ANALYSIS OF POST-INSTALLED GLASS FIBER-REINFORCED POLYMER ANCHORAGE IN BEAM-COLUMN JOINTS

University of Minnesota Duluth University Honors

Senior Capstone Report

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Background and Motivation

This Undergraduate Research Opportunities Program project was performed during the Spring of 2017 at the University of Minnesota Duluth Civil Engineering Department under the advisement of Dr. Ben Dymond. The project serves as a subset of work to be used by a M.S. student, Muhammad Bajwa, in the Civil Engineering graduate program. Accordingly, Mr. Bajwa worked alongside Matthew McDermott throughout many stages of the project as an integral team member.

This project sought to examine the performance of glass fiber-reinforced polymer (GFRP) bars in post-installed anchorage of beam-column joints. Post-installing is a common and often preferable method of making structural concrete connections in buildings and other structures as the system offers much flexibility. Some applications include cantilever beams, slab widening, and diaphragm wall construction. Post-installing requires little installation time, can be installed in many orientations, and is serviceable shortly after installation (Hilti, 2011). The method involves drilling a hole in a hardened concrete member and anchoring a bar of some type into the hole. Most commonly, an adjacent member is cast around the post-installed bar. In other cases, fixtures are attached to the post-installed bar such as hand rails or window framing systems. Regardless of the application, the connection of the bar to the adjoining concrete in a drilled hole is the critical link for post-installed connections.

Post-installed connections fall into two categories including mechanical and adhesive systems. Common mechanical connections consist of installing a threaded bar that induces an outward force on the sides of a drilled hole. This engages the bar with the surrounding concrete and provides axial force resistance. On the other hand, adhesive connections involve filling a drilled hole with some form of adhesive and installing a smaller diameter bar than the surrounding hole into the adhesive filled hole. After curing, the adhesive engages with both the bar and the surrounding concrete, thus resisting axial load on the bar.

For adhesive post-installed connections, mild steel bar is commonly employed although other types of bars have potential to be used instead. This project embraced the opportunity to use another kind of bar and explored using GFRP bars in adhesive post-installed connections. Compared to steel, GFRP bars are preferable as they are light weight, noncorrosive, and have high fatigue endurance (ACI Committee 440, 2006). Steel bars are susceptible to corrosion which is difficult to inspect and can lead to increased long-term maintenance costs as well as potentially reduced capacity. If GFRP bars are found to be suitable for post-installed connections, corrosion concerns associated with steel could be avoided. Given the potential benefits offered by GFRP bars, this project aimed to better understand the anchorage behavior and confirm the suitability of GFRP bars in post-installed anchorage.

Methods

A common beam-column connection was replicated in the design of an appropriate specimen geometry for experimental testing in a laboratory setting. Referring to Figure 1, the horizontal base element of the specimen was designed to replicate a column and the two vertical elements serve as beams framing into the column. Note that the specimens are rotated 90 degrees compared to a real-world scenario with the column on its side. For these experimental specimens, the two vertical elements were attached to the base element by means of post-installing as would be the case with attaching beams to a column after the column has been cast and hardened. The performance of the post-installed bars connected to the base element was the focus of testing, so the specimens were designed to not fail by any other modes. As a result, substantial reinforcement was included in both the base and vertical elements to avoid flexure and shear failures during loading.

Substantial construction was required to construct a set of 4 specimens. Chronologically, formwork was designed and constructed, the reinforcement cage of the base element was tied, the base element was cast, GFRP bars were post-installed into the base element, the vertical element cage was tied, and the vertical element was cast. Between each of the 4 specimens, embedment length, GFRP bar manufacturer, and adhesive type were varied. Differences in these characteristics were intended to help understand what factors influence the connection performance. Reference Table 1 for each specimen's specific characteristics.

As beams are generally subjected to gravity load, the vertical element was loaded in a direction parallel to the column. To avoid building an external reaction frame in the laboratory, two vertical elements were simply loaded simultaneously in opposite directions. This is illustrated in Figures 1 and 2. Note that the GFRP bar was placed on different sides of each vertical element in relation to the applied load so as to induce tensile axial force on the post-installed GFRP bar. To apply load, 2 hydraulic rams were attached to the top of the vertical elements. Additionally, spreader beams were placed between the rams and vertical elements to evenly distribute load across the vertical element width.

Resulting from the application of load, peak loading, ductility of the connection, and connection failure mode were of particular interest. To determine peak loading, a pressure sensor was added in line with the hydraulic system with measurements recorded using a data acquisition system. By multiplying the total area of the ram piston heads by the measured pressure, applied load was determined at a 1 second resolution. Linear voltage displacement transducers (LVDTs) were employed to measure the displacement at the top of the vertical elements and recorded at the same frequency as the pressure sensor. This information was used to evaluate the ductility of the connection. To further understand the failure mode, loading was paused often through the testing to examine and photograph the resulting surface cracking. Following the testing, the failure mode was evaluated to either be a cone or pullout failure.

Given the fine resolution of recorded data and length of time testing, thousands of pressure and displacement data points were generated for each specimen. To generate a plot of applied load versus displacement at the vertical element top, increments of steady load were averaged with their associated displacements and a condensed series data points were collected. These points were then plotted to visually examine and compare peak load and ductility between each of the specimens.

Results and Analysis

Upon examining the recorded peak loads as presented in Figure 3, peak load was determined to vary linearly with embedment length. The peak load of the specimens with 6 inch embedments were around 14 kip whereas the specimens with 11.5 inch embedments had a peak load of around 29 kip. This observation is reasonable because the surface area of concrete engaged by the post-installing increases linearly with embedment length. It is logical to associate increased contact area with increased connection capacity, so this linear relationship is sensible.

The performance of the two manufacturers was assessed by comparing peak loads of the two 11.5 inch embedment specimens. The peak load of the specimen employing GFRP from V-ROD had a peak load of about 31 kip whereas the complementary specimen that used GFRP from Hughes had a peak load of around 28 kip. This is likely due to the difference in bar surface finish between the manufacturers. V-ROD bars had a ribbed surface whereas Hughes bars had a flatter sand-coated surface. Because the connection is loaded axially, the interaction between the bar and adhesive and the bar is likely improved by the more roughened bar surface provided by V-ROD. See Figure 4 to compare surface characteristics of each manufacturer's GFRP bars.

For the use of GFRP bar in post-installed anchorage to be suitable, sufficient ductility must be demonstrated. As with most structural connections, brittle failures are unsafe because visual signs of distress before failure are minimal. For a beam-column connection in a building, it is preferable to have a ductile failure. This means the beam will visually deflect as the connection approaches failure. As the beam deflects, the capacity of the connection is maintained in a ductile design allowing inhabitants to respond to the visual signs of distress and exit the building before failure. Examining Figure 3, ductility of the post-installed connection is illustrated by the amount of displacement at the top of the vertical element while maintaining load. Each of the specimens in this project demonstrated moderate ductility. While this project's scope did not include a through comparison of GFRP performance with traditional steel bars, the ductilities of GFRP connections in this project were within range of complementary steel values (Hamad, 2006). This means post-installed GFRP connections demonstrate suitable ductility.

While peak load and ductility were directly measured by instruments, the failure mode of the connections was determined by inspecting the development of cracking at the surface of the base element. All the specimens exhibited a cone failure mode as imaged in Figure 5. The two failure modes of post-installed anchorage include cone and pullout. In a cone failure, a cone of concrete originating at the top of a post-installed bar fails. Pullout failures are due to a failure in the adhesive performance allowing the bar to pull out of the connection. In the evaluation of a post-installed connection, cone failures are preferable because the capacity of the adhesive to engage with the bar and surrounding concrete exceeds that of the concrete. In simple terms, cone failures mean the post-installing activities are not the weak link in the connection.

Finally, both cementitious and epoxy adhesive types were included in the testing matrix. By comparing the specimens with 6 inch embedments only the adhesive type is varied. The connection that used epoxy demonstrated a slightly improved peak load compared to the cementitious adhesive. While this difference is minimal, it may be preferable to use epoxy given the choice between epoxy and cementitious adhesives.

Conclusions

Using GFRP bars in post-installed beam-column connections is desirable compared to traditional steel bars as the noncorrosive GFRP bars will mitigate long-term bar deterioration and maintenance needs. To confirm the anchorage behavior of post installed GFRP bars, an experimental program was developed including variations in embedment depth, GFRP manufacturer, and adhesive type. Following testing of the specimens, peak load, ductility, and failure mode were examined. Within the scope of this project, the use of GFRP bars in post-installed anchorage was found to be suitable as peak load and connection ductility were adequate. Peak load was found to vary linearly with embedment depth. Between the manufacturers, V-ROD GFRP carried a higher peak load than Hughes GFRP. Finally, epoxy adhesive performed slightly better than cementitious adhesive.

The matrix of variables observed in this project offered useful, but limited insight into the behavior of GFRP bars in post-installed anchorage connections. To further understand this connection performance and explore other means to improve design, the graduate research of Mr. Bajwa will continue over the coming year. Within his experimental program, 12 more specimens will be constructed and new variables such as bar size and concrete strength will be explored.

References

ACI Committee 440. (2006). Guide for the Design and Construction of Structural Concrete Reinforce with FRP Bars (ACI 440-1R-06). Farmington Hills, MI: American Concrete Institute.

Hamad, B., Al Hammoud, R., & Kunz, J. (2006). Evaluation of Bond Strength of Bonded-In or Post-Installed Reinforcement. American Concrete Institute Structural Journal, 207-218.

Hilti Inc. (2011). Technical Manual for Post-Installed Rebar Connections, 10th edition, Zollikofen, Switzerland.

Appendix: Tables and Figures

Table 1. Specimen characteristics.

Specimen	Embedment	Bar	Adhesive
1	6 in.	V-ROD	Epoxy
2	6 in.	V-ROD	Cementitious
3	11.5 in.	V-ROD	Epoxy
4	11.5 in.	Hughes	Epoxy

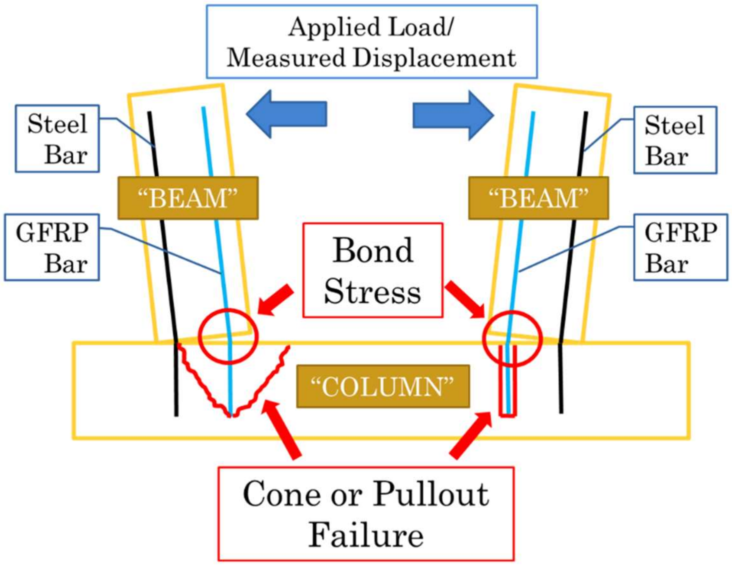

Figure 1. Specimen testing schematic.

Figure 2. Test setup prior to loading.

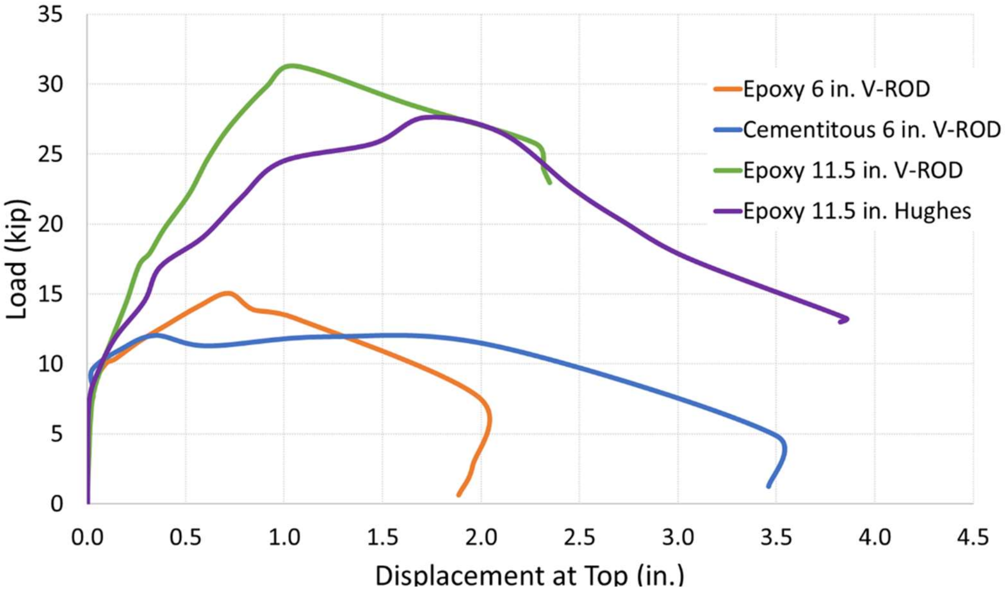

Figure 3. Plot of load versus displacement plot.

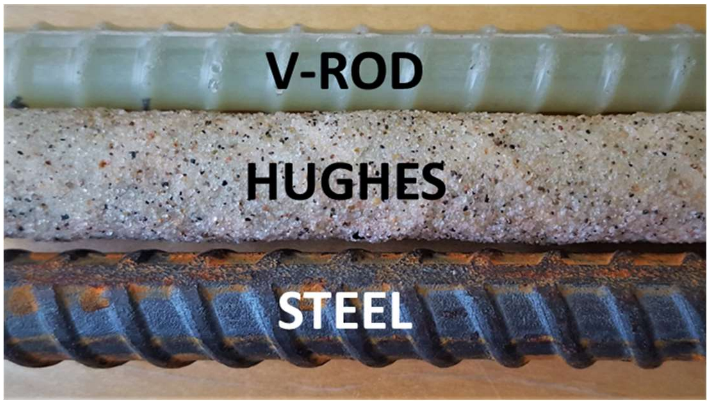

Figure 4. Surface characteristics of GFRP bars between manufacturers.

Figure 5. Example of cone failure mode in epoxy 11.5 in. V-ROD specimen.