APPLICATIONS OF COMPOSITES IN REPAIR REINFORCED CONCRETE SUBASSEMBLIES

Ayman S. Mosallam, Ph.D., P.E.
Division of Engineering
California State University, Fullerton, CA 92834, USA

SUMMARY

The paper introduces a new application of polymer composites in repair and rehabilitation of reinforced concrete (R/C) frame connections. In this pilot study, a total of six half-scale reversal cyclic tests were preformed. The tests were conducted on half-scale specimens simulating interior beam-to-column sub-assemblages of a typical R/C structure. 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.

KEYWORDS: Seismic Repair, Reinforced Concrete, Moment Connections, Construction.

INTRODUCTION

For the past few years, several major research projects were launched to investigate the feasibility of using composites in both seismic and corrosion repair of structural systems made of reinforced concrete, steel, and wood materials. The majority of these programs were sponsored by the state and federal government as joint programs with the industry. The overwhelming experimental and analytical results have encouraged the civil engineers and the construction industry to consider polymer composites as an alternative construction material and system. One of the successful applications of polymer composites, is columns seismic repair and rehab. The advantage of composites in this application is the ability of decoupling the stiffness and strength, by applying the majority of fibers in the hoop directions. This application has been extended to cover not only the ductility enhancements, but also structural upgrading of both the flexural and axial stiffness and strength of reinforced concrete columns. In addition, similar applications included repair and rehab of reinforced and unreinforced bearing and shear walls, slabs, and beams. A comprehensive state-of-the-art review on the different composite repair systems is presented by Marsh [1].

As it was mentioned earlier, a heavy investment by both the government and the industry was allocated to verify, support, and develop repair 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*).

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

On January 17, 1994, the Los Angeles basin suffered a magnitude 6.8 earthquake that resulted in 58 deaths and an estimated economic loss of over $30 billion. This catastrophe caused severe damage to over 11,000 homes as well as residential and commercial infrastructures. In addition, it caused the collapse of six major highway structures and damaged over 100 highway overpasses. The Northridge earthquake points to the inadequacy of the existing infrastructures for maintaining structural integrity. Reinforced concrete buildings constructed prior to the major revision of the building code in 1981 suffered the most severe damages. This earthquake also serves as a grim reminder that while natural disasters cannot be prevented, engineers and researchers must devise methodologies for building structures that can withstand high magnitude quakes. Moreover, we must able to retrofit existing buildings and infrastructures to minimize their vulnerability to seismic forces.

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.

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 Second 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)).

FIGURE (1): Failure of Beam-Column Joints during the Northridge Earthquake, California, 1994

3. RELATED RESEARCH WORK

Over the years, several researchers, including pressure epoxy injection, epoxy impregnation [2], and external steel plating [3] have investigated numerous seismic repair and retrofitting techniques. However, there are a number of drawbacks associated with these techniques. The 1995 Federal Emergency Management Agency (FEMA)-97 Report questions the effectiveness of the pressure injection technique in completely restoring bonds between the reinforcement and concrete. The epoxy impregnation method, while able to overcome the partial fulfillment of air void problem, is extremely difficult to apply on large practical scales. Externally steel plate bonding has it own set of problems. It is costly to implement, steel corrodes, and is heavy and difficult to manipulate at the job site.

Some successful experimental investigations of polymer composites are in the area of repairing and retrofitting the structural performance of reinforced concrete members such as columns, beams, and slabs. The key advantage of composites in these applications is its tailorability, which enables the engineer to decouple its stiffness and strength. This property is critical in the seismic repair of columns [4]. demonstrated that ductility was enhanced without changing the stiffness of the members by applying the majority of fibers in the hoop direction. In this configuration, the composite reinforcement was highly effective because it confined the core concrete and prevented the steel longitudinal rebars from buckling under reversal loading.

Chakrabarti and Mosallam [5] conducted a pilot study on developing repair techniques for damaged steel interior and exterior beam-column connections using 3-D braided graphite/epoxy composite connectors attached to the flanges of both beam and columns. This research is among the first to test moment steel beam-column joints using polymer composites after the Northridge earthquakes. Test results indicated that the proposed experimental repair/rehab techniques satisfied the ductility requirements recommended by the 1995 and 1997 FEMA guidelines on steel moment frame structures.

Parvin and Granata [6] presented a preliminary discussion on the use of FRP overlays at exterior beam-column connections. They concluded through finite element analysis that the peeling stress at the junction of the tensile faces of the beam and column is critical. The study further indicated that the use fiber wrap over the fiber overlay would be effective in preventing peeling of the overlay due to stress. Recently, a field study was conducted by researchers at University of Utah on the feasibility of using polymer composites for retrofit beam-column pier joints at Interstate 80.

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 (Φ 15.9 mm) rebars were used for both column vertical reinforcement as well as for the beam horizontal reinforcements. Number 2 (Φ 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 layups.

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).

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.

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.

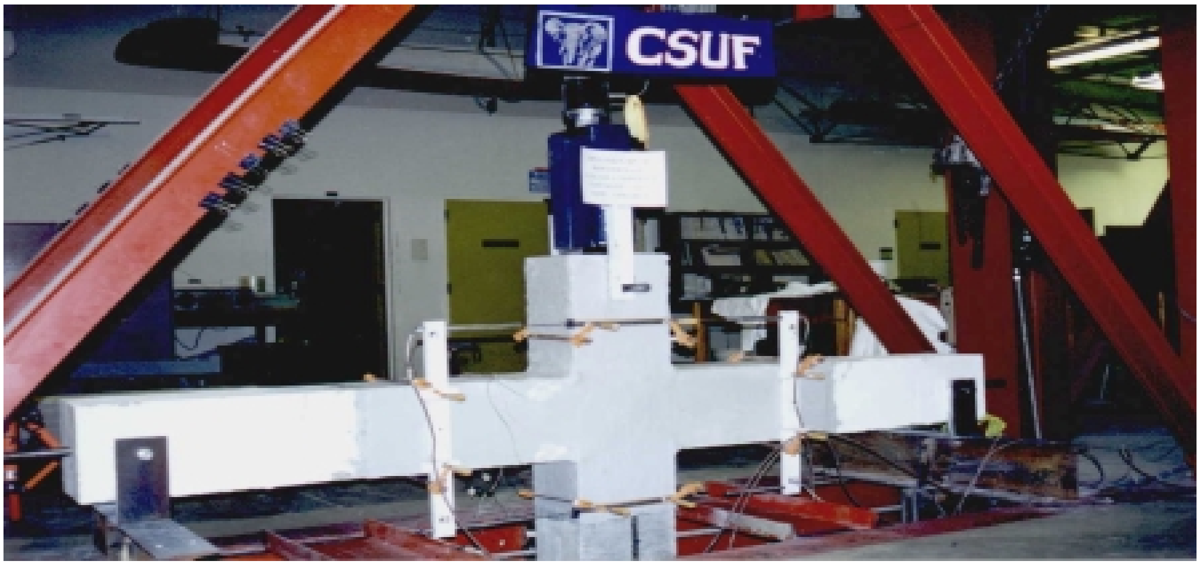

FIGURE (2): Beam-to-Column Connection Test Setup

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.

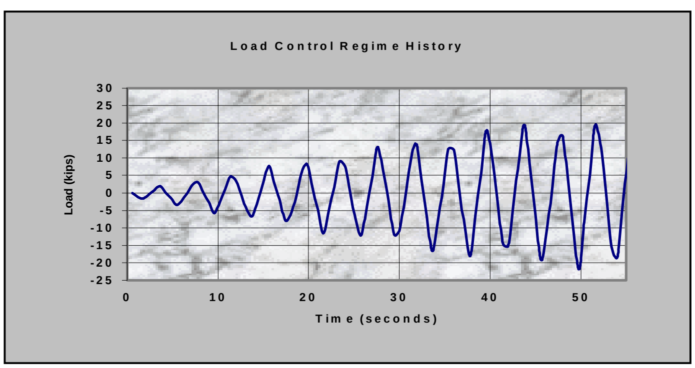

FIGURE (3): Typical Load Control Regime History

5. SUMMARY OF RESULTS

Table 1 condenses the test results in a tabulated format and the following discussion summarizes the results and observations collected from the experimental program:

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.

7. RECOMMENDATIONS & FUTURE RESEARCH

Although the results of this pilot research project have provided valuable information regarding the overall reversal cyclic loading behavior of reinforced concrete moment frame connections repaired and retrofitted with polymer composites, there are several related aspects that need further investigation.

This study focused on the investigating experimentally “engineered” composite systems to repair and upgrade the structural performance of reinforced concrete connections. Theoretical and numerical analysis is in progress.

Additional experimental work is needed to further isolate several variables in order to fully characterize their effects on the repairing and retrofitting of the reinforced concrete moment frame connections. This includes (i) the effect of changing the fiber architecture of the laminate, (ii) the effect of changing the load history, (iii) the effect of changing the specimen size, (iii) the effect of three-dimensional elements such as beams and slabs orthogonal to the tested beam direction, (iv) the effect of the use of epoxy injection vs. surface repair using epoxy, and (v) the use of other types of fibers including Kevlar/epoxy.

One of the critical issues that needs further investigation is the durability and the long-term behavior of these composite systems. This includes temperature (and ultimately fire), humidity, chemical attacks, creeps and creep rupture, and other environmental factors on stressed and unstressed specimens. Researchers at California State University at Fullerton are currently conducting a comprehensive durability study on this system.

Notwithstanding some of the unknowns that require further research work, polymer composites constitute a strong and viable member of the civil engineering structure components into the next millennium.

8. REFERENCES

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

Dr. Mosallam has over twenty years of experience with analysis, design, and full-scale testing of composite frame structures and connections. He has published over *seventy* 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* on two chapters of this design manual, namely, *i)* the chapter on Creep *of Polymer Composite, and ii) Design of Composite Joints and Frame 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 for his excellent research work and development of structural design tools for predicting the Creep behavior of polymer composites. The proposed work is a logical extension of earlier and current work. Dr. Mosallam is a registered Structural Engineer in Washington, D.C. He has been awarded four prestigious awards on his research work and developments in the area of composite connections. Dr. Mosallam is the developer of the Universal Connector, which was accepted and used by the industry since 1993.