 MPa
tensile modulus of elasticity E_{ft}=240 GPa
fracture tensile strain 1.7%

Characteristics of the used resin paste:

S&P Resin 55 HP
compressive strength 100 MPa
modulus of elasticity 3.2 GPa

Fig. 2 Application of C-FRP sheets

2. Experimental program

2.1 Characteristics and materials of the specimens

The effectiveness of the technique under investigation regarding the seismic capacity of exterior beam-column joint subassemblages has been examined through the experimental results of 10 original and retrofitted specimens. The experimental project reported herein includes 5 full scale exterior beam-column joint specimens that were constructed for the purposes of this investigation. The specimens were initially tested and damaged under increasing cyclic loading, then retrofitted using the FRP sheets, and finally retested in the same loading sequence. The beam-column connection subassemblages were constructed with different arrangement of reinforcement in the joint, covering the usually applied reinforcing philosophies. The program was designed to investigate the repair efficiency with reference to the damage severity and the shear reinforcement of the joint area. Geometrical characteristics were common for all specimens (Fig. 1); total column length and cross sectional dimensions were 3.00 m and 350/250 mm, respectively, whereas beam length and cross-sectional dimensions were 1875 mm and 350/250 mm, respectively. The reinforcement arrangements of all specimens are presented in Fig. 1.

The compressive strength of the used concrete was measured by supplementary compression tests of six standard $D\times h$=150×300 mm cylinders. The mean value at the age of 28 days was f_c=34 MPa. The steel of the longitudinal bars and the stirrups was S500 with yield tensile strength f_y=550 MPa. The type of C-FRP sheets used was S&P C-Sheet. The thickness of the C-FRP sheets was t_f=0.168 mm. The main behavior characteristics of the fibres and the epoxy resin used in this work are given in detail in Fig. 2.

Test specimens were given code names consisting of the letter *J* for joint followed by alphanumeric characters. The first letter after *J* is A or B depending on the amount of the longitudinal reinforcement of the beam. Thus, letter A denotes beam with 4 bars of 12 mm diameter at the top and 4 bars of 12 mm diameter at the bottom whereas letter B denotes beam with 4 bars of 14 mm diameter at the top and 4 bars of 14 mm diameter at the bottom. The third numeric character indicates the number of the stirrups in the body of the joint. Letter *X* indicates the application of *X*-type reinforcement in the joint body. Letter *V* indicates specimen with two extra steel bars of 12 mm diameter each one positioned in the middle of each long side of the column cross-section added as supplementary vertical shear reinforcement of the joint body for the improvement of the joint performance (Karayannis *et al*. 1998). Finally, the letter *R* at the end of the code name denotes that the specimen is a retrofitted specimen. This joint has been subjected to the second loading after the first loading as the original specimen with the same code name without R and the subsequent application of the FRP sheets.

2.2 Test setup

Test set-up and instrumentation details are shown in Fig. 3. Each specimen was rotated 90° degrees, so that the beam was in the vertical direction and the column in the horizontal direction. Supporting devices that allow rotation

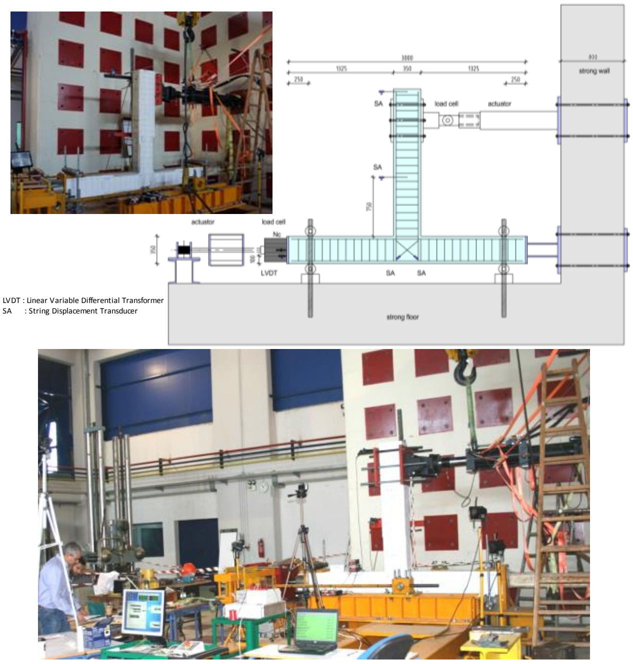


Fig. 3 Test setup

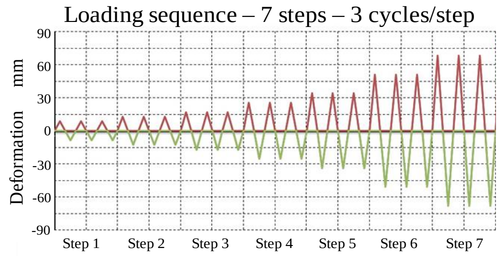


Fig. 4 Loading sequence. Seven loading steps and each step comprises three full loading cycles

were applied to simulate the inflection points in the middle of the columns in a laterally-loaded frame structure. Column compressive axial load N_c, equal to $0.05A_c f_c$, was constantly applied during the experimental procedure in all the specimens. The value of the column axial load was controlled to remain constant during the entire loading procedure at the level of 150 kN for all specimens.

2.3 Loading sequence

All beam-column joints were subjected to full cycle deformations. The deformations were imposed at the free end of the beam which as it can be seen in the setup, was in the vertical direction (Fig. 3). The moment arm for the applied load was equal to 1.475 m. Tested specimens suffered a loading history of seven full loading steps with maximum displacements ±8.5 mm, ±12.75 mm, ±17 mm, ±25.5 mm, ±34 mm, ±51 mm and ±68 mm, respectively. Each loading step consists of three full loading cycles; thus the loading sequence was performed the way it is shown in Fig. 4. The applied loading sequence was expected to cause minor damage to the original specimens JA1 and JB0XV during the first loading whereas it is expected to bring about moderate to severe damage to joints JB0, JB1 and JB1V.

It is noted that in order to put in use results obtained from cyclic loading tests on RC elements for a general performance evaluation it is necessary to establish a loading history that captures the critical issues of the element capacity as well as the seismic demands. In inelastic seismic problems, capacity and demands cannot be considered separate to one another since one may strongly depend on the other. Basic seismic capacity parameters for a structural element are strength, stiffness, inelastic deformation capacity (ductility) and cumulative damage capacity parameters such as energy dissipation capacity. All these parameters are expected to deteriorate as the number of damaging cycles and the amplitude of cycling increase.

Every excursion in the inelastic range causes cumulative damage in a structural element. In the adopted loading program emphasis is given on a multi-cycle loading sequence since repeated loading cycles may cause the type of damage that is a usual case after moderate excitations and therefore it is within the targets of this investigation. Thus, in order to draw conclusions for the presented damage technique each loading step includes three full loading cycles whereas a program that includes steps with constantly increasing displacement has been chosen. The importance of sequence effects has not been yet established through research and the sequence of large *versus* small excursions in an element of a structure subjected to a severe earthquake does not follow any consistent pattern. The number of the inelastic excursions increases with a decrease in the period of the structural system, the rate of increase being very high for short period systems. It is to be recognized that demands for structures depend on a great number of variables and a unique loading history will always be a compromise but the one that should be conservative for most practical cases has to be applied. A multi-cycle loading program has been adopted (Fig. 4).

Consequently, the used loading program is a comprehensive testing program (cumulative damage testing program) that permits the determination of structural performance parameters, which, together with a cumulative damage model, can be utilized to evaluate performance under arbitrary seismic excitations. For this reason the use of a damage index has also been employed in this study. The established damage index for RC members by Park and Ang (1985) has been chosen in order to maximize information for an in-depth capacity assessment and comparison of the initial response of the joints to the response of the joints after the intervention.

3. Design of specimens

The complete apprehension of the inner mechanics and the seismic response of the RC beam-column joints have not been yet fully achieved and as a result of this lack of knowledge until now there is not a commonly acceptable model for the joint design. In any case, the estimation of the horizontal secant shear (V_{jh}) of the joint is an important factor for the evaluation of the shear stress τ and therefore for the calculation of the required shear reinforcement in the body of the joint.

External joint shear can be calculated as $V_{jh}=A_{s1}f_{su}-V_{col}$ where A_{s1} is the beam's tensile reinforcement, f_{su} the steel strength, V_{col} the shear force of the column given as $V_{col}=M_{b,y}/\ell_c$ where $M_{b,y}$ is the yielding moment of the beam and ℓ_c the average length of the upper and lower columns of the joint considering the subassemblage as part of a RC frame and $\ell_c=(\ell_{c,up}+\ell_{c,lo})/2$.

According to Eurocode 8 for specimen JA1 the maximum horizontal shear induced in the joint by the beam's reinforcement, is V_{jhd}=0.23 MN and the shear stress τ=2.70 MPa, whereas for all the other specimens the horizontal shear is V_{jhd}=0.32 MN and the shear stress τ=3.67 MPa. Further, the diagonal compression induced in the joint shall not exceed the compressive strength of concrete in the presence of transverse tensile strains. This requirement is satisfied by means of the rule

$$V_{jhd} \leq 0.8 \cdot \eta \cdot f_{cd} \sqrt{1-\frac{\nu_d}{\eta}} \cdot b_j \cdot h_{jc} \qquad \text{(Eurocode 8)}$$

Thus applying this rule for the joints under consideration it yields that the diagonal compression induced in the joint does not exceed the compressive strength of concrete in the presence of transverse tensile strains if $V_{jhd}\leq$0.23 MN.

For specimen JA1 the maximum induced shear force is almost equal to the maximum strength and therefore according to EC8 the main damage is expected in the beam since the diagonal compression strength is not exceeded. Nevertheless, minor cracks can be brought about in the body of the joint due to the almost critical level of the induced shear and the usual local material uncertainties. *X*-shape cracks are expected in the joint area for the specimens JB0, JB1, JB1V and JB0XV since the maximum induced shear force exceeds the maximum strength 0.23MN of the diagonal compression strength. In these cases though, the severity of the cracks depends on the amount and the shape of the existing shear reinforcement in the joint body.

In the case of specimen JB0XV due to the existence of the *X*-type reinforcement in the joint body, the main damage is expected to occur in the beam leaving the body of the joint almost intact (Karayannis *et al*. 1998, Tsonos 2008, Tsonos *et al*. 2017). It is noted that the anchorage of the longitudinal bars of the beam, for all specimens, has sufficient total length.

According to ACI external joints have to satisfy the relationships $\Sigma M_{Rc}/M_{Rb}$>1.40 and $\varphi V_n \geq V_u$. For the specimen JA1 holds that $\Sigma M_{Rc}/M_{Rb}$=1.93, whereas for the specimens JB0, JB1, JB1V and JB0XV holds that $\Sigma M_{Rc}/M_{Rb}$=1.43. Therefore, for joint JA1 the main damage is expected in the beam whereas for the other specimens cracks are expected in the joint area.

Furthermore, without considering safety factors the maximum acting shear force and shear stress for specimen JA1 can reach the values V_{jh}=223.9 kN and shear stress τ=1.83 MPa. For the other specimens JB0, JB1, JB1V and JB0XV the maximum acting shear force is V_{jh}=305.1 kN and the shear stress τ=3.49 MPa.

The design of the strengthening of external joints using FRP is an open field of research in the literature. Few design procedures have been proposed so far. Gergely *et al*. (2000) have calculated the FRP contribution in the shear strength joints considering FRP as stirrups. Tsonos (2008) followed the same approach but they considered that FRP stress was equal to ε_p=0.0035. The present study has experimental orientation and the design approach adopted for the examined specimens is the simplified and easy-to-apply approach by Tsonos (2008) and Gergely *et al*. (2000).

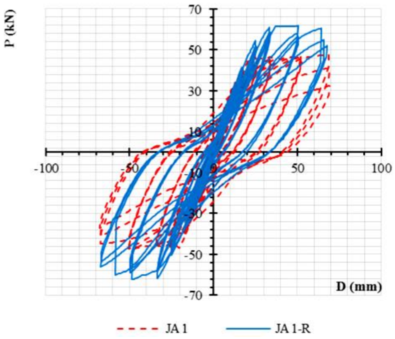
A rather large length for the legs of the *U*-shape FRP sheets (sheet No. 1 in Fig. 2) was chosen to prevent anchorage failure. Furthermore, two layers of FRP sheets were also applied in the beam near the joint to avoid anchorage failure of the *U*-shape FRPs. Finally, two layers of FRP sheets were applied in the areas of the column near the joint to enhance the confinement and the ductility of these areas.

In the overall design process, it is noted that retrofitting of a specific length of the beam close to the conjunction with the joint, can relocate the plastic hinge of the repaired elements far from the column with all the known shortcomings (e.g., substantial increase of beam plastic rotation demand for a given level of interstorey drift). However, the repair of the severe beam damages of this area to a certain measure was considered as part of the needed repair works in these cases since in real structures all damaged areas have to be repaired.

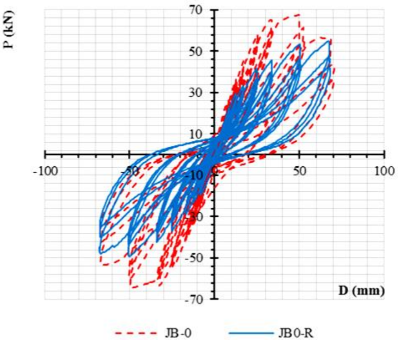
The purpose of this work is not to contribute towards the development of design process tools or the verification of existing ones but to provide practical solutions for on-site applications based on experimental results about the examined repairing technique of external beam-column joints and to extract useful and practical conclusions. Thus, a relatively long length of 850mm of U-shaped sheet (Fig. 2) was applied to specimens in order to cover the beam's damages and simultaneously to ensure the anchorage of *U*-shaped FRP (FRP sheet No. 1 in Fig. 2).

4. Test results and hysteretic responses

To assess the effectiveness of the applied retrofitting technique, the seismic overall performance of each original beam-column subassemblage is examined and compared with the performance of the corresponding retrofitted one. The hysteretic responses in terms of full loading cycle curves (loading force *versus* deformation diagrams) for all tested specimens are presented in Fig. 5; in all these figures, the dashed red lines represent the response of the original specimens, whereas the solid blue lines represent the response of the corresponding retrofitted ones. The comparisons of the seismic performance between the original joints and the corresponding retrofitted joints indicated that all the retrofitted specimens using the FRP sheets exhibited that this retrofitting technique restores the capacity values of the damaged joints with respect to those of the original specimens to a great degree. Load bearing capacity values of all the retrofitted joints were almost equal to the ones of the original specimens in every loading step of the loading history. Further, indication about the bond deterioration between the reinforcement and the concrete may be obtained based on the shape of the load versus deflection plots (Fig. 5). The pinching effect of the



(a)



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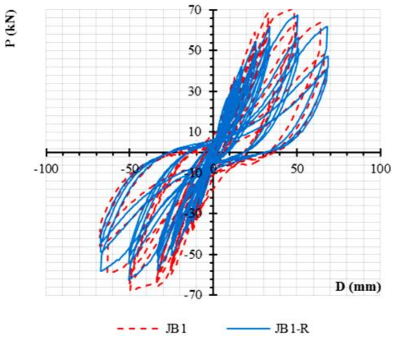

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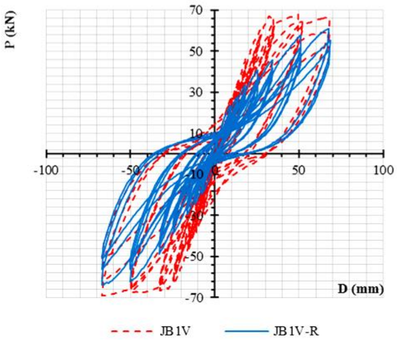
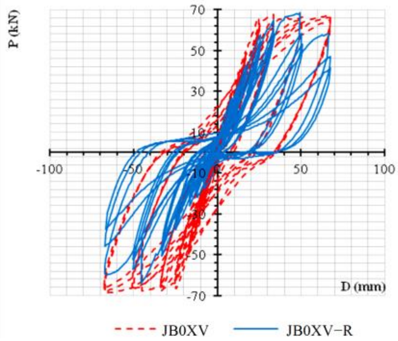


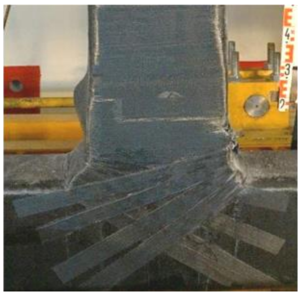
(d)



(e)

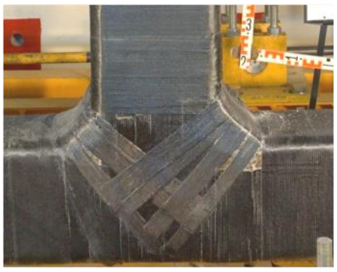
Fig. 5 Hysteretic responses of the tested specimens. Comparative presentation of the original specimens with the corresponding retrofitted ones

(a) JA1

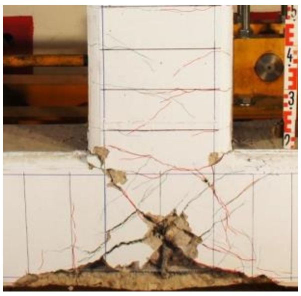


(b) JA1−R

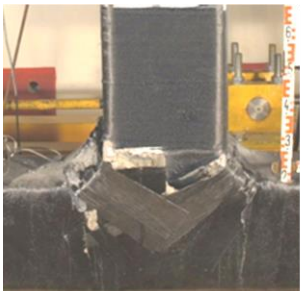
(c) JB0



(d) JB0−R

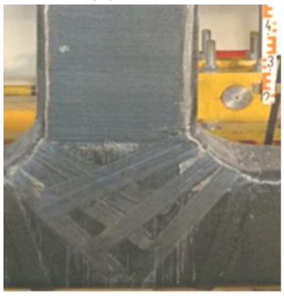


(e) JB1

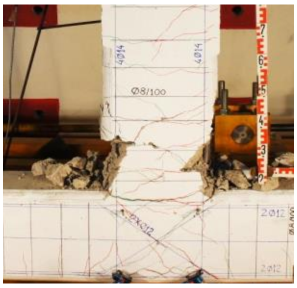


(f) JB1−R

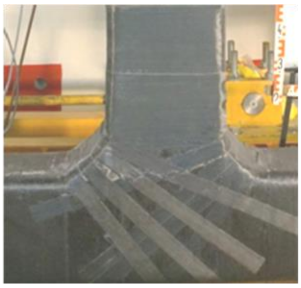
(g) JB1V



(h) JB1V−R



(i) JB0XV



(j) JB0XV−R

Fig. 6 Final damage mode of the tested beam-column connections

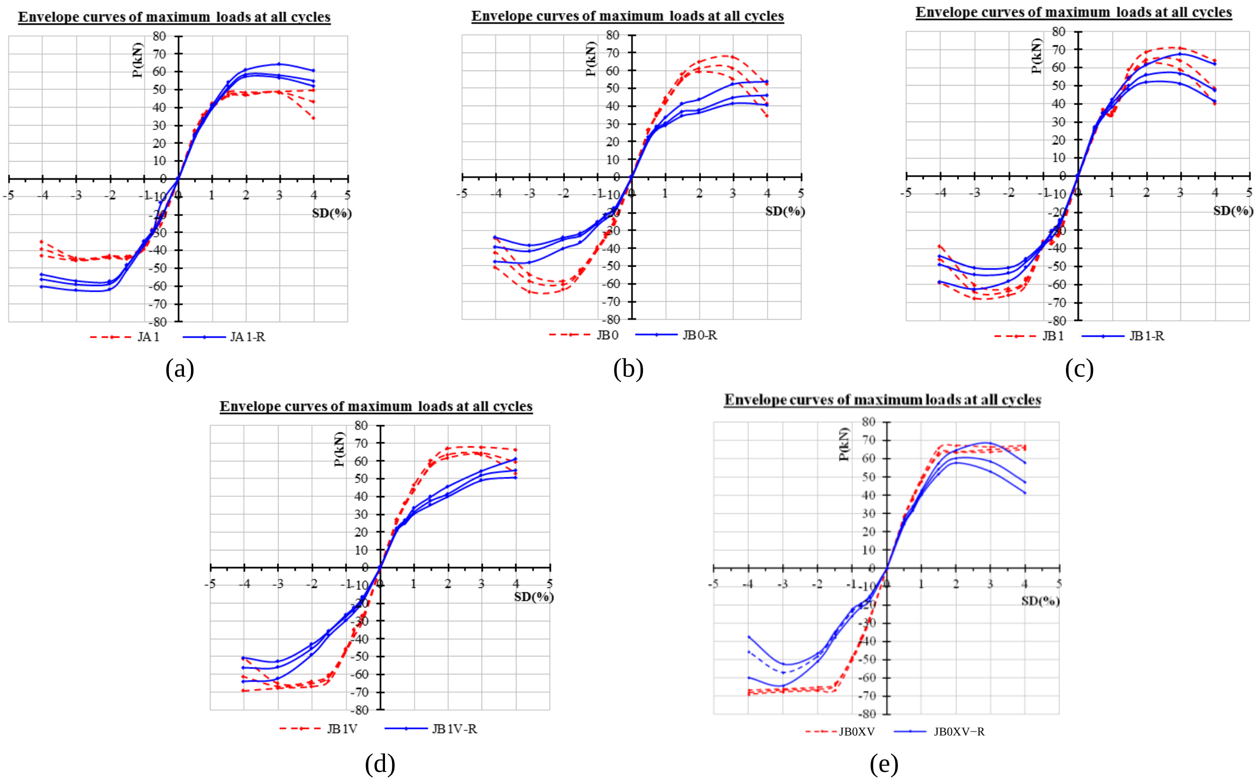


Fig. 7 Envelope curves of the hysteretic responses. Comparisons between the envelope curves of the original beam-column connections and the envelope curves of the corresponding repaired ones

hysteretic responses of the examined joints indicates that bond deterioration has developed in the original joints JB0 and JB1 (Figs. 5(b) and 5(c)). Furthermore, it seems that bond deterioration has been developed in the retrofitted specimens, too. This conclusion can be deduced from the pinching observed in the hysteretic responses of the retrofitted specimens JB0-R, JB1-R, JB1V-R and JB0VX-R shown in Figs. 5(b),(c),(d) and (e), respectively.

The final damage modes of all specimens, original and retrofitted ones, are shown in Fig. 6. From Fig. 6 it can be observed that the damage in the original specimens JA1 and JB0XV was mainly localized in the beam whereas only a few cracks can be traced in the joint body. In these cases the damage can be characterized as a minor damage for the joint body. In specimen JB1V the cracks in the joint body are dense (Fig. 6(g)) and therefore the joint damage is characterized as minor to moderate damage. For the joints JB0 and JB1 (Figs. 6(c) and 6(e), respectively) the damage level of the joint body can be considered as moderate to severe.

The envelope curves of the hysteretic responses of all the specimens in diagrams of loading (P) versus Story Drift (SD) for the three full loading cycles of all loading steps are presented in Fig. 7. Moreover, the observed stiffness of the 1st cycle loading of each loading step of all specimens is shown in Fig. 8. In these figures (Figs. 7 and 8) the dashed red lines represent the response of the original specimens, whereas the solid blue lines represent the response of the corresponding retrofitted ones. In these figures the comparison between the envelope curves and characteristic loading stiffness values of the original specimens with the envelope curves and the corresponding loading values of the rehabilitated specimens of all loading steps can be observed.

5. Methods for the evaluation of the experimental results

5.1 Damage index

Several quantitative dimensionless measures of the deterioration of RC members and structures due to inelastic dynamic excitations have been reported in the literature. Most of these indices consider damage to individual elements and are based on displacement ductility ratio and hysteretic dissipated energy. The damage index model by Park and Ang (1985) has been widely used in the recent years because of its simplicity and the fact that it has been calibrated using experimental data from various structures damaged during past earthquakes. This damage index is defined as the linear combination of the ultimate displacement and the dissipated energy, by the following expression

$$D = \frac{\delta_M}{\delta_u} + \frac{\beta}{M_y \delta_u} \int dE$$

where δ_M is the maximum deflection attained during seismic loading; δ_u is the ultimate deflection capacity under monotonic load; β is a model parameter that depends on the value of shear and axial forces and the amount of

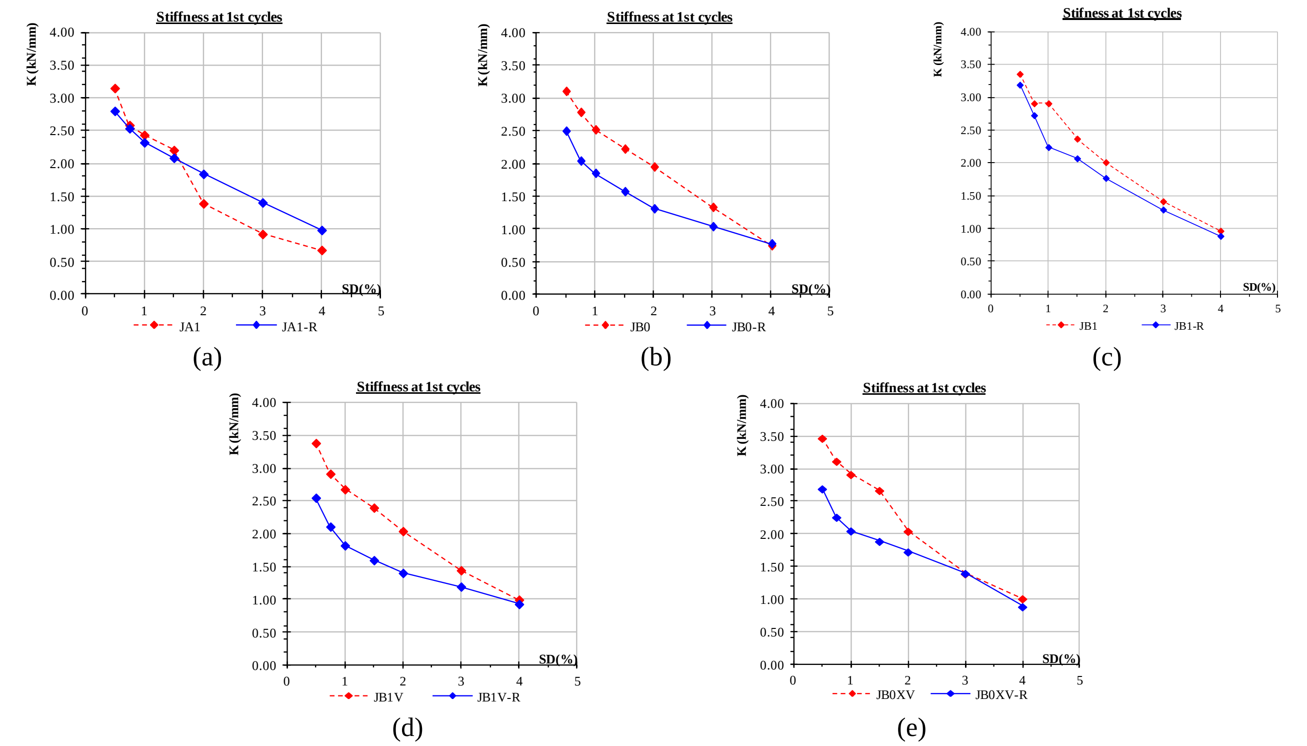


Fig. 8 Observed stiffness of the 1st cycle loading of each loading step. Comparisons between the loading stiffness of the original specimens with the loading stiffness of the corresponding repaired ones

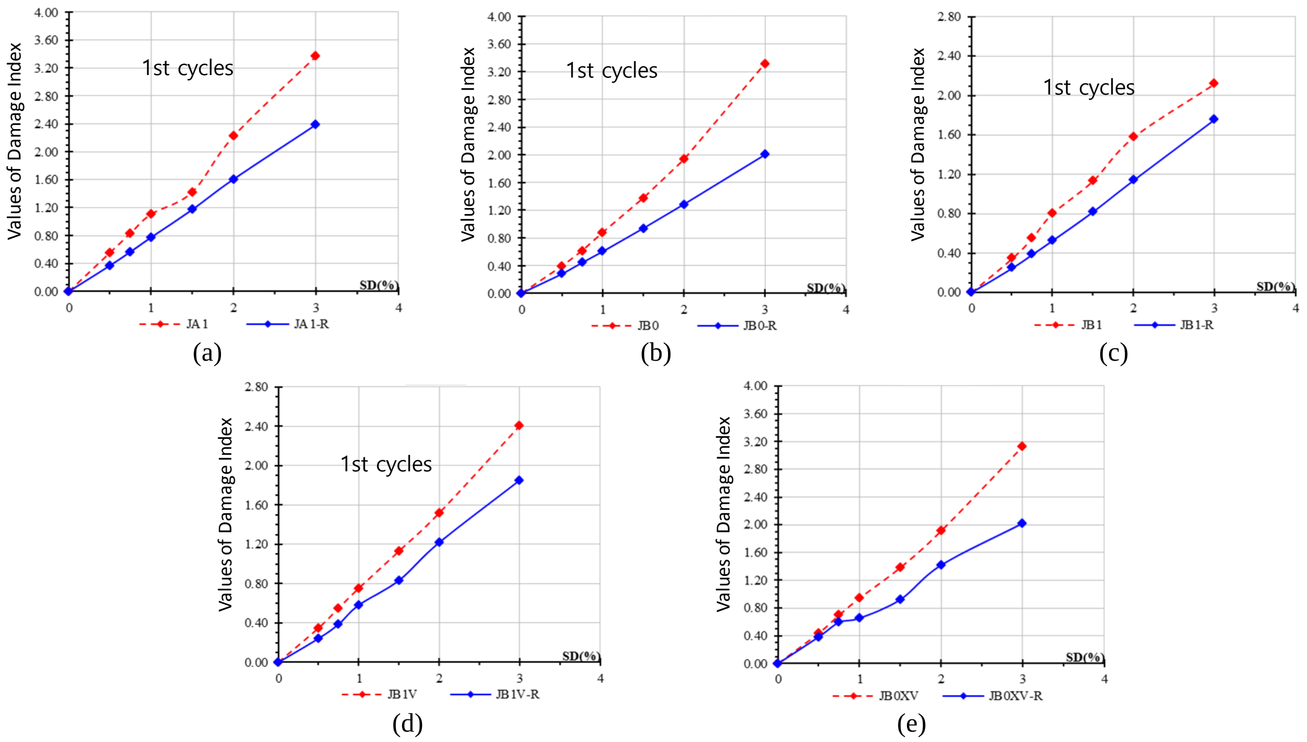


Fig. 9 Values of damage index for the 1st cycles of each loading step. Comparisons of the damage index values of the original specimens with the damage index values of the corresponding repaired ones

longitudinal and confinement reinforcement; M_y is the calculated yield strength; and dE is the incremental dissipated hysteretic energy.

In this study, in order to obtain objective conclusions for the effectiveness of the described FRP sheet application as a repair technique for the exterior beam-column joint subassemblages, the abovementioned damage index model is used to evaluate the damage level of the tested specimens at each step of the loading sequence.

The values of δ_M, M_y, and dE of this model were yielded

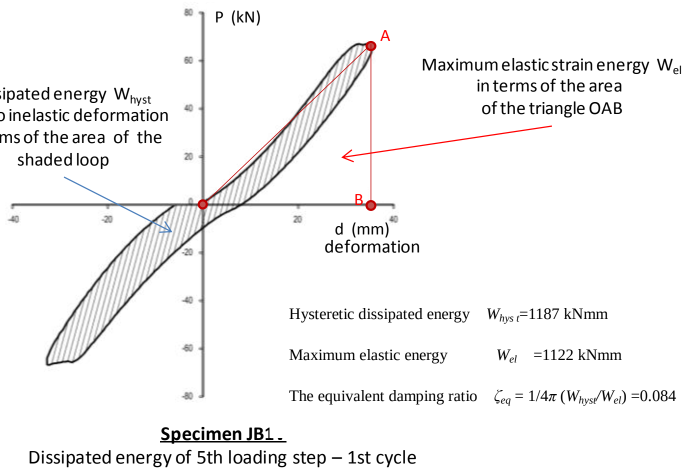


Fig. 10 The hysteresis loop of the 1st loading cycle of the 5th loading step of the specimen JB1V. The dissipated energy due to the inelastic deformations W_{hyst}, the corresponding maximum elastic energy W_{el} and the equivalent damping ratio ζ_{eq} are presented in the figure

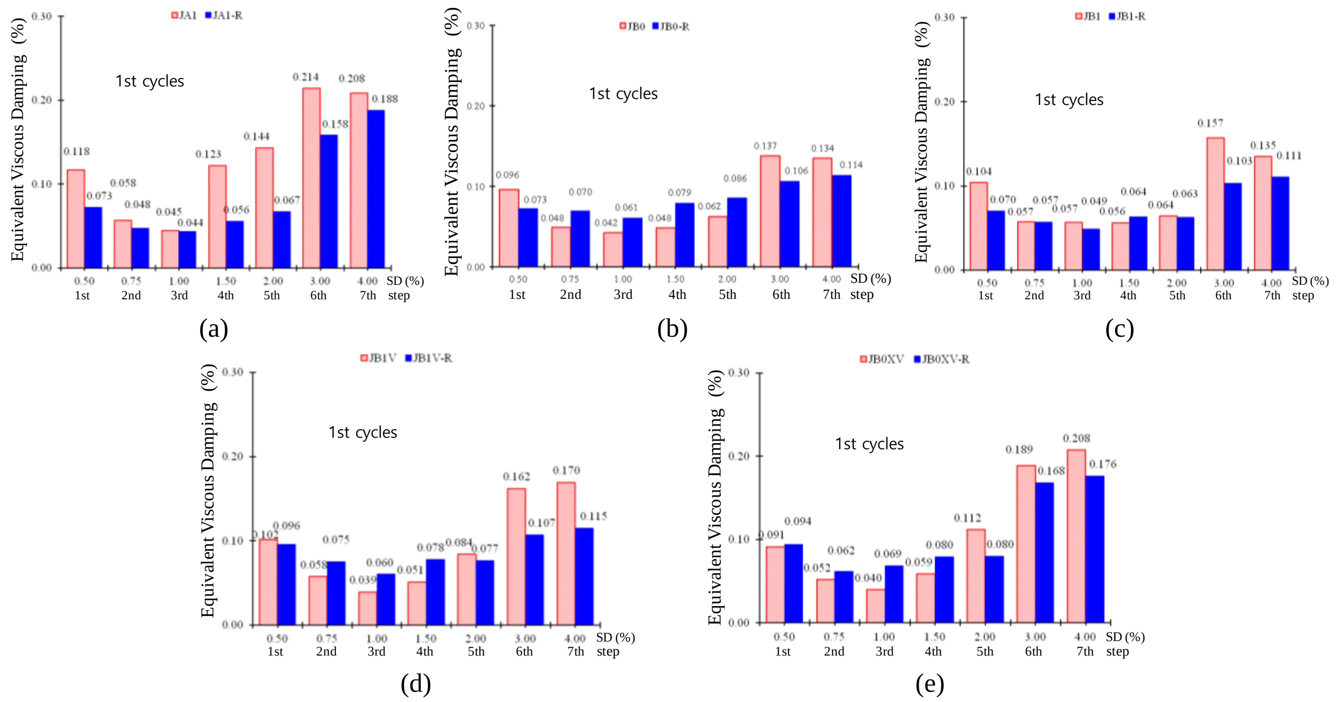


Fig. 11 Equivalent viscous damping. Comparisons between the equivalent viscous damping of the original specimens with the equivalent viscous damping of the corresponding repaired specimens

from the test results of the joint specimens, whereas the value of δ_u was estimated using an empirical formula for the calculation of ultimate drift according to Eurocode 8. Further, for the quantitative estimation of coefficient β, extensive experimental results reported a range between about –0.3 and 1.2 with a median of about 0.15 (Cosenza *et al*. 1993). It is mentioned that the value of β=0.15 correlates closely with the results of other damage models, and this value has widely been adopted by the researchers. The calculated values of damage indices based on the above described model are given in Fig. 9 for all the tested specimens. In these figures the damage index values of the original specimens are compared with the damage index values of the corresponding repaired specimens (Fig. 9).

From these results it can be deduced that all of the retrofitted specimens (JA1-R, JB0-R, JB1-R, JB1V-R, JB0XV-R) present quite lower damage factors than the corresponding original ones during the initial loading.

5.2 Equivalent viscous damping

In addition to the damage index another useful indicator for the energy dissipation capacity per loading cycle is the equivalent viscous damping indicator ζ_{eq}. Energy dissipation is an indication of the specimen capacity to be stressed until failure and defines the energy that could be dissipated before the loss of system stability. The inelastic deformations lead to energy dissipation that can be considered as damping.

A general form of the stress-strain diagram of a structural subassemblage under cyclic loading can be seen in Fig. 10 with several variations depending on the special characteristics of the joint specimen. The area of the shaded loop shown in this particular figure represents the energy (W_{hyst}) that is dissipated during the 1st loading cycle of the 5th loading step of the specimen JB1V due to inelastic hysteretic behavior of the materials. Evidently, the higher the plastic strain level of the materials is the larger the area of the hysteretic loop and, consequently, the larger are the dissipated energy and the damping.

The maximum elastic strain energy W_{el} corresponding to this level of deformation is equal to the triangle OAB (Fig. 10).

The hysteretic damping may be expressed in the form of viscous damping employing the equivalent hysteretic damping ratio ζ_{eq}:

$$\zeta_{eq} = \frac{1}{4\pi} \cdot \frac{W_{hyst}}{W_{el}}$$

Based on the equivalent viscous damping indicator ζ_{eq} useful conclusions can be drawn about the efficiency of the examined repair technique concerning the restoring of the energy dissipation capacity of the damaged joints.

The values of the dissipated energy of all the tested specimens in terms of equivalent viscous damping are presented in Fig. 11. In this figure comparisons between the equivalent viscous damping of the original specimens with the equivalent viscous damping of the corresponding repaired specimens are presented for the first cycles of all loading steps of the loading sequence.

In the cases of the specimen JA1 (Fig. 11(a)) and partly for the specimen JB0XV (Fig. 11(e)) the damage was located at the beam near the joint (see also Figs. 6(a) and 6(i)) and therefore the indicator denotes that the superficial damage repair and the application of FRP sheets does not fully restore the energy dissipation capacity of the beam.

On the contrary, for the other specimens in which the major part of the damage is located in the body of the joint, from the presented comparisons of the equivalent viscous damping values in Figs. 11(b)-(d), it can be suggested that the applied repair technique restored the energy dissipation capacity. Nevertheless, even in these cases the indicator's values for the repaired specimens in high levels of story drifts (6th and 7th loading steps) are lower than the ones of the corresponding original specimens.

6. Concluding remarks

The effectiveness of the application of FRP sheets, after a superficial repair of the cracks with high strength resin paste, for the rehabilitation of RC exterior beam-column joints damaged under cyclic deformation, is experimentally investigated. The technique has been applied to joints with various damage level and different joint reinforcement arrangements. According to the experimental results reported herein the following concluding remarks can be yielded:

- The advantages of the described locally applied FRP sheets in comparison to the commonly used RC jacketing are focused on the fact that the technique is a fast and easy-to-apply procedure and furthermore the dimensions of the retrofitted elements are not changed in respect to their initial size. Consequently, the available structural system geometry and the building mass are not modified, and therefore the dynamic characteristics of the structure remain practically unaffected.
- The described technique seems to be an easy to apply and rather effective method for the repair and the rehabilitation of damaged RC joints with minor to moderate damage level since in these cases the hysteretic response of the retrofitted specimens reported herein was restored to a great extent compared to the response of the original joints in the initial loading. These conclusions are mainly based on the observation that the retrofitted specimens in comparison with the original ones exhibited more or less similar load capacity and stiffness level.
- Moreover, in an attempt to obtain objective conclusions for the effectiveness of the examined repair technique, the progress of the damage level during the test procedure of the original and the retrofitted specimens is evaluated using the well-established damage index model by Park and Ang and the efficiency of the repair technique regarding the restoring of the energy dissipation capacity of the damaged joints is examined based on the equivalent viscous damping indicator. From these comparisons it is deduced that the technique under investigation can be considered to be a rather satisfactory one for exterior joints with minor to moderate damage taking into account the rapid, convenient and easy-to-apply character of its application. Nevertheless, even in these cases, there are reservations for the efficiency of the technique in the restoration of the energy dissipation capacity, since the indicator's values for the repaired specimens in high levels of story drifts are lower than the ones of the corresponding original specimens.

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