BEHAVIOR OF FULL-SCALE SHEAR DEFICIENT CORNER RC BEAM-COLUMN CONNECTIONS RETROFITTED WITH CFRP SHEETS

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ABSTRACT

In the current paper, an innovative and practical technique for the seismic rehabilitation of poorly detailed beam-column corner joints using FRP composite sheets has been proposed. A full scale corner beam-column specimen was constructed with inadequate joint shear strength and no transverse reinforcement in the joint; representing pre-seismic code design construction practices of joints and encompassing the vast majority of existing joints. This specimen was subjected to cyclic lateral load histories so as to provide the equivalent of severe earthquake damage. After testing the specimen, the damaged specimen was repaired by filling the cracks through epoxy and externally bonding the CFRP sheets to the joint, beam and part of the column regions. The repaired specimen was then subjected to the similar cyclic lateral load history and its response history was obtained. Response histories of before repair (i.e. original specimen) and after repair specimens were then compared. The results were compared through hysteretic loops, load-displacement envelopes, ductility and stiffness degradation. The results show that CFRP sheets improve the shear resistance and ductility, and delays the stiffness degradation.

1. INTRODUCTION

Load carrying capacity and ductility of reinforced concrete building frames are highly dependent on the reinforcement detailing of the joint connections between its independent members, such as beams and columns. Accordingly, to obtain a sound structural behavior, the joints must be constructed to be at least as strong as the structural members connected to them and show ductile behavior in the ultimate limit state. In a moment resisting reinforced concrete framed buildings, these joints are of three types: interior, exterior and corner. Interior and exterior joints are found at bottom and intermediate levels, and corner joints at the roof level. The corner joints, if designed only for gravity loads and are based on pre-seismic codes, may suffer substantial damage during earthquakes. Several techniques of repair and strengthening of reinforced concrete joints, damaged by earthquakes, have been reported in earthquake prone countries such as Japan, Mexico, and Peru. Of the various repair techniques used, the most common involved were RC or steel jackets. Plain or corrugated steel plates have also been tried. These techniques cause various difficulties in practical implementation at the joint, namely intensive labor, artful detailing, increased dimensions, corrosion protection and special attachments. To overcome the difficulties associated with these techniques recent research efforts have focused on the use of epoxy-bonded Fiber Reinforced Polymer (FRP) sheets or strips with fibers oriented properly so as to carry tension forces due to shear.

In the last four decades several research papers have been published about studying the effect of seismic loads on poorly detailed reinforced concrete beam-column joints, typical of pre-seismic code designed moment resisting frames. Hanson and Connor [1], Zerbe and Durrani [2], Paulay [3], Pantazopoulou and Bonacci [4], Cheung et al. [5], Pantazopoulou and Bonacci [6], Hakuto et al. [7], Hwang and Lee [8], Baglin and Scott

[9] are some of the important contributions. The research papers, however, on FRP-repaired/strengthened beam-column joints are limited. Antonopoulous and Triantafillou [10] conducted a comprehensive experimental program through 2/3-scale testing of 18 exterior joints. Their study demonstrated the role of various parameters, e.g. area fraction of FRP, distribution of FRP etc., on shear strength of exterior joints. They also highlighted the importance of mechanical anchorages in limiting premature debonding. Ghobarah and Said [11,12], El-Amoury and Ghobarah [13] and Al-Salloum and Almusallam [14] developed effective selective rehabilitation schemes for R/C beam-column joints using advanced composite materials. Mukherjee and Joshi [15] studied experimentally the effect of FRP in improving shear strength and ductility of RC beam-column joints under simulated seismic forces. Ghobarah and El-Amoury [16] developed effective rehabilitation systems to upgrade the resistance to bond-slip of the bottom steel bars anchored in the joint zone and to upgrade the shear resistance of beam-column joints. Antonopoulos and Triantafillou [17], Gergely et al. [18] and Almusallam and Al-Salloum [19] presented analytical models for the prediction of shear capacity of the FRP-strengthened beam-column joints.

A detailed review of literature shows that although substantial work is reported on interior and exterior joints but work on corner joints are very limited. Also systematic studies to determine the behavior of the repaired and/or strengthened members under cyclic loading are limited. Moreover, the behavior of seismically excited FRP repaired beam-column joints is not well established at various stages of response e.g. before and after yielding of reinforcements, crushing of concrete, fiber fracture or debonding. The present paper aims to study these issues for corner joints. In the present study, efficiency and effectiveness of carbon fiber reinforced polymers (CFRP) in upgrading the shear strength and ductility of seismically deficient beam-column joints have been studied. A full scale corner beam-column specimen was constructed with inadequate joint shear strength and no transverse reinforcement in the joint; representing pre-seismic code design construction practices of joints and encompassing the vast majority of existing joints. This specimen was subjected to cyclic lateral load history so as to provide the equivalent of severe earthquake damage. After testing the specimen, the damaged specimen was repaired by filling the cracks through epoxy and externally bonding the CFRP sheets to the joint, beam and part of the column regions. The repaired specimen was then subjected to the similar cyclic lateral load history and its response history was obtained. Response histories of before repair (i.e. original specimen) and after repair specimens were then compared. The results were compared through hysteretic loops, load-displacement envelopes, ductility and stiffness degradation.

2. EXPERIMENTAL PROGRAM

One of the main objectives of the present study is to evaluate seismic performance of as-built RC corner joint specimens (Fig. 1) and then compare their seismic performance with that of CFRP-repaired specimen. To accomplish this, a reinforced concrete baseline specimen was cast. In order to make the specimen as representative of pre-seismic code designed beam-column joints, no shear reinforcements were provided in the joint. In finding out the size of the specimen, first a prototype member size was chosen and then a crude analysis was carried out to come up with the most reasonable scale for the test specimen that comply with the available testing facility and equipment. Full scale beam-column joint was found to be the most practical specimen size. The dimensions of the full-scale test specimen are shown in Fig. 1.

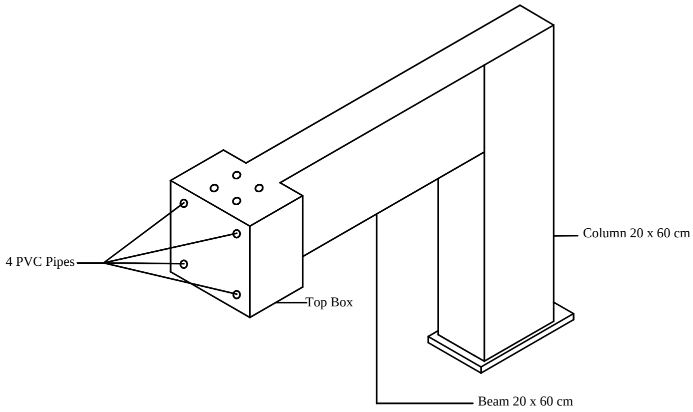

Figure 1: Schematic diagram of corner joint specimen.

The specimen was subjected to cyclic lateral load history so as to provide the equivalent of severe earthquake damage. After testing the specimen, the damaged specimen was repaired by filling the cracks through epoxy and externally bonding the CFRP sheets to the joint, beam and part of the column regions (Fig. 2). The orientation of primary fibers was maintained as shown by horizontal or vertical lines in Fig. 2. The repaired specimen (CR) was then subjected to the similar cyclic lateral load history and its response history was obtained. Response histories of before repair and after repair specimens were then compared.

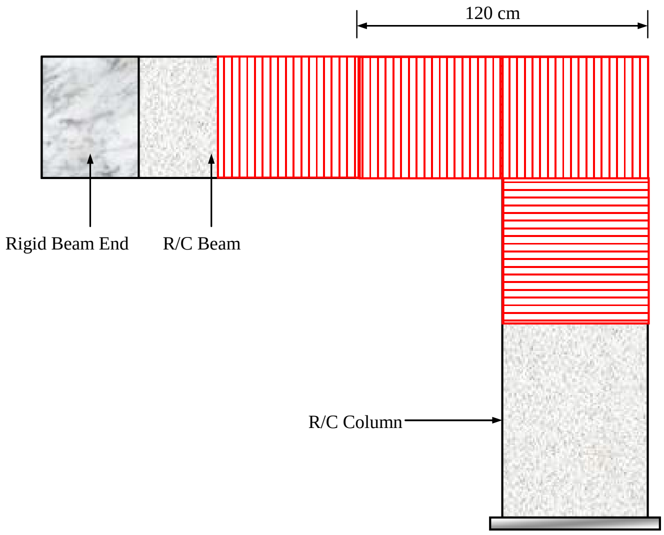

Figure 2: Schematic representation of FRP strengthening/repair scheme.

The corner joint specimens (i.e. before repair and after repair) were tested using the testing apparatus designed and installed in the Structural Test Hall, Department of Civil Engineering, King Saud University, Saudi Arabia (Fig. 3). To apply the simulated seismic type cyclic load on the specimens, a 500-kN servo-controlled hydraulic actuator was connected to a reaction steel frame, stands on a strong concrete floor. Fig. 3 show the experimental set-up designed for testing of corner joint specimens. The bottom of the column surface was attached to a base pivot using 4 high strength threaded rods. The base pivot, in turn, was fastened to a strong steel I-beam. The latter was post-tensioned to the lab floor using high strength post-tensioning rods. The rigid end of the concrete beam was tied to a rigid link through steel pivots.

Figure 3: FRP scheme, instrumentation and test setup.

The specimens were instrumented with several measuring instruments. Four string potentiometers were affixed along the face of the column to measure lateral deflection at different locations along the column height. In order to measure the joint rotation at the beam-column interface, four inclinometers were attached to the concrete surface as shown in Fig. 3. Two LVDTs were placed diagonally at the panel zone in order to assess the joint shear distortion during the experiment.

Internal strain gages were used to measure strain of the longitudinal steel bars and transverse stirrups for both beam and column. These strain gages were mounted in the middle of beam stirrups, column ties and at 5 cm distance from beam-column faces respectively. As corner joints are found at the roof level of moment resisting frames, these specimens were not subjected to the axial load.

In order to test the specimens conventional guidelines of quasi-static type testing, followed by most researchers in simulating seismic forces, was followed (Al-Salloum and Almusallam 2007). All the loading cycles were controlled by the peak displacement until failure. For each displacement level, three fully reversed cycles were completed. It is important to note that the frequency of applied load (or induced displacement) was maintained constant throughout the test program; it was picked up to be around one cycle per minute, which corresponds to a frequency of 0.0167 hertz. All cycles were started with the pull direction first then went into the push direction. For testing of specimens, 1 mm increment was maintained for first 10 mm displacements and then 2 mm increment was used until failure. The two different increments were used in order to complete the tests in a relatively less time as running the actuator for very long time was likely to bring some mechanical troubles in the actuator.

3. EXPERIMENTAL RESULTS

3.1 Hysteretic behavior

The load-displacement relationships for before repair and after repair specimens are shown as hysteretic curves in Figs. 4 and 5. Fig. 5 shows that the ultimate load for repaired specimen is significantly higher than its corresponding before repair specimen (Fig. 4). This is primarily due to the increased confinement of joint resulting from externally bonded CFRP sheets. Further, a comparison of deformation capacity of repaired specimen with before repair specimen illustrate that, the use of CFRP increases the deformation capacity of repaired specimens considerably. This may again be attributed to increased confinement of joint core, adjacent beam and column due to external bonding of CFRP sheets in these regions.

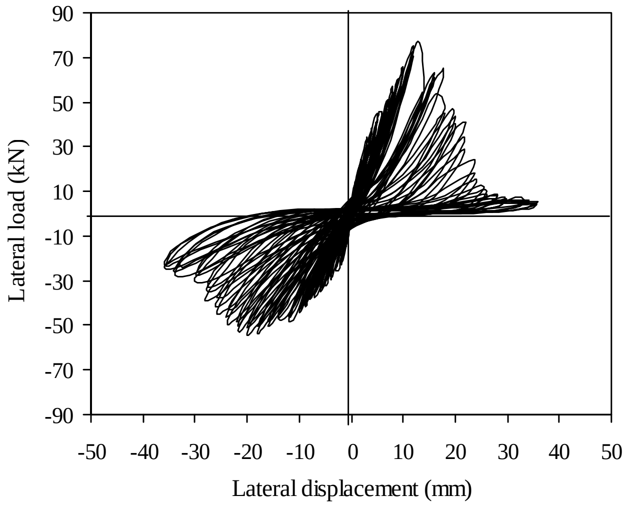

Figure 4: Load-displacement hysteretic plots for before repair specimen.

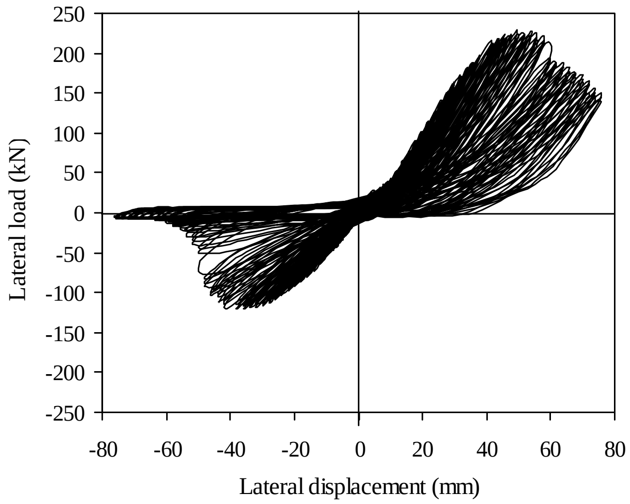

Figure 5: Load-displacement hysteretic plot for repaired specimen CR.

It is to be also noted that hysteretic curves are considerably different in push and pull directions (positive hysteretic plots show push values whereas negative region curves indicate pull values. This difference is due to asymmetric geometry of corner joint and substantially different stiffness in push and pulls directions. Push direction is stiffer than pull direction and therefore in order to have same displacement in push and pull directions (as loading is displacement controlled) actuator applies significantly higher force in the push direction than pull direction.

3.2 Load-Displacement Envelopes

In order to study load carrying capacity and ductility of joint specimens, envelopes of load-displacement hysteretic curves for before repair and after repair specimens are plotted and shown in Figure 6. Using these envelopes the peak load, ultimate displacements, and ductility for the specimens are obtained and listed in Table 1. The third column of this table shows the average peak load (i.e average of peak push and pull values). The Fourth column of this table shows the displacement corresponding to yield displacement. This displacement is required to calculate ductility of the specimen. Other columns of the table are self evident in their meanings. The estimated ductility, an important parameter for earthquake resistant construction, is shown in the last column of this Table. The ductility is computed as the ratio of ultimate displacement to the displacement at first yield of internal steel. For computation, the ultimate displacement was set at a displacement corresponding to 20% drops of peak load. The values of average peak load and displacement clearly show that the application of CFRP sheets has improved the load carrying capacity and deformation capacity of repaired specimen considerably. Such a high improvement in the load carrying capacity and deformation capacity show excellent potential of CFRP sheets in structural rehabilitation.

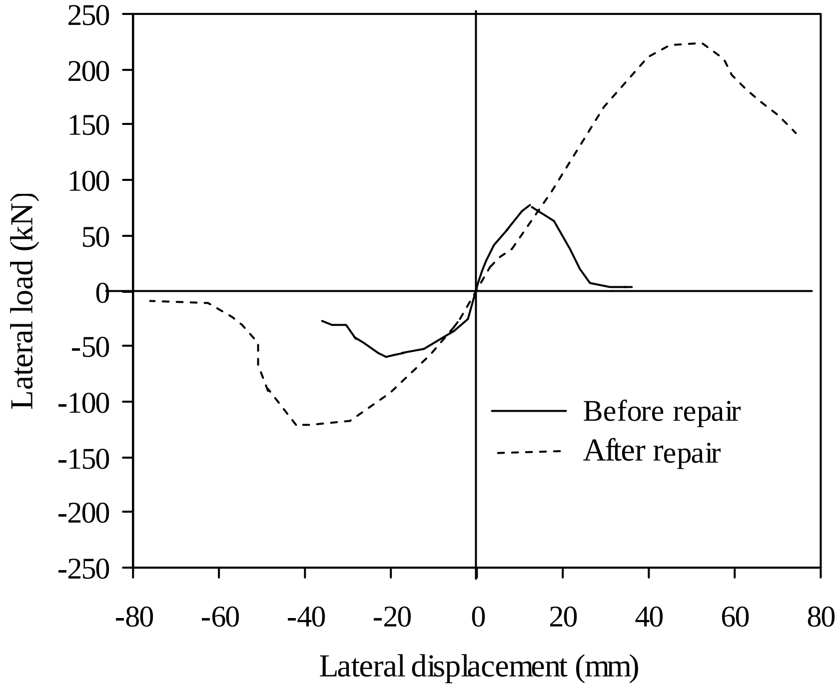

Figure 6: Envelope of hysteretic loops for before repair and after repair specimens.

Table 1: Peak test load and displacement ductility.

Specimens	Average Peak load kN	Displacement at first yield of steel Δ_y (mm)	Average displacement at 20% drop of peak load Δ_{20} (mm)	Displacement ductility Δ_{20}/Δ_y
Before repair	65.90	14.98	22.95	1.53
After repair	174.57	14.98*	58.90	3.93

**Taken same as "before repair" value*

3.3 Stiffness Degradation

Stiffness degradation means, loss in stiffness with increasing lateral movement of the structure (i.e. progress of loading). In other words, as the material of the specimen degrades with progress of load, for a given displacement, required force will keep decreasing. This degradation may be attributed to concrete non-linear deformations, flexural and shear cracking, distortion of the joint panel, loss of cover, slippage or yielding of reinforcement and deterioration in CFRP etc. Figure 7 shows the stiffness degradation with lateral displacement. A comparison of repaired specimen curve with before repair specimen curve shows that the initial stiffness of repaired specimen is substantially less than the before repair specimen. This lower initial stiffness may be attributed to initial damage, lower elastic modulus of the CFRP sheet, and/or yielded steel bars at the initiation of the test. However, this figure reveals clearly that in CFRP repaired specimen, the degradation of stiffness with lateral movement is slow compared to corresponding before repair (control) specimen. This is a desirable property in earthquake like situations. It was observed, in the past earthquakes, most of the RC structures failed (or collapsed) due to sudden loss of stiffness of structural joints with increasing lateral movement of the structure.

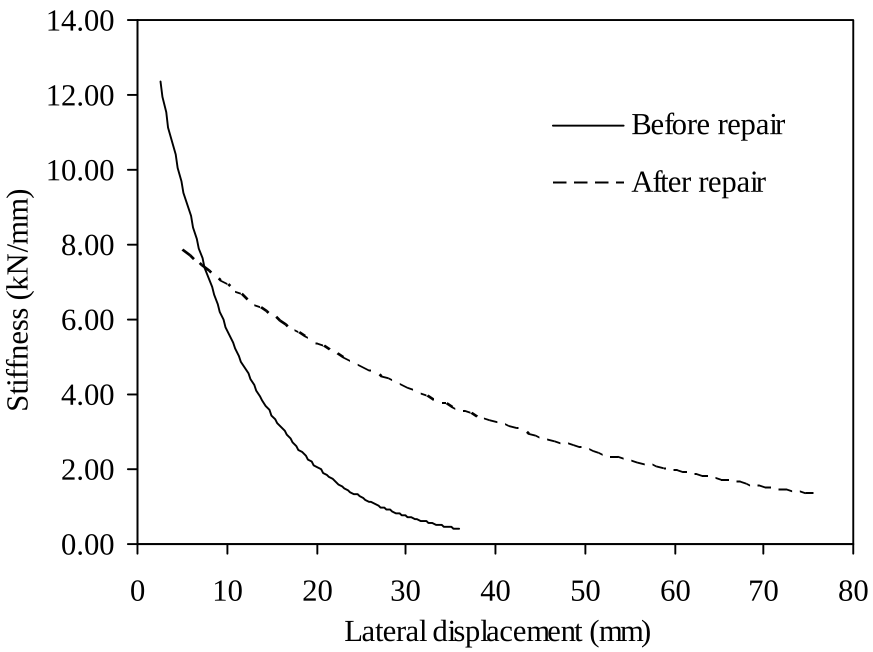

Figure 7: Stiffness degradation in before repair (control) and after repair specimens.

4. CONCLUSIONS

In this paper, effectiveness of externally bonded CFRP sheets in seismic repair of beam-column joints has been studied through full scale testing of corner beam-column assemblages. It was observed that externally bonded CFRP sheets can effectively improve both the shear strength and deformation capacity of corner joints. It was also noticed that CFRP sheets improve the stiffness of damaged specimen and decrease the rate of stiffness degradation substantially.

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