2845

AN INNOVATIVE APPROACH FOR SEISMIC REPAIR AND UPGRADE OF REINFORCED CONCRETE MOMENT FRAME CONNECTIONS

Ayman S MOSOSALLAM[1]

SUMMARY

This paper presents a new potential repair and rehab structural application for polymer composites. The paper investigates the applications of polymeric composite materials and adhesives in developing repair and retrofit systems for reinforced concrete beam-column joint subassemblages. Primary focus is on the low cyclic fatigue behavior of interior beam-column reinforced concrete joints. A description of a pilot research project in this area, at CSUF is presented. In this program, a number of half-scale reinforced concrete connection specimens were fabricated, and instrumented. Two connection specimens were used as control specimens and were tested to failure. These two "repairable" damaged specimens were re-tested under a similar loading regime after being repaired with both epoxy injection and carbon/epoxy & E-glass/epoxy quasi-isotropic laminates. To investigate the performance of the composite systems as retrofit systems, two other half-scale tests were conducted on undamaged specimens strengthened with both E-glass/epoxy quasi-isotropic laminates. Test results indicated that the use of composite overlays has contributed in an appreciable increase in both stiffness and strength of these connections. In addition, the ductility of the repaired connection specimens has been increased up to 42% as compared to the control specimens. Discussion on the advantages and disadvantages of using E-glass/epoxy vs. carbon epoxy laminates is also presented.

INTRODUCTION

For the past few years, both the government and the industry, including the Composites Institute, invested in several major research and demonstration programs to verify, support, and develop repair and rehabilitation systems to upgrade the structural performance of slabs, beams and columns. In rehab applications, test results indicated that the use of composite laminates result in an appreciable increase of the loading capacity of the floor system (beam & slabs), columns and/or walls. The structural capacity gain is translated into the ability of adding more loads to the existing structure. These additional loads have to pass from the upgraded floor system to the upgraded columns or walls via some type of connection. If this connection is not properly upgraded to carry the additional floor loads, sever limitations will be imposed on the amount of composite reinforcements and the allowable upgrade capacity to be added to existing structures which can limit the market of composites in such applications. The main reason is that, by increasing the strength and stiffness of the connected members (e.g. beams and columns), the possibility of *plastic hinge* formation at the column's location will increase substantially. Structural engineers have avoided this concept when designing reinforced concrete ductile moment resisting frames (*DMRF's*).

The design philosophy of DMRF frames follows a concept called "*weak girder-strong column.*" In this procedure, the connection is designed in such a way that the joints and the column remain essentially elastic under the action of the earthquake forces, in order to ensure adequate *energy dissipation* and to provide proper lateral stability of the reinforced concrete structure.

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[1] *Division of Engineering California State University, Fullerton Fullerton, CA 92834, USA*

2. INFLUENCE OF CONNECTION BEHAVIOR OF THE OVERALL SEISMIC PERFORMANCE OF DMRF STRUCTURES

Stiffness or strength degradation of the connection in a DMRF structure has a major impact on the lateral-load resistance of such structures. For this reason, the joint has been identified as the "*weak link*" in DMRF structures. During an earthquake, connection damages can lead to substantial drifts and can increase the possibility of building collapse due to what is called the *P-delta* effects.

The major influence of beam-column connections on the structural integrity and seismic performance of reinforced concrete structures has more evident after the 1989 *Loma Prieta* and the 1994 *Northridge* earthquakes. Post earthquake reports of the Loma Prieta, indicated that one of the main reasons behind the collapse of the *Cypress Viaduct*, and the damage of the *China Basin* and the *I-80 Freeway* is the failure of connections. A site survey, conducted by the Principal Author, of several parking structures in the L.A. in January 1994, indicated that collapse of several portal frame structures were mainly due to the failure of beam-column and column-base connections (see Figure (1))

Designing beam-column joints is considered to be a complex and challenging task for the structural engineer. This is because although the sizing of the connection is determined by the size of the framing members, these joints will be subjected to a different set of loads from those used in designing both the column and the beams. For example, it is necessary to provide a relatively large number of transverse reinforcement (*in form of steel stirrups*) to control cracks and to provide adequate confinement to the joint. These stirrups are difficult to be placed in very limited joint zone and can generally result in improper compaction of concrete at the connection area. One of the determining factors in designing beam-column connections in DMRF structures is the ratio of column-to-beam flexural capacity M_R;

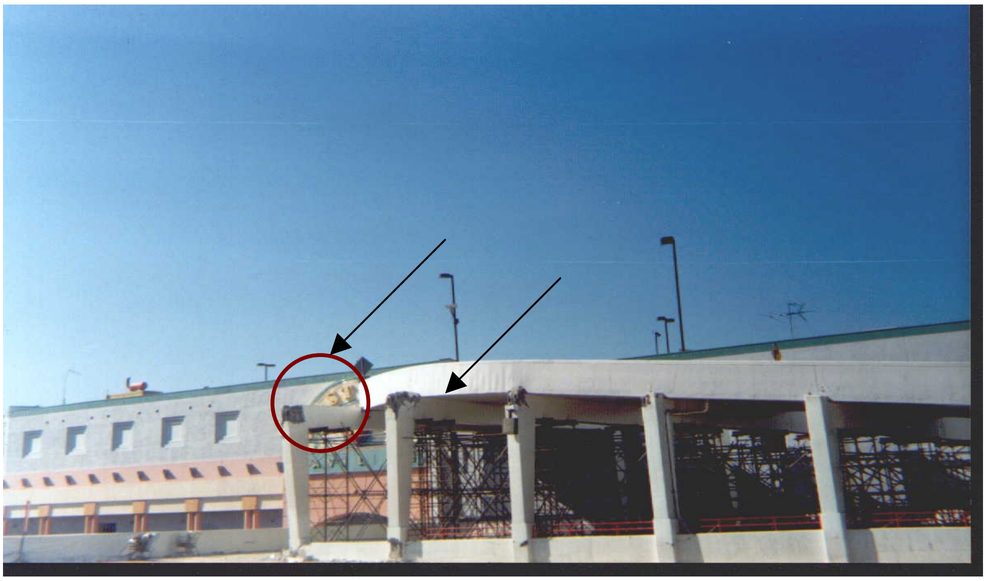

Figure (1): Typical Exterior (Knee) Connection Frame Failure (*Photos: A. Mosallam, January 1994)*

$$M_R = \frac{\Sigma M_C}{\Sigma M_B}$$

Where M_C, M_B are the sum of the flexural capacities of the columns, and beam, respectively. Experimental results indicated that in order to avoid formation of the plastic hinges in the joint, the minimum flexural strength ratio is 1.40. The reason behind that is if the frame structure is subjected to large seismic forces which resulted in some deterioration of the column strength, there is a possibility that the plastic hinge may shift from the beams to the column, which was mentioned earlier should be avoided.

The weak girder-strong column approach requires that in one side, the steel rebars will go from yielding to some or no compression at the other side of the joint. In this case, the beam steel rebars will be exposed to a very high bond stresses. This will result in substantial degradation in the bond strength, and possibility steel reinforcement slippage when exposed to seismic forces. In addition, during an earthquake, the joints will likely be exposed to biaxial forces. In this case, the shear stresses at the joint area will increase. As a result, severe cracking and bond deterioration will likely occur at the connection zone.

3. WHY COMPOSITES?

3.1 General

The building code requirements for structural concrete, ACI 318-95 has been substantially upgrading its provisions for seismic design. However, there are many existing reinforced concrete structures that were built to earlier and less stringent code requirements. As a result, post-earthquake surveys indicated that a number of constructed facilities were found to suffer from damages and collapse that are linked to failure of such connections.

3.2 How Can I convince the Owner or the "Engineer-in-Record"?

For the past few decades, several techniques have been used to repair and upgrade the structural capacity of reinforced concrete frame connections. These include the use of steel stiffeners, external prestressing, epoxy injection, and the use of discontinuous steel fibers concrete at the connection zone. The process of repairing and upgrading the structural capacity of joints using conventional methods is complex, labor intensive, and very costly.

As it was mentioned earlier, over the past few years polymer composites have been utilized successfully in repair and rehab of walls, columns, beams, and slabs of both buildings and highway bridges. Similar performance is expected when using composites in repair and upgrade reinforced concrete connections. There several attractive features which qualify these material in performing this complex task, including:

☛ The *tailorability* of composites can provide the structural engineer with a flexible tool in adding stiffness and or strength to the joint in different directions. For example, simple applications of cross-ply laminate at the joint area will increase the connection shear capacity and will assist in minimizing the development of shear cracking at the joint. For new structures, composites can also be used to minimize the large amount of transverse reinforcement ties that are usually difficult to be placed in the very limited area of the joint.

☛ Under repeated seismic loads, bond strength degradation, and slippage of the steel reinforcement is likely to occur. The use of composite laminate at the joint zone, can minimize the both bond strength deterioration and the possibility of slippage.

☛ The *lightweight* feature of composites will provide several benefits in repairing connections. This include, i) minimizing additional masses, ii) ease of handling and application, iii) eliminating or minimizing the need of heavy equipment, and iv) increasing the site safety,

☛ Composites have a relatively high-energy dissipation capability. This property is important in absorbing the seismic energy, and it acts as polymer dampers at connection zone.

4. EXPERIMENTAL PROGRAM

4.1 Materials and Methods

4.1.1 Beam-Column Specimens.

A total of six half-scale beam-column connection tests were conducted in this pilot study. The beam-column assemblages were designed using the earlier American Concrete Institute (ACI) codes. The specimen size and reinforcements were controlled by ±50 kips (222.40 kN) cyclic load capacity of the hydraulic actuators and the test frame. The yielding strength (f_y) of the steel rebars was 60,000 psi (413.68 MPa). Number 5 (□ 15.9 mm) rebars were used for both column vertical reinforcement as well as for the beam horizontal reinforcements.

Number 2 (∅ 6.35 mm) rebars were used for stirrups. The specimen ends were supported using a special hinged fixture using steel sleeves embedded in the reinforced concrete.

4.1.2 Composites & Epoxy Systems.

Both E-glass/epoxy and carbon/epoxy composites were used in these experiments. The fiber architecture of all laminates was quasi-isotropic ($0^o/90^o/\underline{+}45^o$). This laminate design was based on the cyclic loading demand and the anticipated directions of both flexural and shear cracks. The E-glass laminates were preformed using stitching techniques. Due to the unavailability of the preformed stitched Quadra-axial carbon fiber laminates at the time of the experiment, the quasi-isotropic laminates were constructed using two layers of $0^o/90^o$ laminates with an offset of 45^o. The E-glass/epoxy system was used in the repairing specimen SP-1 and for retrofitting specimen SP-3. For connection specimens SP-2 and SP-4, carbon/epoxy laminates were used.

In these experiments, three types of epoxies were used, namely, a high modulus/high strength, epoxy paste, a high modulus/low viscosity/high strength epoxy to fill cracks and voids on the damaged SP-1 and SP-2, and a two parts high modulus/high strength/medium viscosity epoxy as the polymer matrix for the composite lay-ups. Prior to the application of the composite systems, two methods using epoxy were used to fill the cracks. For specimen SP-1, a manual epoxy gravity-feeding method was used, while specimen SP-2 was repaired using powered epoxy injection technique. All concrete surfaces were ground smooth, wiped clean, and dried completely prior to the application of the composite systems. During the application of the polymer composites, care was taken to ensure full impregnation of the fibers, and excess epoxy was squeezed off to eliminate the chances of creating air voids and epoxy-rich weak links.

4.1.3 Test Fixtures and Instrumentation.

The specimens were tested in a 30 feet (9.15 m), 2-D test frame. This test frame is equipped with dual hydraulic actuators and each actuator has the capacity of ±50,000 pounds (±222.40 kN). Load, deflection, and strain were automatically recorded using a computerized data acquisition system. The relative rotation between the beam and the column was captured using four LVDT's as shown in Figure (2).

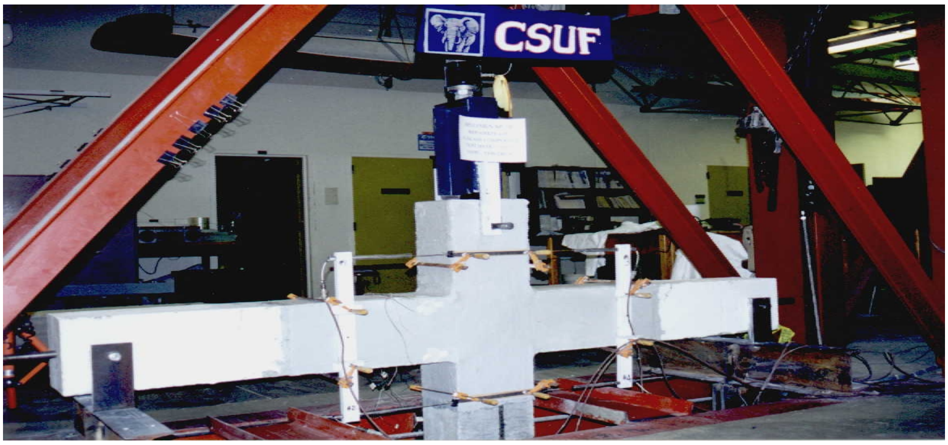

Figure (2): Beam-to-Column Connection Test Setup

4.1.4 Loading Protocol-

The reversal loads were applied to the top of column centerline using a ±50 kips (±222.40 kN). During the load-control regime, an increment of 2 kips (8.9 kN)/ cycle was used. An increment of 0.25 in (63.50 mm) was used for the displacement-control portion of all tests. The loading frequency was selected at 0.25 Hz.

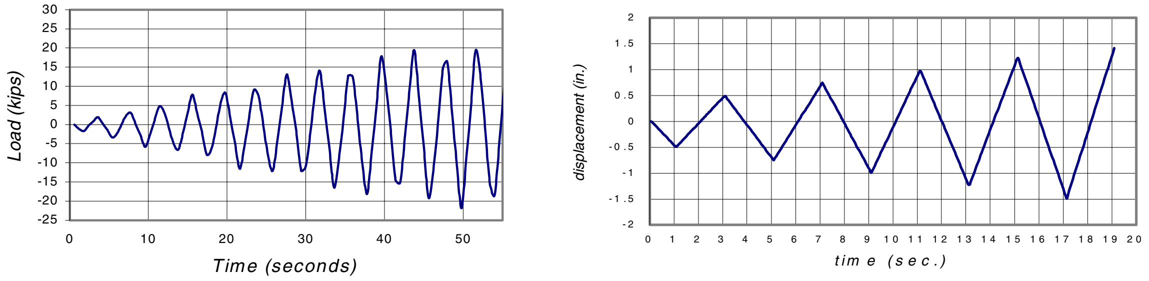

Figure (3): Typical Load Control Regime History for SP-1 and SP-2 and Displacement Control Regime History for All Specimens.

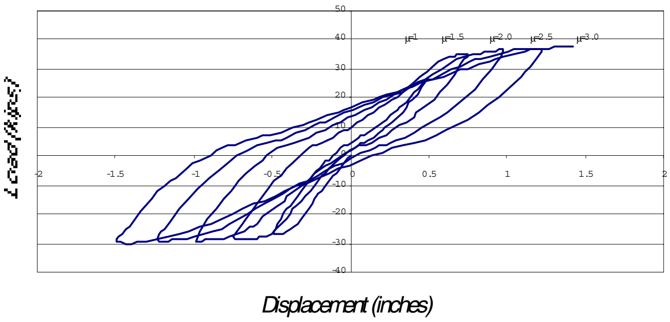

Figure (4): P/δ Hysteresis for A Typical Interior Beam-Column Connection.

Initially, the load-control regime was used to capture the steel reinforcement yielding point of specimens SP-1 and SP-2. The displacements at yield were recorded and used as the calculation baselines for the ductility comparison. Subsequent tests were performed using displacement- control regime up to the ultimate failure load of the connection specimens. Figure 2 depicts the typical load control regime history for specimens SP-1 and SP-2 and the typical displacement regime history for all the specimens. After repairing specimens SP-1 and SP-2, these two were re-designated as SP-1R and SP-2R. Specimens SP-3 and SP-4 were the undamaged specimens and retrofitted with E-glass and carbon composites, respectively. Displacement controlled regime test were performed on SP-1R, SP-2R, SP-3, and SP-4. Figure (4) shows some an example of the P/δ hysteresis curve for beam-column connection tested in this program.

5. SUMMARY OF RESULTS

The use of E-glass/epoxy quasi-isotropic composites for repair of “repairable” damage specimens due to low reversal cyclic loading not only contributed in an appreciable increase in both stiffness, strength, but also enhanced the connection ductility. For specimen SP-1R, the ductility index was 3.40 as compared to 2.4 for the control specimen with an increase of about 42%. This ductility gain is very critical in seismic design of such connections. The increase in ultimate strength and initial stiffness was of the order of 15% and 21%, respectively.

For carbon/epoxy quasi-isotropic laminated repair system of specimen SP-2R, a slight increase in both the ultimate strength and initial rotational stiffness was achieved. However, the repaired damaged specimen exhibited lower ductility as compare to the undamaged connection specimen SP-2. This was expected due to the fact that carbon fiber composites have a higher effective stiffness as compared to E-glass/epoxy laminates.

The use of E-glass/epoxy quasi-isotropic laminates to retrofit undamaged connections in specimen SP-3 has contributed in an increase of about 20% of the initial stiffness of the retrofitted connection as compared to the initial stiffness of the control specimen SP-2 with comparable concrete compressive strength. In addition, the retrofitted connection ultimate strength has been increased about 44% as compared to the same control specimen SP-2.

The results of the destructive test on connections retrofitted with quasi-isotropic Carbon/epoxy quasi-isotropic laminates indicated that an appreciable increase in the connection ultimate strength could be achieved using this lay-up. The increase in the connection strength was in the order of 10% as compared to the control specimen SP-2 with comparable concrete strength. In addition, a 45% increase in the connection initial stiffness was gained by using carbon/epoxy retrofit system.

6. CONCLUSIONS

From the experiments carried out here, it is concluded that in general, the use of quasi-isotropic polymer composites laminates increases both the rotation stiffness and the ultimate strength of the reinforced concrete moment frame connections. Due to the inherent lower stiffness of E-glass/epoxy composites, this system could be used to enhance the ductility of both damaged and retrofitted reinforced concrete connections. In cases where strength is the major design criterion, test results indicated that the use of carbon/epoxy quasi-isotropic laminates is recommended as compared to E-glass/epoxy composites. However, if the ductility is the major criterion, E-glass/epoxy will offer better performance as compared to carbon/epoxy composites.
In all tests, a cohesive failure was achieved; this failure mode is desirable to ensure complete bond between both the sound concrete and the composite laminate(s). In order to achieve that, the concrete surface must be carefully prepared and cleaned to ensure complete bond between the two phases (concrete-composites).

For all specimens, the failure was controlled to occur at the beam. This failure mode is of paramount importance according to the strong-column-weak-beam design philosophy.

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ABOUT THE AUTHOR

Professor Ayman Mosallam, Ph.D., P.E.

Dr. Mosallam is a Research Professor and the director of the Composite structures Group at California State University, Fullerton. He is a registered Structural Engineer. Professor Mosallam has over twenty years of experience with analysis, design, and full-scale testing of composite frame structures and connections. He has published over *eighty* technical papers, chapters, and reports on structural performance of structural systems. In 1996, Dr. Mosallam has been selected as a Subcontractor and Technical Consultant for the ASCE/PIC Prestandard Document on *Structural Design of Pultruded FRP Composite Structures.* In 1993, he has been selected to work as the Technical Advisor for the Pultrusion Industry Council of the SPI on the Phase I of the *Pultrusion Design Manual*. He served as the Chairman of the ASCE/SCAP Subcommittee on Composite Connections, and currently he is the *Chairman* of the ASCE Standards Subcommittee on Composite Connections. He also the *Secretary* of the ASCE/SCAP Subcommittee on the ASCE Structural Plastics Design Manual (SPDM) Revision, and acting as the *Topic Leader* the chapters on *Creep* and *Design of Composite Connections.* Dr. Mosallam is serving on the editorial board of *Composites*: Part B Journal since 1995 and he is the *Guest Editor* of the Journal's Special Issues on Infrastructure Application of Composites. Professor Mosallam has been awarded the Best Design Paper Award from the Composite Institute in both 1992 and 1995, The *Best Commercial Innovation Paper Award* from Plastics World Magazine in 1992, The *Overall Paper Award* from McGraw-Hill Publishing Co. 1992, and the *Faculty Research Achievement Award* from the School of Engineering and computer science, California State university, Fullerton in 1998. He is listed in *Who's Who* in Technology (1997/1998). This year he was recognized by the International Concrete Repair Institute (ICRI) for his technical Contribution.

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Abstract

This paper presents a new potential repair and rehab structural application for polymer composites. The paper investigates the applications of polymeric composite materials and adhesives in developing repair and retrofit systems for reinforced concrete beam-column joint subassemblages. Primary focus is on the low cyclic fatigue behavior of interior beam-column reinforced concrete joints. A description of a pilot research project in this area, at CSUF is presented. In this program, a number of half-scale reinforced concrete connection specimens were fabricated, and instrumented. Two connection specimens were used as control specimens and were tested to failure. These two “repairable” damaged specimens were re-tested under a similar loading regime after being repaired with both epoxy injection and carbon/epoxy & E-glass/epoxy quasi-isotropic laminates. To investigate the performance of the composite systems as retrofit systems, two other half-scale tests were conducted on undamaged specimens strengthened with both E-glass/epoxy quasi-isotropic laminates. Test results indicated that the use of composite overlays has contributed in an appreciable increase in both stiffness and strength of these connections. In addition, the ductility of the repaired connection specimens has been increased up to 42% as compared to the control specimens. Discussion on the advantages and disadvantages of using E-glass/epoxy vs. carbon epoxy laminates is also presented.

[1] *Division of Engineering California State University, Fullerton Fullerton, CA 92834, USA*

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