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LOCAL FRP-RETROFITTING OF EXTERIOR REINFORCED CONCRETE BEAM-COLUMN JOINTS UNDER CYCLIC LATERAL LOADING

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ABSTRACT

Rehabilitation of seismically damaged Reinforced Concrete (RC) structural members is a challenging issue within the field of earthquake engineering which entails experimental testing. This study presents the experimental findings of the cyclic response of two full scale external beam-column joint subassemblages (Group B specimens: B-S1 and B-S1(R)) in order to draw useful and practical conclusions concerning the effectiveness of the examined FRP-retrofitted technique. Elaborate data of two more beam-column joints (Group A specimens: A-S0 and A-S0(R)) is also included in this study to enable comparisons. Beam-column joint subassemblages A-S0 and B-S1 are the reference specimens. These specimens had been tested under cyclic loading and then the damaged specimens were locally strengthened with Carbon FRP sheets (specimens A-S0(R) and B-S1(R) respectively). Group B subassemblages are full scale specimens. The response of the tested specimens indicated that the applied retrofitting techniques are appropriate for the rehabilitation of the overall hysteretic performance of seismically damaged joints. In particular, when epoxy resin injections were applied to the cracking system of the damaged specimen prior to the application of the FRPs the experimental results suggested that this technique leads to a significant improvement of the load carrying capacity, the energy absorption and the ductility of the initial joints. Therefore, from the hysteretic response curves and the energy absorption curves we conclude that the rehabilitation technique applied to Group A specimens and the one applied to Group B specimens could be considered a strengthening intervention and a repair intervention, respectively. In addition, the observed response of the tested specimens suggests that both applied retrofitting techniques are appropriate for the rehabilitation of the overall hysteretic performance of seismically damaged joints. Furthermore, the FRP-strengthened joints exhibited an improved type of damage when it was compared against the damage modes of the reference specimens.

Keywords: External beam-column joint; local FRP-retrofitting; full-scale tests; repair; cyclic loading

1. INTRODUCTION

The rehabilitation and upgrading of Reinforced Concrete (RC) structures damaged by seismic activity are challenging tasks in the field of earthquake engineering. Research in this area is vital for engineers in earthquake prone regions since they are often involved in the design of rehabilitation works for old or damaged buildings under no regulations (Karayannis et al 1998, 2003, 2006, Karayannis & Sirkelis 2002, 2008). Applications of Fibre Reinforced Polymer (FRP) sheets have been proven to be a promising retrofitting technique although common constructional limitations and premature debonding failures reduce the effectiveness of this strengthening method (Chalioris 2003, 2007). It is also well known that the hysteretic response of exterior RC beam-column joints greatly affects the overall performance of the RC frame structure and therefore the rehabilitation and upgrading of these members is often rendered essential (Paulay & Park 1984, ACI-352R 2002, Karayannis & Sirkelis 2005, 2008).
The experimental study presented herein contributes to the evaluation of the effectiveness of the use of

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epoxy injections for the repair of beam-column connections damaged by cyclic deformations. In the last decades fibre-reinforced composite sheets have been extensively used as confining jacketing systems for the rehabilitation of damaged reinforced concrete members in order for the members to benefit from the confinement of the concrete. The effectiveness of the use of fibre reinforced plastics for the strengthening of beam-column connections has not been studied sufficiently either experimentally or analytically yet.

This work presents an attempt to use Fibre Reinforced Plastics (FRP) sheets for the rehabilitation of the seismic capacity of damaged reinforced concrete 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 is the main motive behind this research. Furthermore the combination of the use of epoxy injections with the application of FRPs may be proven a very effective technique (Karayannis & Sirkelis 2002, 2008, Tsonos & Stylianidis 1999, 2000). A full scale beam-column joint specimen (specimen B-S1) is tested under cyclic loading and then it is rehabilitated by applying C-FRP sheets without the prior application of resin injections in the cracking system. The rehabilitated joint (specimen B-S1(R)) is re-tested under the same loading. The results from these two tests are presented and compared to each other and comparisons and conclusions are presented in this work. Elaborate data from a beam-column joint (specimen A-S0) that was first meticulously repaired with the application of epoxy resin injections (Karayannis & Sirkelis 2008) and then strengthened with C-FRP sheets is also presented herein for comparisons to be made.

2. CHARACTERISTICS OF SPECIMENS - TEST SETUP

The geometry and the reinforcement characteristics of specimens A-S0 and rehabilitated A-S0(R) are (Table 1): Total column length and cross-section dimensions are 1800 mm and 200/200 mm, respectively, whereas beam length and cross-section dimensions are 1100 mm and 200/300 mm, respectively and stirrups are ∅8/150mm. Beam reinforcement of specimens comprises 2∅10 deformed steel bars at the top and 2∅10 deformed steel bars at the bottom. Column reinforcement comprises 4∅10 corner deformed steel bars and ∅8/150mm stirrups (Karayannis & Sirkelis 2008). Concrete mean cylinder compressive strength at the age of 28 days was f_{cm} = 36.4 MPa and the nominal steel yield strength was 500 MPa.

The geometry and the reinforcement characteristics of specimens B-S1 and rehabilitated B-S1(R) are (Table 1 and Figure 1): Total column length and cross-section dimensions are 3000 mm and 350/250 mm, respectively, whereas the beam length and cross-section dimensions are 1875 mm and 250/350 mm, respectively and stirrups are ∅8/100mm. Beam reinforcement of specimens comprises 4∅14 deformed steel bars at the top and 4∅14 deformed steel bars at the bottom. Column reinforcement comprises 4∅14 corner deformed steel bars and ∅8/100mm stirrups. Concrete mean cylinder compressive strength at the age of 28 days was f_{cm} = 34 MPa and the nominal steel yield strength was 500 MPa.

Table 1. Geometry, reinforcement arrangement and rehabilitation procedure of the beam-column joint specimens.

Specimen	Columns	Beam	Joint area	Rehabilitation
A-S0	Total length 1800 mm 200×200 mm 4∅10 (corner bars) Stirrups: ∅8/150 mm	200/300 mm 2∅10 (top bars) 2∅10 (bottom bars) Stirrups: ∅8/150 mm	-	-
A-S0 (R)				meticulously repaired with epoxy resin injections and strengthened with FRPs
B-S1	Total length 3000mm	250/350 mm 4∅14 (top bars)	1∅8 (∅8/175 mm)	-

B-S1(R)	250×350 mm 4∅14 (corner bars) Stirrups: ∅8/100 mm	4∅14 (bottom bars) Stirrups: ∅8/100 mm		roughly repaired with high strength cement mortar and strengthened with FRPs

For all specimens supports that allow rotation were used to simulate the inflection points assumed to occur at the mid-height of the columns in a laterally loaded frame structure. The test setup and instrumentation for specimens B-S1 and B-S1(R) can be seen in the pictures of Figure 5. Column axial load N_c equal to $0.05A_cf_c$ was applied during the tests to all the specimens.

The specimens were subjected to increasing full cyclic deformation imposed near the free end of the beam by an actuator. For the specimens A-S0 and A-S0(R) each loading step included one full loading cycle and the imposed deformation was 10mm/cycle whereas these specimens suffered four (4) loading steps. For the specimens B-S1 and B-S1(R) each loading step involved three (3) full loading cycles and these specimens suffered a loading history of six loading steps with maximum displacements ± 8.5 mm, ± 12.75 mm, ± 17 mm, ± 25.5 mm, ± 34 mm, ± 51mm, respectively.

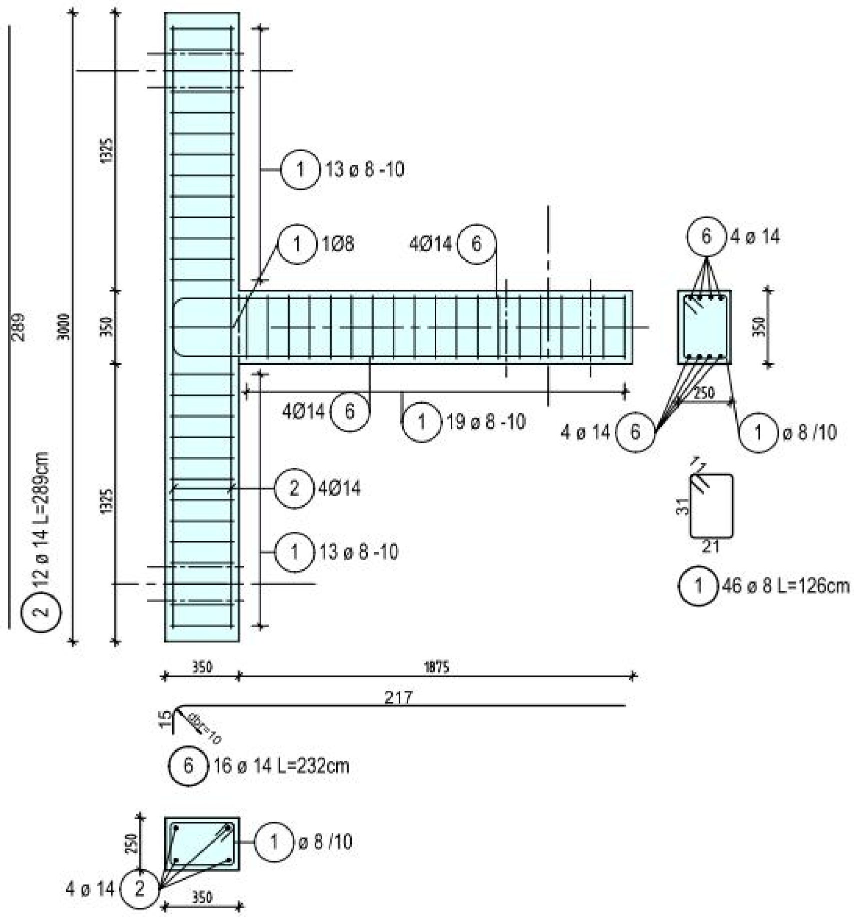


Figure 1. Specimen B-S1.

The rehabilitation of the specimens has been performed using C-FRP sheets. The specimen A-S0 was first meticulously repaired with the application of epoxy resin injections. The repair technique applied in the case of specimen A-S0(R) (repaired specimen A-S0) entailed superficial sealing of all visible cracks with a layer of thick epoxy resin paste and followed by a thin epoxy resin injection into the crack system of the damaged area of the joint until total fill up was achieved (Karayannis et al 1998, 2003, Karayannis & Sirkelis 2008). Finally, the repaired specimen was strengthened with two layers of C-FRP sheets.

The specimen B-S1 was first roughly repaired with the superficial application of high strength cement mortar. After that the specimen was rehabilitated using C-FRP sheets. FRP retrofitting scheme for specimen B-S1(R) is shown in Figure 2. The FRP sheets application in the common case that transverse beams coexist in the joint can be considered a major shortcoming of this technique. Carbon FRP sheets with nominal values of modulus of elasticity ≥ 240 GPa, tensional strength ≥ 4 GPa, strain elongation at fibre rupture 1.70 % were used.

3. TEST RESULTS - COMPARISONS

To assess the effectiveness of the two rehabilitating techniques we examined the hysteretic response of the beam-column subassemblages A-S0 and B-S1 and compared it with the hysteretic response of the corresponding rehabilitated specimens A-S0(R) and B-S1(R).

The hysteretic response of specimen A-S0 and the corresponding rehabilitated specimen A-S0(R) are presented in Figure 3a and are compared to each other (Group A). Furthermore the hysteretic response of specimen B-S1 and the corresponding rehabilitated specimen B-S1(R) are presented in Figure 3b and are compared to each other (Group B), too.

From the hysteretic response diagrams (Figure 3) it can be deduced that the application of the C-FRP sheets was successful in the presented cases. In Group A the application of resin injections prior to the application of the FRP sheets was significant and resulted in the strengthening of capacities (see also Figure 3a) of specimen A-S0(R).

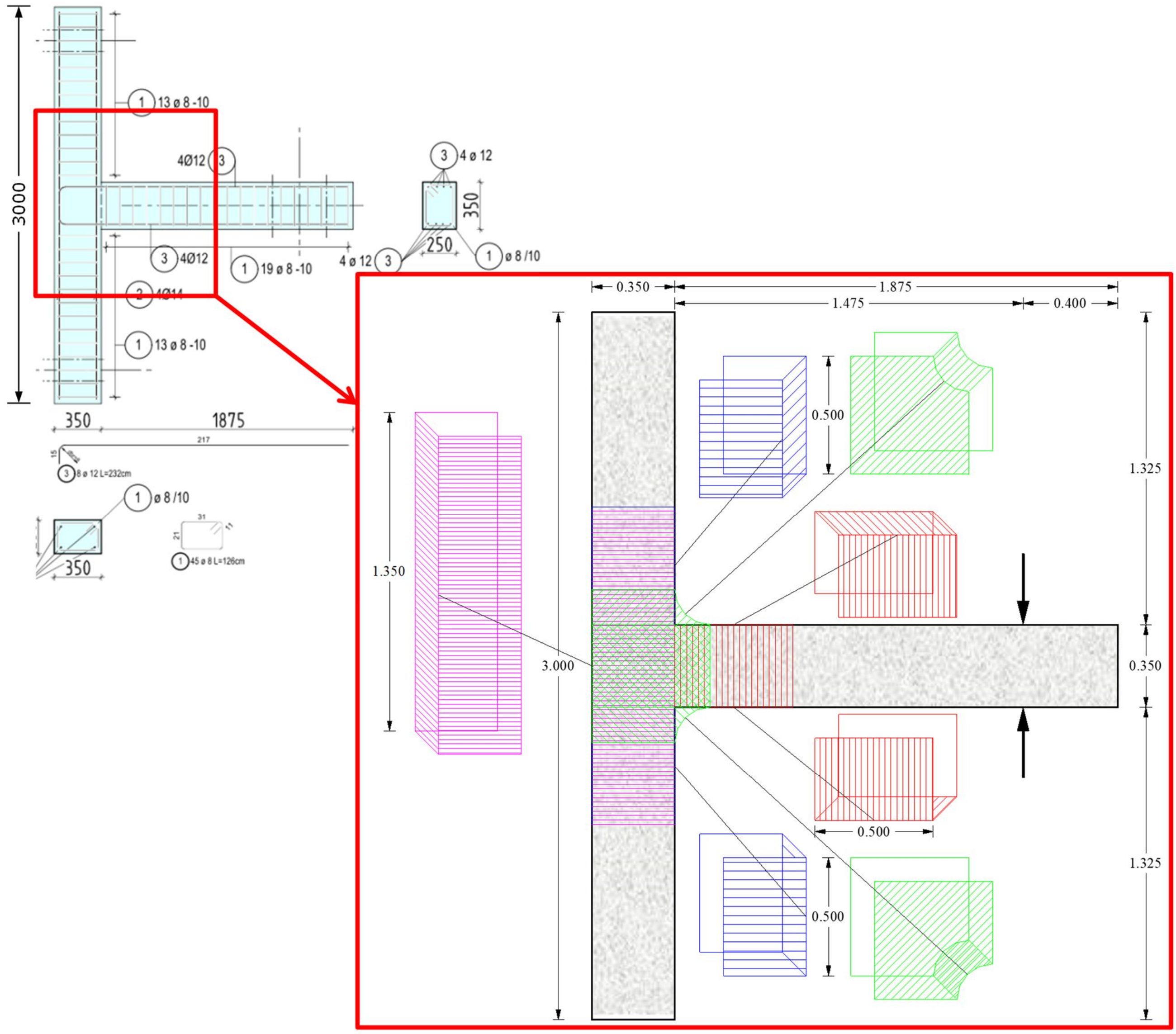


Figure 2. FRP-retrofitting scheme of specimen B-S1(R)

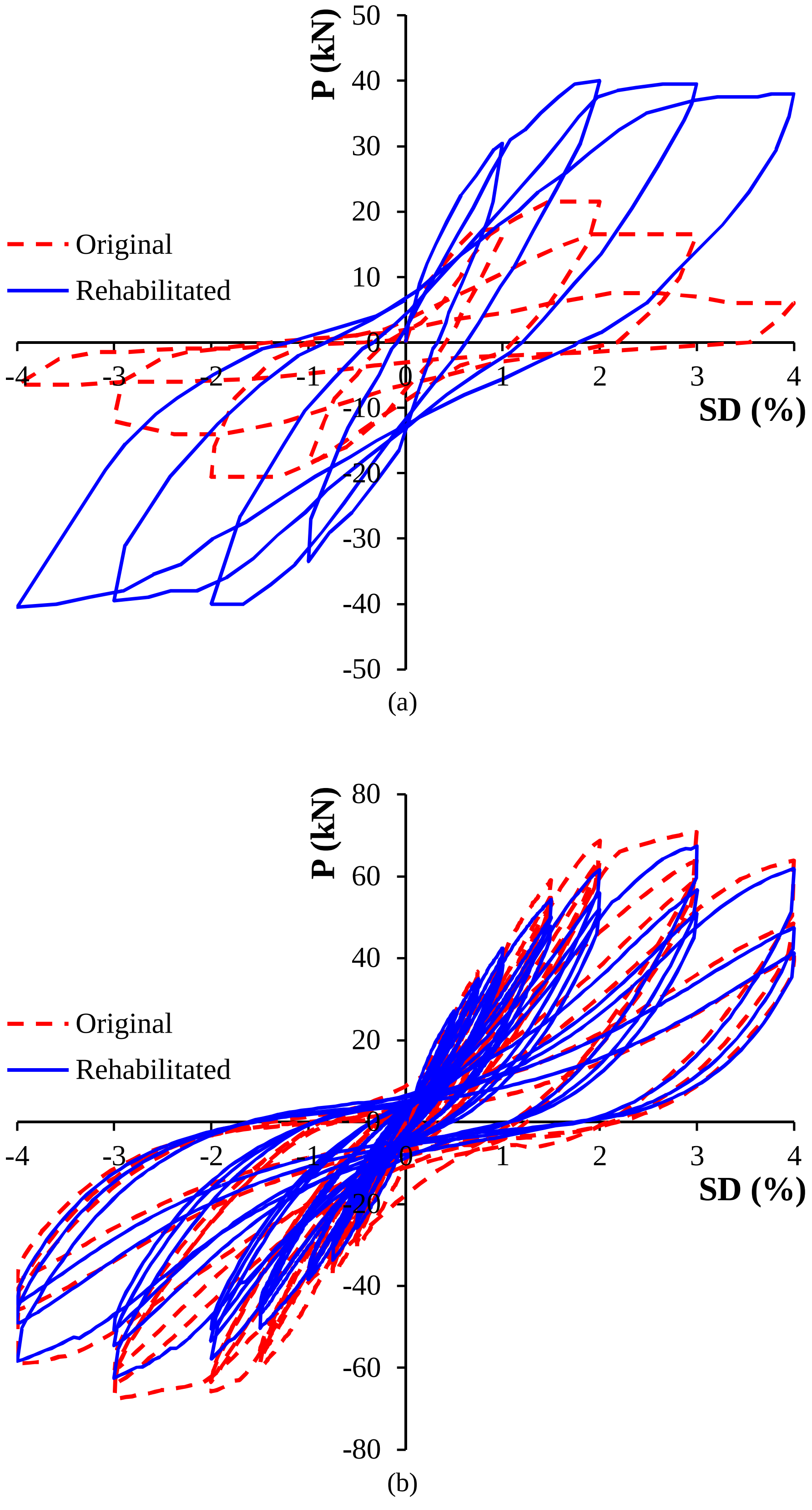
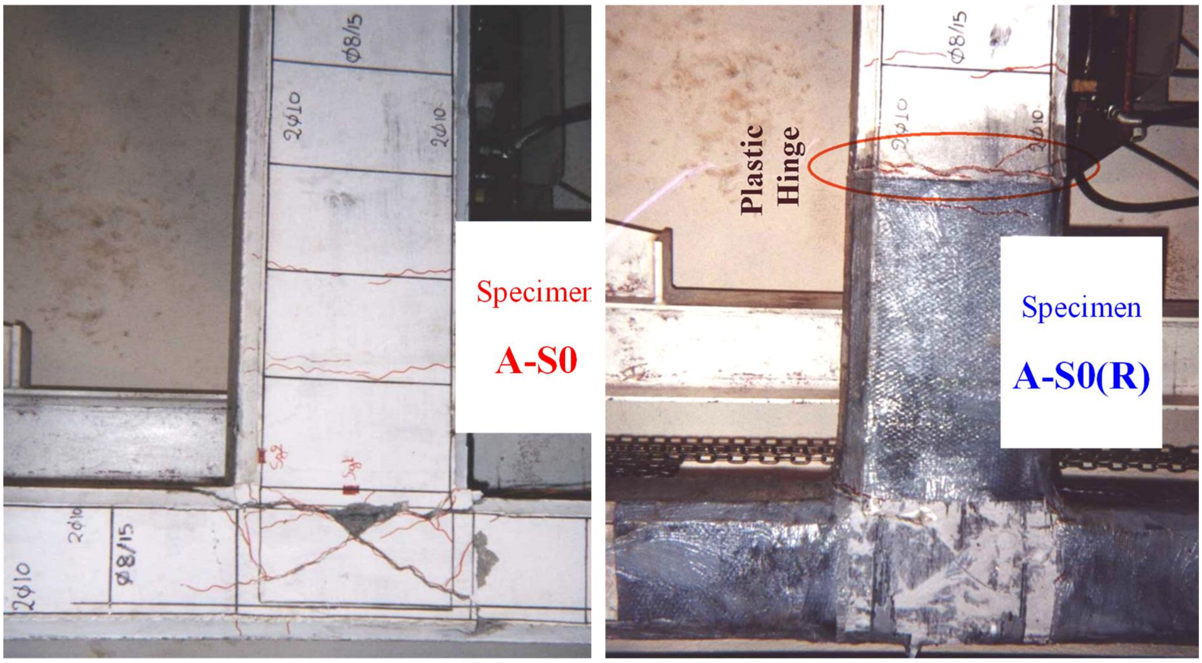


Figure 3. Hysteretic response diagrams of the tested specimens: (a) beam-column joint specimens of group A, (b) beam-column joint specimens of group B

The specimen A-S0 had no shear reinforcement in the joint body therefore significant cracks were formed in the early stages of the loading in the joint body. A severe diagonal crack appeared at the centre of the joint body due to the internal tension forces caused by the pull out of the insufficient straight length of the anchorage of the beam bars (Figure 4a). In the 4th loading cycle, at a displacement level equal to ±40mm, the load capacity of the specimen was reduced (see red dashed line in Figure 3a). The rear part of the joint remained intact.

The rehabilitated specimen A-S0(R) was repaired with epoxy resin and strengthened with two layers of C-FRP sheets. It had suffered the same cyclic loading sequence as specimen A-S0 without significant decrease in the load. The response of this specimen was totally different from the initial one since damage appeared during the loading cycles in the part of the beam body that was not wrapped with the C-FRP sheets. Flexural cracks appeared and eventually a plastic hinge was formed in the beam body near the end of the beam part that was wrapped, as shown in Figure 4b (Karayannis & Sirkelis 2008).

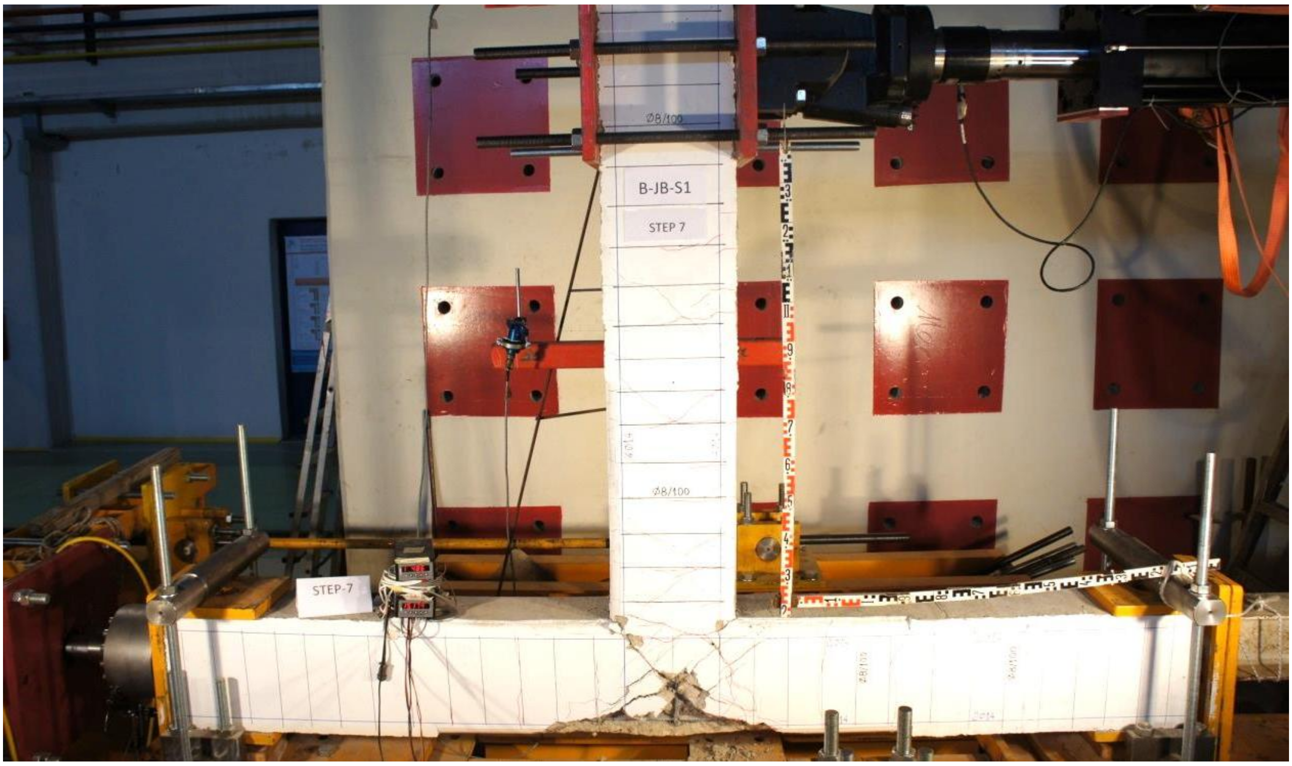


(a) (b)

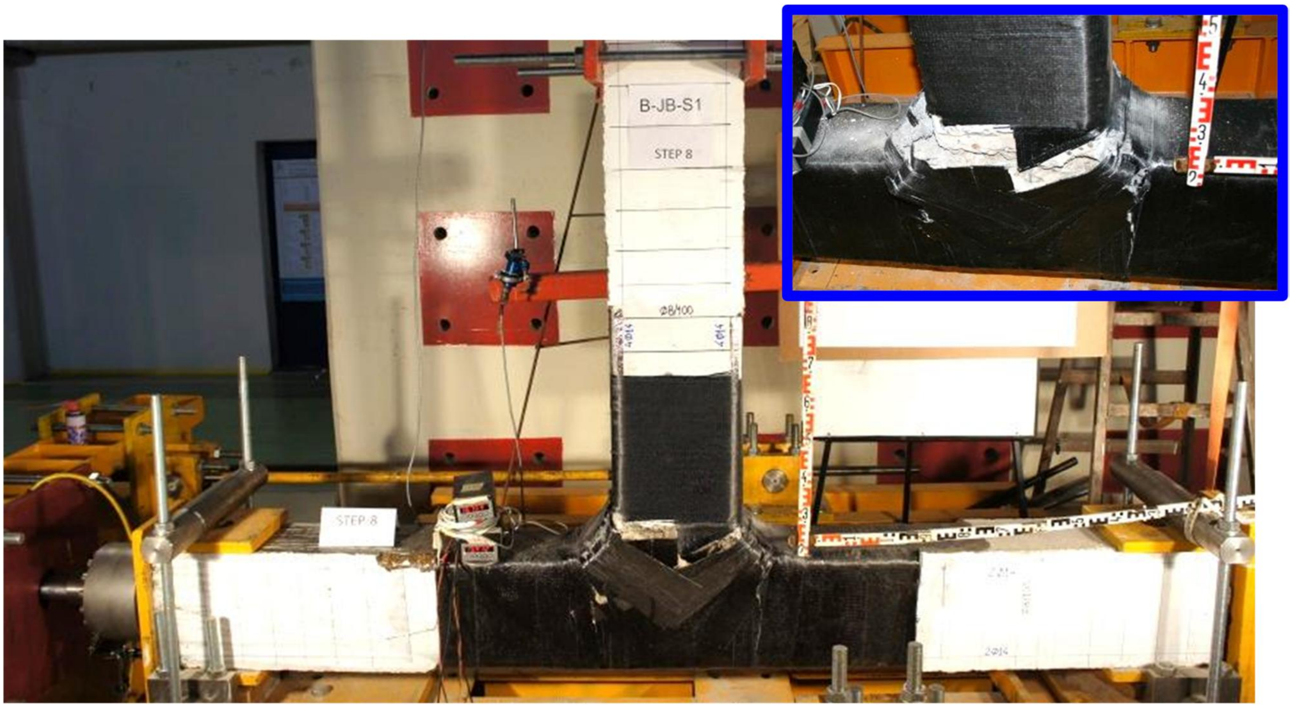
Figure 4. Damage modes and crack patterns of the tested beam-column joint specimens of group A: (a) Original specimen A-S0, (b) Rehabilitated specimen A-S0(R)

Specimen B-S1 had only 1 stirrup as shear reinforcement in the joint body and therefore major cracks were formed in the joint body. Severe diagonal cracks appeared at the centre of the joint body due to the internal tension forces caused by the pull out of the insufficient straight length of the anchorage of the beam bars. After that point the load increase was insignificant and the joint body rapidly disintegrated (Figure 5a). In the 4th loading cycle, at a displacement level equal to ±40mm, the load capacity of the specimen was considerably reduced (see red dashed line in Figure 3b).The rear part of the joint did not remain intact.

The rehabilitated specimen B-S1(R) was rehabilitated with C-FRP sheets as shown in Figure 2. After that it suffered the same cyclic loading sequence as specimen B-S1 without significant decrease in the load. The response of this specimen was almost identical to the initial one as clearly shown in Figure 3b. Damage appeared during the loading cycles in the part of the beam body that was not wrapped with the C-FRP sheets as seen in Figure 5b.



(a)

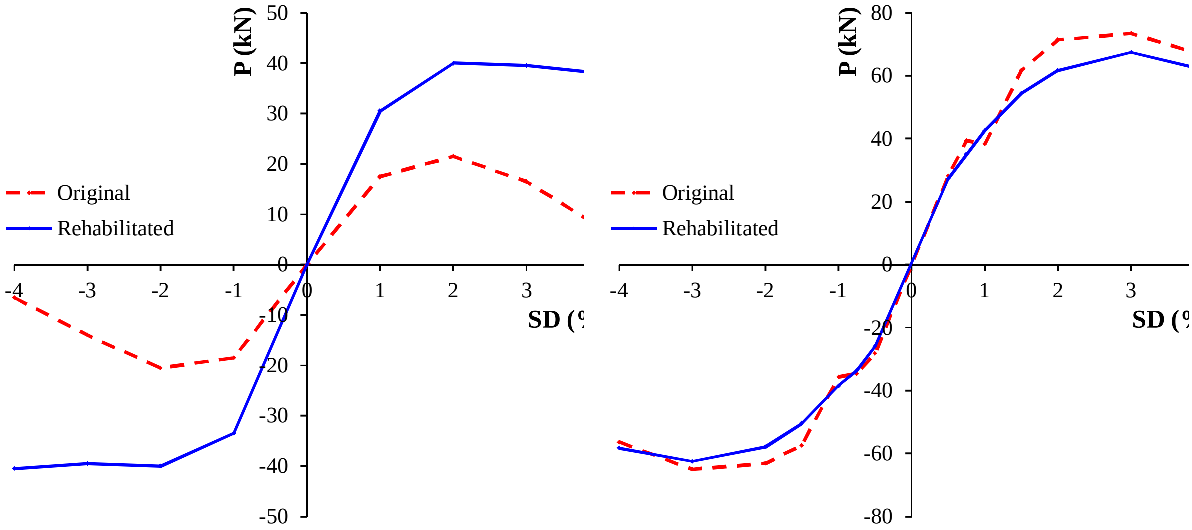


(b)

Figure 5. Damage modes and crack patterns of the tested beam-column joint specimens of group B: (a) Original specimen B-S1, (b) Rehabilitated specimen B-S1(R)

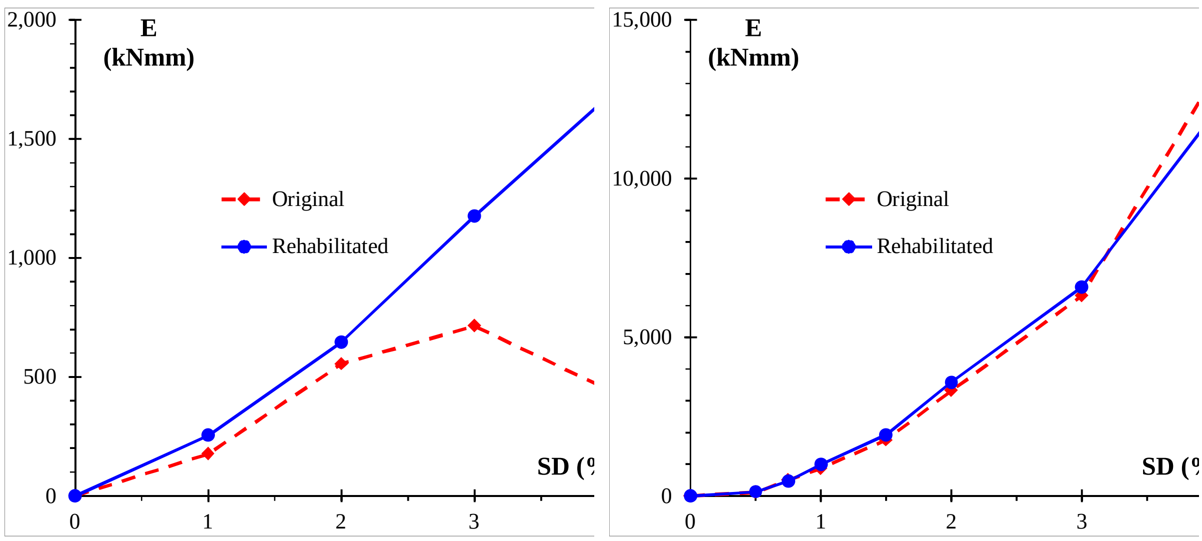
To enable a better understanding of the behavioural characteristics of the rehabilitated joint specimens data concerning the maximum cycle loads of the rehabilitated specimens was collected and presented in comparison with the corresponding one of the initial specimens in the form of envelope curve diagrams as shown in Figure 6. These curves indicate that the rehabilitation technique applied to Group A specimens can be considered a strengthening intervention whereas the rehabilitation technique applied to Group B specimens can be seen as a repair intervention.

Furthermore data concerning the hysteretic energy absorption capability of the rehabilitated specimens was acquired and is presented in comparison with the corresponding one of the initial specimens in Figure 7.



(a) (b)

Figure 6. Envelope curves of observed maximum loads of the hysteretic response of the tested specimens: (a) Beam-column joint specimens of group A, (b) Beam-column joint specimens of group B



(a) (b)

Figure 7. Energy absorption of the tested specimens: (a) Beam-column joint specimens of group A, (b) Beam-column joint specimens of group B

4. CONCLUDING REMARKS

The experimental results of the cyclic response of two full scale external beam-column joint subassemblages (Group B specimens: B-S1 and the rehabilitated B-S1(R)) have been presented. Furthermore elaborate data of two more beam-column joints (Group A specimens: A-S0 and the repaired-strengthened A-S0(R)) taken from the literature (Karayannis & Sirkelis 2008) is also included in this study to enable comparisons.

A full scale beam-column joint specimen (specimen B-S1) is tested under cyclic loading and then it is rehabilitated with the application of C-FRP sheets without prior application of resin injections to the cracking system. The rehabilitated joint (specimen B-S1(R)) is then re-tested under the same loading. According to the findings, the rehabilitated specimen B-S1(R) was affected without significant decrease in the load in the second testing compared to the initial test of B-S1(R). The response of this specimen was almost the same as the initial one. These observations can lead to the concluding remark that this rehabilitation technique can be considered a successful repair technique.

To enable comparisons elaborate data from a beam-column joint (specimen A-S0) that was first meticulously repaired with the application of epoxy resin injections and then strengthened with C-FRP sheets was also presented herein. This specimen, A-S0(R), was repaired with epoxy resin injections and strengthened with two layers of C-FRP sheets. After that it suffered the same cyclic loading sequence as specimen A-S0 without significant decrease in the load. The response of this specimen was totally different from the initial one since damage appeared during the loading cycles in the part of the beam body that was not wrapped with the C-FRP sheets. In this particular case, epoxy resin injections were applied to the cracking system of the damaged specimen prior to the application of the FRPs and the experimental findings suggest that this technique is a significant improvement on the load carrying capacity, the energy absorption and the ductility of the initial joints. Furthermore, the FRP-strengthened joints exhibited an improved type of damage comparing to the damage modes of the reference specimens.

From the hysteretic response curves and the energy absorption curves it can be concluded that the rehabilitation technique applied to Group A specimens can be considered a strengthening intervention whereas the rehabilitation technique applied to Group B specimens should be seen as a repair intervention. Nevertheless, from the observed response of the tested specimens it can be deduced that both applied retrofitting techniques are appropriate for the rehabilitation of the overall hysteretic performance of seismically damaged joints. Furthermore, the FRP-strengthened joints exhibited an improved type of damage compared to the damage modes of the reference specimens. Finally a shortcoming of the FRP technique can be considered the difficulty of the application of FRP sheets in the common case that transverse beams coexist in the joint.

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