Ultra-high-performance fiber reinforced concrete: an innovative solution for strengthening old R/C structures and for improving the FRP strengthening method

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Abstract

In this study a new innovative method of earthquake-resistant strengthening of reinforced concrete (R/C) structures is presented for the first time. Strengthening according to this new method consists of the construction of steel fiber ultra-high-strength concrete jackets without conventional reinforcement, which is usually applied in the construction of conventional reinforced concrete jackets. An innovative solution is also proposed for the first time that ensures a satisfactory seismic performance of existing reinforced concrete structures, strengthened by using composite materials. The weak point of the use of such materials in repairing and strengthening old R/C structures is the area of beam-column joints. According to the proposed solution, the joints can be strengthened with a steel fiber ultra-high-strength concrete jacket, while strengthening of columns can be achieved by using CFRPs. The experimental results showed that the performance of the subassemblage strengthened with the proposed mixed solution was much better than that of the subassemblage retrofitted completely with CFRPs.

Keywords: steel fiber ultra high-strength concrete, reinforced concrete jackets, fiber reinforced polymers, beam-column joints, columns, cyclic loads.

1 Introduction

Damage incurred by earthquakes over the years has indicated that many reinforced concrete (R/C) buildings, designed and constructed during the 1960s

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and 1970s, were found to have serious structural deficiencies today. These deficiencies are mainly due to lack of capacity design approach and/or poor detailing of the reinforcement. As a result, lateral strength and ductility of these structures were minimal and hence some of them collapsed [1–3]. One of the most popular pre-and post-earthquake retrofitting methods for columns, beam-column joints and walls is the use of reinforced concrete jacketing. In retrofitting building columns, b/c joints and walls with outer R/C jackets, the usual practice consists of first assembling the jacket reinforcement cages, arranging the formwork and then placing the concrete jacket [4–7]. Shotcrete can be used in lieu of conventional concrete in the repair works and, in some cases, offers advantages over it, the choice being based on convenience and cost.

The wrapping of reinforced concrete members (usually columns, b/c joints and walls) with fiber-reinforced polymer (FRP) sheets including carbon (C), glass (G) or aramid (A) fibers, bonded together in a matrix made of epoxy, vinylester or polyester, has been used extensively through the world in numerous retrofit applications in reinforced concrete buildings. These are recognized as alternate strengthening systems to conventional methods such as plate bonding and shotcreting [8, 9].

The best choice of the appropriate retrofitting method highly depends on the feasibility of the method, on the cost and on the simplicity of the application. Of course, it is well known that the works related to strengthening of buildings have higher difficulties and cost compared to the usual construction works related to the construction of new reinforced concrete buildings.

According to the above conception it would be very interesting to create and introduce in the marketing a new method of retrofitting old reinforced concrete structures, as effective as the other methods of retrofitting but simpler in application and more economical. An earthquake strengthening system with the aforementioned qualifications would be very competitive among the others.

Henager [10], successfully replaced all the hoops of the joint region and part of the hoops of the critical regions of the adjacent beam and column of an earthquake-resistant beam-column subassemblage, by steel fibers (1.67% fiber volume fraction is used). This replacement involved 50% reduction in building costs.

Fiber Reinforced Concrete or Shotcrete has been successfully applied in many construction applications eliminating or significantly reducing the conventional reinforcement of R/C structures and reducing the construction costs.

The advantages of Fiber Reinforced Concrete has been worldwide recognized, however has not been found yet a reliable way of application of this material in the retrofitting of old reinforced concrete structures, by eliminating or significantly reducing the conventional reinforcement of the R/C jacketings and generally by reducing the cost of retrofitting compared to that involved by the use of other strengthening methods as plate bonding and FRPs. A relatively new process called SIMCON (Slurry Infiltrated Mat Concrete) developed by Hackman et al. [11], seems to be very effective in strengthening applications. SIMCON is made by infiltrating continuous steel fiber-mats, with specially designed cement-based slurry. Nevertheless, SIMCON technique has the same

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disadvantages as FRPs. Their strengthening layers wrap usually horizontally the columns and the walls increasing their shear strength and ductility, but these layers are terminating in the slabs of the strengthening reinforced concrete buildings. The strengthening layers could not effectively pass through the slabs, thus these layers could not increase the flexural strength of the columns and walls and could not effectively retrofit the beam-column joint regions. The existing experimental results related to the retrofitting of beam-column subassemblages of reinforced concrete structures demonstrated significant damage concentration in the joint regions, although the subassemblages used were of planar-type, without slabs and the retrofitting works related to SIMCON application were easy [12].

2 The proposed new innovative strengthening method

An important experiment was conducted by Tsonos [13]. An exterior beam-column subassemblage L_3 poorly detailed in the joint region was subjected to unidirectional reversed cyclic lateral loading. The joint region of this subassemblage was representative of the joint regions of old structures built during the 1960s and 1970s. The subassemblage was reinforced in the joint region by one hoop of diameter 8mm instead of the five hoops of the same diameter required by the ACI-ASCE Committee 352 (ACI 352R-02) [14]. The joint shear stress of the specimen was higher than the maximum allowable joint shear stress by the same Committee ($\tau_{joint} = 1.36\sqrt{f'_c} > \tau_{permitted} = 1.0\sqrt{f'_c}$). As expected, this specimen failed in pure and premature joint shear failure from the early stages of the seismic-type loading. The removal and replacement of the damaged concrete in the joint by a non-shrink, non-segregating steel fiber concrete of high-strength with only 0.5% fiber volume fraction and the removal and replacement of the damaged concrete cover of part of the columns' critical regions with the same steel fiber high-strength concrete, resulted in a pure beam failure, when the repaired subassemblage RL_3 was imposed to the same loading as the original control subassemblage L_3.

The above experiment led us to the idea of using the same non-shrink, non-segregating steel fiber high-strength concrete for the strengthening of old reinforced concrete buildings, by jacketing not with the use of conventional reinforcement, longitudinal bars or hoops [15]. For this purpose and for best results, it was decided to increase the fiber volume fraction and to increase the compressive and tensile strengths of the steel fiber concrete. The following large experimental program was implemented. Four identical exterior beam-column subassemblages were constructed, using normal weight concrete and deformed reinforcement. The test specimens were 1:2 scale models of the representative 40cm×40cm square columns and beam-column joints which are usually found in building constructions within Greece and Europe in general. The columns and b/c joints of these specimens were poorly detailed in order to represent columns and b/c joints of old buildings built in 1960s and 1970s. In figure 1 are shown the dimensions and cross-sectional details of these specimens. Their columns had less longitudinal and transverse reinforcement than the modern columns and their joint regions had not joint hoops, the joint shear stress were $2.20\sqrt{f'_c}$ MPa $> 1.0\sqrt{f'_c}$ MPa, and the flexural strength ratios of these specimens were lower than 1.0. The concrete compressive strength of these original specimens was approximately 8.50MPa. Thus, a premature joint shear failure is expected for all these subassemblages during a seismic type loading. All these original specimens were subjected to cyclic lateral load histories so as to provide the equivalent of severe earthquake damage. In figure 2 is shown the failure mode of the representative specimen O_3 and its hysteresis loops. The failure of O_3 was concentrated mainly in the joint which lost almost all of the core's concrete.

In the following are described in brief the retrofitting works for specimens O_3, W_2, M_1, and M_3.

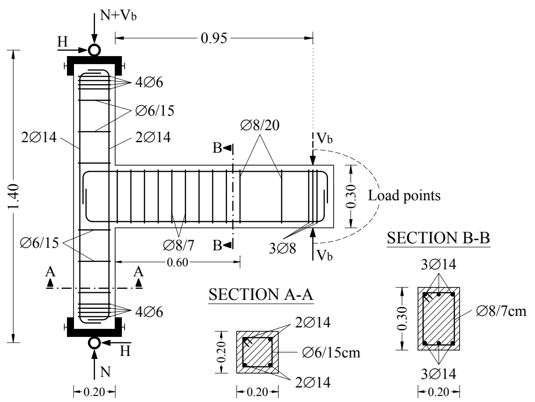


Figure 1: Dimensions and cross-sectional details of original subassemblages O_3, W_2, W_3, M_1, and M_3.

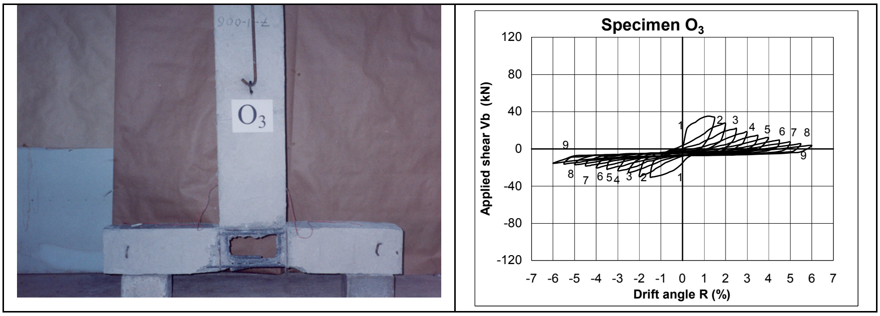


Figure 2: Plots of applied shear versus drift angle and failure mode of the original subassemblage O_3.

1. Specimen O_3 was retrofitted by reinforced concrete jacket in the columns and beam-column joint region. The compressive strength of the jacket's concrete was 31.70MPa. Deformed bars were used for the construction of the steel cage of the jacket. After the interventions this specimen was designated SO_3. In figure 3 is shown the jacketing of column and beam-column connection of subassemblage SO_3.
2. Specimen W_2 was strengthened by a high-strength fiber jacketing in the joint region and on the columns (see figure 3). The damaged concrete of the joint region of specimen W_2 was removed and replaced by a premixed, non-shrink, rheoplastic, flowable and non-segregating concrete of high-strength. The repaired and subsequently strengthened specimen was named FW_2. The design for the retrofit process with carbon fiber-reinforced polymer sheets (CFRPs) was based on $E_f = 235$GPa, $t_f = 0.11$mm (t_f = layer thickness) and $\varepsilon_{fu} = 1.5\%$ (ε_{fu} = ultimate FRP strain).
3. Subassemblage M_1 was strengthened by jacketing with ultra high-strength steel fiber-reinforced concrete (UHSFC) with 1.5% fiber volume fraction in the columns and in the joint region. The thickness of the jacket was only 4.0cm. The repaired and subsequently retrofitted specimen was named $HSFM_1$ (see figure 3).
4. Subassemblage M_3 was retrofitted by jacketing with UHSFC with 1.0% fiber volume fraction, in the columns and in the joint region. The thickness of the jacket was 6.0cm. The repaired and strengthened specimen was named $HSFM_3$ (see figure 3).

The compressive strengths of the UHSFC used for the strengthening of $HSFM_1$ and $HSFM_3$ were 106.33MPa and 102.30MPa respectively. The tensile strength of the UHSFC used, was approximately equal to 12MPa. The steel fibers used were Dramix ZP 30/0.6.

All the above strengthened subassemblage SO_3, FW_2, $HSFM_1$ and $HSFM_3$ were imposed to the same loading as that of their original subassemblages. All strengthened specimens demonstrated increased strength, stiffness and energy dissipation capacity as compared to those of their original specimens (compare hysteresis loops between the original and the upgraded subassemblages in figures 2 and 4 e.g. O_3 – $HSFM_1$). However, the failure mode of SO_3 and FW_2 was quite different from that of all upgraded specimens by the new proposed jackets $HSFM_1$ and $HSFM_3$. Thus although, the beams of both SO_3 and FW_2 yielded, the majority of the damage was concentrated in their joint regions, see failure modes of specimens in figure 4. On the contrary, the failure mode of both specimens $HSFM_1$ and $HSFM_3$ was the optimum one. Formation of plastic hinge in their beams was observed from the first cycles of loading, while the following cycles resulted in damage concentration only in the critical regions of their beams near their joints. A mixed flexural – shear failure mode was observed in their beams at the end of the tests, which was accompanied by severe buckling of the longitudinal beam reinforcement. The joints and the columns of both these specimens were intact at the conclusion of the tests. This excellent seismic performance of both the $HSFM_1$ and $HSFM_3$ subassemblages was demonstrated both in their failure modes (figure 4) and in their hysteresis loops (figure 4).

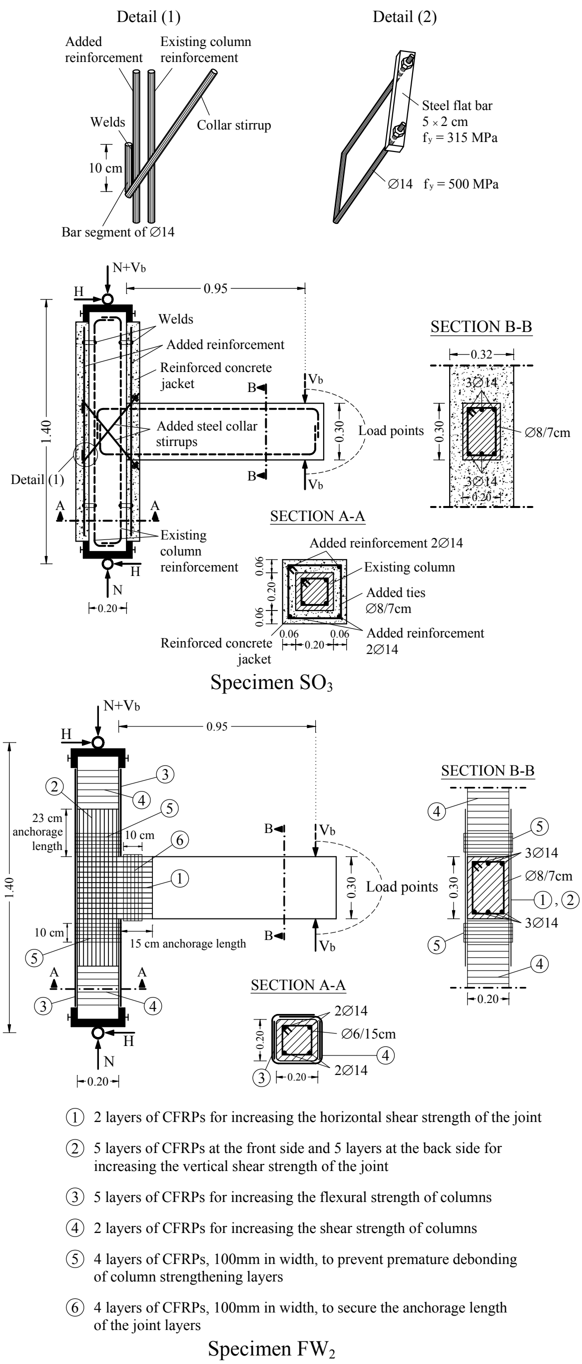
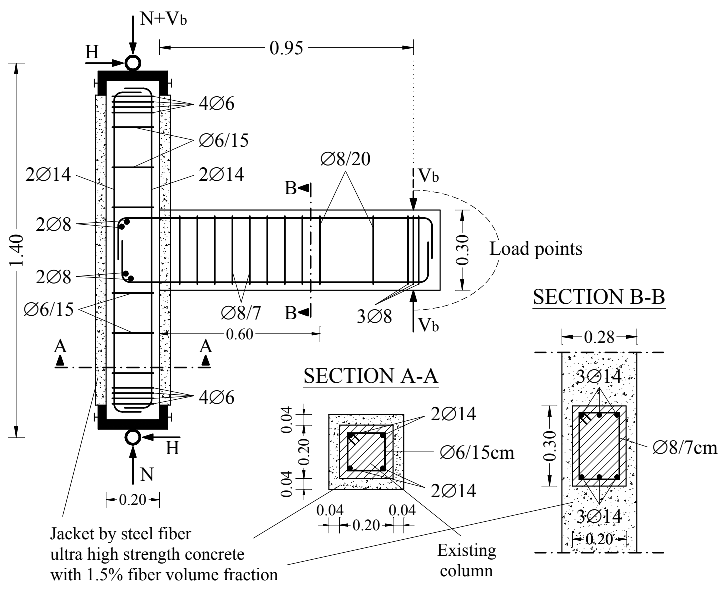
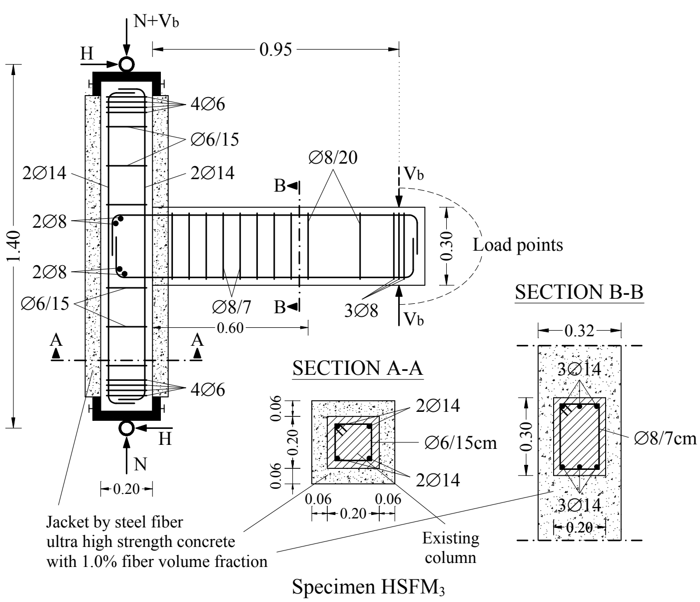


Figure 3: Jacketing of column and beam-column connection of subassemblages SO_3, FW_2, $HSFM_1$, and $HSFM_3$.



Specimen HSFM$_1$



Specimen HSFM$_3$

Figure 3: Continued.

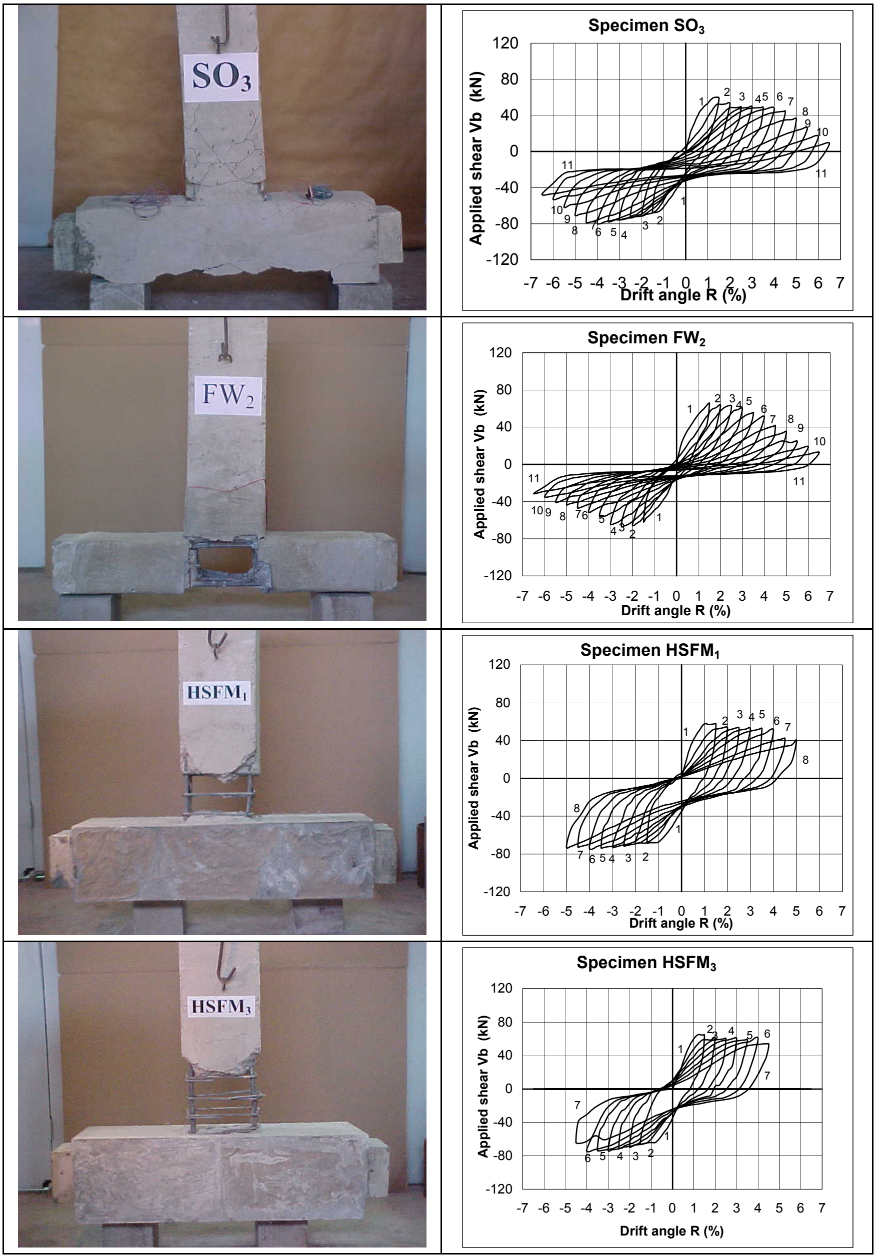


Figure 4: Plots of applied shear versus drift angle and failure mode of the strengthened subassemblages SO_3, FW_2, $HSFM_1$ and $HSFM_3$.

The seismic behavior of both these subassemblages was superior to those of specimens SO_3 and FW_2 retrofitted by reinforced concrete jackets and FRP-jackets.

A patent No 1005657 was awarded to Professor Tsonos [16] by the Greek Industrial Property Organization for the above invention.

3 An innovative new solution for improving the FRP strengthening method

An innovative solution is proposed also for the first time. This solution ensures a satisfactory and perhaps perfect seismic performance of existing old reinforced concrete buildings strengthened by using composite materials FRPs. The weak point in using such materials in repairing and strengthening reinforced concrete structures is the area of beam-column joints. Indeed, all the strengthened subassemblages in the beam-column region with composite materials FRPs of the literature demonstrated in the best case a mixed type failure during seismic type loading. Thus, during the first cycles of loading their beams yielded, however during the following cycles a large part of damage of these strengthened subassemblages was concentrated in their joint regions. Of course, this failure mode is highly dangerous for the people who live in old buildings which were retrofitted in post-earthquake or pre-earthquake cases. The representative failure mode of subassemblage FW_2 clearly demonstrates this critical situation, figure 4. The whole strengthened beam-column joint region of FW_2 not only failed but also was removed (i.e. leaving a hole in this position) during the last cycles of loading. This exactly is the reason why the Greek Code of the Repair and Strengthening of Reinforced Concrete Buildings [17] does not allow the use of composite materials for the strengthening of reinforced concrete beam-column joints.

The second innovative solution presented in this study consists of strengthening the joint regions of subassemblages with a local jacket of ultra-high-strength steel fiber concrete with 1.5% fiber volume fraction, while retrofitting the columns can be achieved by using composite materials FRPs. In order to investigate the effectiveness of the proposed solution of mixed type strengthening a new beam-column subassemblage W_3 identical with the other four (O_3, W_2, M_1 and M_3, figure 1), was constructed and was imposed to seismic type loading as the other original subassemblages. The failure mode of W_3 was the same as that of O_3 previously described. The subassemblage was retrofitted by the new mixed type technique shown in figure 5. After the interventions this specimen was designated $FHSFW_3$. The columns of $FHSFW_3$ and FW_2 were retrofitted exactly in the same way with composite materials CFRPs, while the joint region was retrofitted with ultra high-strength steel fiber concrete with 1.5% fiber volume fraction. Specimen $FHSFW_3$ was imposed to the same type loading as that of the original specimen W_3. The seismic performance of $FHSFW_3$ was optimal. The damage was concentrated only in the critical region of the beam, while the columns and the joint region were intact at the conclusion of the tests. This optimal performance was demonstrated also in the hysteresis loops of the subassemblage $FHSFW_3$. The hysteresis loops of $FHSFW_3$ were

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much better than the loops of FW_2, figures 4 and 6. The latter indicate the serious and almost premature joint shear failure of the subassemblage FW_2, (see fig. 4).

4 Conclusions

1. A new innovative technique for strengthening of poorly detailed structural members of old buildings is proposed for the first time. This method consists of jacketing the structural members with non-shrink, non-segregating steel fiber concrete of ultra high-strength, without the addition of conventional reinforcement in the jackets.
2. This new innovative method was found to be much more effective than the conventional reinforced concrete jackets and especially the FRP-jackets.
3. Beam-column subassemblages, which had failed in pure joint shear failure during seismic-type loading and upgraded in the columns and beam-column joint region by the new innovative technique (patent No 1005657/2007) demonstrated the optimal failure mode, with damage concentration only in the beam region during re-loading with the same loading.
4. A second innovative solution is presented in this study also for the first time. This mixed type technique, by using local jacketing with steel fiber ultra-high-strength concrete only in the joint region, while the columns were upgraded by composite materials, eliminated the disadvantages of the application of composite materials FRPs for the strengthening of old building structures, due to the ineffective strengthening of beam-column joints by FRPs.

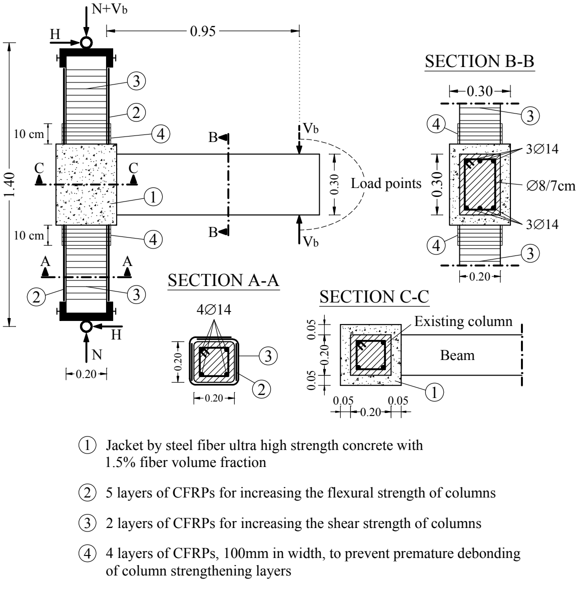

Figure 5: Strengthening of column and beam-column connection of subassemblage $FHSFW_3$ by the new mixed type technique.

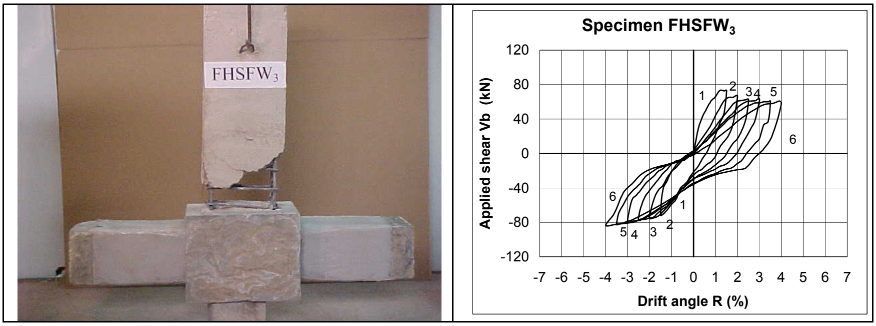

Figure 6: Plots of applied shear versus drift angle and failure mode of the strengthened subassemblage $FHSFW_3$.

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