

Experimental Investigation on Carbon Fibre Reinforced Polymer to Reinforced Concrete in Shear Application

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Abstract – In this modern era, most of the buildings all over the world are made up of RCC. A structure is intended for a particular period and relying upon the idea of the structure, its plan life fluctuates. For a residential structure, this plan life could be as low as a quarter century, while for an open structure, it could be fifty years. Weakening in solid structures is a noteworthy test looked by the framework and extension businesses around the world. The decay can be predominantly because of natural impacts, which incorporates erosion of steel, progressive loss of solidarity with maturing, rehased high force stacking, variety in temperature, solidify defrost cycles, contact with synthetics and saline water and introduction to ultra-violet radiations. As complete substitution or reproduction of the structure will be savvy, fortifying or retrofitting is a viable method to reinforce the equivalent.

In this research, The primary objective of this study is to examine the application of GFRP fabric wrap to strengthen concrete beams and the associated failure modes. the effects of the number of GFRP layers on the strength and ductility of beams are investigated. To study the ultimate load carrying capacity, deflection of normal beam and beams strengthened with GFRP fabric wrap. A comparison shall also be done with the ultimate load carrying capacity and deflection of normal beam and beams strengthened with GFRP wraps.

From conclusions, it is seen that from Experimental Study on Structural Strengthening of Beams using Glass Fibre Reinforced Polymer Composites conclude the strength of the beams can be increased by wrapping with Glass Fibre Reinforced Polymer Composites.

Keywords- Glass Fiber Reinforced Polymer, Reinforced Cement Concrete

I. INTRODUCTION

Fiber Reinforced Polymers

Due to ongoing deterioration and lack of maintenance, a need to rehabilitate and lengthen the serviceable lifetime of deteriorated structures has grown. The crucial cause in the deterioration of our infrastructure is related to environmental effects.

Infiltration of water and salt into concrete structures causes damage to both the concrete and steel reinforcement thereby shortening the structure's life considerably.

Earthquakes also cause damage to steel reinforced concrete (RC) structures. In many cases the damage caused by the corrosion due to water and salt or by an earthquake is not great enough to replace the entire RC structure, but rather it is much more cost effective to rehabilitate individual members of the RC structure to meet the original strength requirements. Traditionally, rehabilitating and retrofitting RC structures was accomplished by casting new sections of concrete reinforced with steel or by fastening steel sheets to the exterior of the damaged concrete members. The major drawback to both of these methods is the amount of work that must be invested into their installation (ICI Committee 440, 2002).

Within the past few decades a new technology has emerged using Fiber Reinforced Polymers (FRP) to rehabilitate and retrofit RC structures. FRPs are lightweight, easy to install, possess a high strength-to-weight ratio, high stiffness-to-weight ratio, and are extremely resistant to environmental corrosion therefore making them a proper material for retrofitting concrete structures (Garden and Hollaway, 1998).

These material properties lead to cost savings in the form of reduced installation time and labor costs and combined they outweigh the increased material cost. A design guideline issued by the Indian Concrete Institute (ICI) entitled *ICI*

440.2R-02 *Guide for the Design and Construction of Externally FRP Systems for Strengthening Concrete Structure* (ICI Committee 440) currently recognizes three systems for the external application of FRPs to RC members: wet layup systems, prepeg systems, and precured systems (ICI Committee 440, 2002). Wet layup systems consist of either unidirectional or multidirectional dry FRP fabric plies that are saturated with an epoxy resin on-site during application. Typically, a layer of epoxy resin is applied to the primed concrete surface after which a layer of FRP is adhered using rollers to remove any trapped air bubbles. Next, a second layer of epoxy resin is applied over the FRP ply to insure complete impregnation. Unlike wet layup systems, prepeg systems are saturated with resin offsite and delivered to the work site in coils. Wrapping machines can be used to automatically draw FRP

from the coils and wrap the FRP around the RC element. Automated wrapping machines are typically utilized on concrete columns.

Prepeg FRP systems are typically cured at a fixed temperature onsite to ensure quality control. Precured systems consist of pultruded rigid FRP laminates that are bonded to a primed concrete surface using an adhesive and rolled to insure that no air bubbles remain trapped and to remove any excess adhesive.

ICI Committee 440 (2002) currently recognizes three types of FRP composites: glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), and aramid fiber reinforced polymer (AFRP). Representative unidirectional material properties of each FRP fiber can be seen in Table 1.1.

Table 1.1 — Mechanical Properties of GFRP, CFRP, and AFRP Fibers (Concrete Society, 2004)

Material	Elongation (%)	Specific Density	Modulus of Elasticity	Tensile Strength
GFRP	3.5-4.7	2.6	10000-12500 ksi [69-86 GPa]	350-500 ksi [2.5-3.5 GPa]
AFRP	2.4	1.44	18000-19000 ksi [124-131 GPa]	450-525 ksi [3.1-3.6 GPa]
CFRP: High Strength	1.9-2.1	1.8	33000-35000 [227.5-241 GPa]	625-715 ksi [4.3-4.9 GPa]
CFRP: High Modulus	0.7-1.9	1.78-1.81	42500-47750 ksi [293-330 GPa]	400-800 ksi [2.7-5.5 GPa]
CFRP: Ultra High Modulus	0.4-0.8	1.91-2.12	78000-93000 ksi [538-641 GPa]	375-580 ksi [2.6-4.0 GPa]

The tensile properties of FRP composites make them an excellent material for increasing the strength of RC elements. FRP fibers are anisotropic and when loaded in direct tension they are very brittle, as they do not exhibit any yielding behavior before rupture. Additionally, the material is considered to be linearly elastic until failure. The longitudinal tensile modulus of high strength CFRP is comparable to that of mild steel however the ultimate tensile strength of high strength CFRP can be six to seven times greater than that of high strength steel.

Strengthening RC Members using FRP Composites

Previous studies have shown that bonding FRP to an RC element can greatly increase the element capacity in a number of ways: (1) increase axial, flexural, and shear loading capacities; (2) increase ductility for enhanced seismic performance;

(3) increase member stiffness thereby minimizing deflections; (4) increase the structures fatigue life; (5) and increase robustness against detrimental environmental effects (Buyukozturk et al., 2004). It should be emphasized that in comparison to flexural strengthening of RC members using bonded FRP, limited research exists on shear strengthening using FRP laminates. A goal of this research program will be to contribute to the understanding of shear strengthening RC elements (beams, walls, columns, etc...) using bonded FRPs. Understanding how bonded FRP laminates increase the shear capacity of RC elements is advantageous due to the fact that shear failures are considered brittle and cataclysmic and may preclude reaching the flexural strength of an element. Increasing the shear capacity of a RC member may allow development of a flexural failure, which is generally more ductile.

Flexural and Shear Strengthening FRP

Techniques

Using FRP to strengthen the flexural capacity of an RC beam consists of applying a single layer of FRP to the bottom face of the strength deficient member. Applying an FRP sheet to the tensile face of an RC element will provide additional flexural strength (see Figure 1.1).

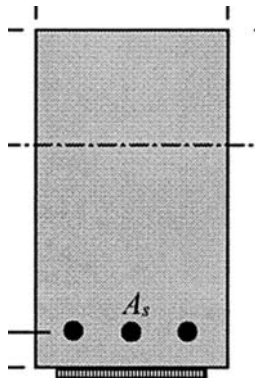


Figure 1.1 — FRP Flexural Strengthened RC Beam (ICI Committee 440, 2002)

Three different techniques are used when using FRP to shear strengthen RC elements: completely wrapped elements, 3-sided wraps, and 2-sided wraps (see Figure 2.1). Completely wrapping elements is considered the most efficient wrapping scheme due to the fact that the full strength of the FRP is developed. However, completely

wrapping RC elements is not always possible due to construction limitations (for example it is not possible to completely wrap a beam that is supporting a slab on its top face). 3-sided wraps consist of using FRP sheets to wrap the web and tensile faces of an RC element. This wrapping scheme is considered moderately efficient. As discussed in Section 1.2.3 the full strength of the FRP sheet is generally not reached in this wrapping scheme due to FRP debonding. 2-sided wrapping schemes consist of bonding FRP sheets to the web faces of an RC beam. This wrapping scheme is considered the most inefficient because failure by debonding occurs at a lower strain than complete wrapping schemes.

II. RESULTS AND DISCUSSION

Effect of Anchor Geometry

The effect of the FRP anchor geometry is an important parameter that governs the shear strength of FRP anchors. The two geometrical parameters studied during this experimental program were FRP anchor splay diameter and FRP anchor diameter. It was determined that FRP anchor length was not a governing parameter for the

anchor length used in this research project based upon the failure modes of the initial Specimens B-Z-2-5-2 and B-Z-4-5-4. The failure modes of these specimens consisted of FRP anchor shear, which illustrated that FRP anchor pullout was not a dominant failure mode; therefore, it was decided to hold this geometrical parameter constant throughout all tests and vary the parameters that governed the effectiveness of FRP anchors. During the failure of Specimen C-X-4-10-6 FRP anchor pullout was identified as one of the failure modes, however, it is believed that this failure mode occurred because the 3/4-inch (1.9 cm) FRP anchors that were used in this specimen were not completely impregnated during the installation procedure. Discussion of the prevention of premature failure modes is presented in Chapter 7.

Effect of Splay Diameter

An important geometrical parameter in determining the strength and effectiveness of FRP anchors is the diameter of the anchor splay. The splay diameter determines the effective width of FRP sheet engaged by an individual anchor and determines the required diameter of the FRP anchor to transfer the force generated on the FRP sheet into the concrete substrate.

During failure of Specimen B-Z-2-5-4, discussed in section 4.6.2.2, it was observed that an FRP anchor with a splay diameter of 2-inches (5.1 cm) and an anchor diameter of 1/2-inch (1.3 cm) was effective in rupturing a 2-inch (5.1 cm) width of FRP sheet leading to the concept that the effective width of FRP sheet that an FRP anchor can engage equals the splay diameter. However, during the failure of Specimen B-Z-4-5-4, which had a splay diameter of 4-inches (10.2 cm) and an anchor diameter of 1/2-inch (1.3 cm), failure of the FRP anchors occurred due to FRP anchor shear. Failure of Specimen B-Z-4-5-4 illustrated that providing a 4-inch (10.2 cm) splay diameter with a 1/2-inch (1.3 cm) anchor diameter engaged a width of FRP sheet that was too large for the FRP anchor shear strength. The diameter of the splay establishes the width of engaged FRP sheet, which then determines the required diameter of the FRP anchor so as not to fail the anchor due to shear.

Effect of Anchor Diameter

Equally as important as the diameter of the FRP splay region is the diameter of the FRP anchor. The FRP anchor diameter is directly related to the force being transferred at the anchor from the FRP sheet into the concrete substrate. As discussed earlier, the splay diameter is the main factor affecting the effective width of FRP laminate

engaged. The FRP anchor diameter, therefore, has to be determined in accordance with the width of FRP laminate being engaged by each anchor splay.

The failure of FRP anchors in Specimen B-Z-2-5-2 (section 4.6.2.1) was caused by FRP anchor shear. The FRP anchors in this specimen had a splay diameter of 2-inches (5.1 cm) and a diameter of 1/4-inch (0.64 cm). This failure mode indicated that the force developed within the 2-inch (5.1 cm) splay diameter was too large for the strength developed by a 1/4-inch (0.64 cm)-diameter anchor causing FRP anchor shear failure.

However, failure of the subsequent test Specimen B-Z-2-5-4, which had a splay diameter of 2-inches (5.1 cm) and an anchor diameter of 1/2-inch (1.3 cm), occurred due to FRP rupture indicating that a 1/2-inch (1.3 cm) anchor diameter was large enough to resist the force developed in the 2-inch (5.1 cm) width of splay region.

The same concept was demonstrated in the testing of Specimens B-Z-4-5-4 and B-Z-4-5-6. Specimen B-Z-4-5-4, with FRP anchors with a splay diameter of 4-inches (10.2 cm) and an anchor diameter of 1/2-inch (1.3 cm), failed due to FRP anchor shear. The failure of Specimen B-Z-4-5-6, which had a splay diameter of 4-inches (10.2 cm) and an anchor diameter of 3/4-inch (1.9 cm) failed due to FRP rupture indicating that for a 4-inch (10.2 cm) splay diameter an anchor diameter of at least 3/4-inch (1.9 cm) is required.

Effect of Anchor Arrangement

The spacing of FRP anchors both longitudinally and transversely within the bonded FRP laminate area is an important factor that affected specimen failure. The failure of Specimen B-Z-2-5-4, had an FRP anchor spacing shown in Figure 3.27, illustrated that the leading FRP anchor closest to the applied load provided the necessary strength to rupture 2-inches (5.2 cm) of FRP sheet directly in front of the anchor. The gain in ultimate capacity of Specimen B-Z-2-5-4 over the control specimen can be directly attributed to the effectiveness of the leading FRP anchor. It is believed that the trailing FRP anchor in Specimen B-Z-2-5-4 provided no additional strength in fastening the FRP sheet to the concrete substrate since the maximum FRP strain was recorded in front of the leading FRP anchor and sheet rupture occurred in the identical location. The failure of Specimen B-Y-2-5-4, with an anchor arrangement as shown in Figure 3.29, further corroborated this observation. Since two FRP anchors with 2-inch (5.2 cm) splays were placed transversely adjacent to one another and failure of the specimen occurred by rupturing 4-inches (10.2 cm) of FRP laminate

directly in front of the FRP anchors as described in section 4.6.8.

Effect of Composite Bond Length

The length of bonded composite laminate behind the FRP anchors was another parameter studied during the experimental program. Providing a longer bond length behind the FRP anchors allowed for a more ductile debonding process and increased the total force at specimen failure. The effectiveness of FRP anchors is dependent upon their ability to prevent FRP laminate debonding throughout the entire FRP sheet length.

The failure of Specimen B-Y-2-5-4, which had a pair FRP anchors spaced transversely across the sheet width and sheet bond length of 30-inches (76.2 cm) (Figure 3.29), was due to FRP rupture in front of the leading FRP anchors. As discussed in section 4.7.3.8 the FRP anchors were effective in preventing debonding to within 17.5-inches (44.5 cm) from the unloaded end of the FRP sheet end. The failure of Specimen B-X-2-5-4, with only half of the bond length of Specimen B-Y-2-5-4, failed from a combination of modes including FRP rupture, delamination, and debonding. The FRP anchors in Specimen B-X-2-5-4 were not effective in preventing debonding to propagate to the sheet end, so failure modes other than FRP rupture occurred causing premature failure of the system. It is evident that bond of the FRP sheet behind the leading anchor allowed higher strains to be developed in the FRP sheet region in front of the anchor section leading to FRP rupture.

Effect of Composite Width

Composite sheet widths of 5-inches (12.7 cm) and 10-inches (25.4 cm) were studied during the experimental program. As discussed in section 2.3.1.1 increasing the nominal bond width increases the bond strength. In order to anchor the entire bond width to achieve FRP sheet rupture it is necessary to place FRP anchors that have splay diameters that cover the entire bonded width.

Failure of Specimen B-Y-2-5-4, which had an anchor placement according to Figure 3.29, was characterized by rupture of a 4-inch (10.2 cm) width of FRP sheet in front of the FRP anchors and FRP debonding of 1/2-inch (1.3 cm) side regions adjacent to the FRP anchors. Similar results occurred during the failure of Specimen C-U-2-10-4, which had twice the number of anchors and bond width compared with Specimen B-Y-2-5-4. Failure in Specimen C-U-2-10-4 occurred by FRP rupture in the 8-inch (20.4 cm) region of FRP sheet in front of the FRP anchors with practically no edge debonding observed on the side regions not anchored by the

FRP anchor splay regions. In conclusion the concepts of FRP anchor design work in developing the force necessary to rupture narrow and wide FRP sheets.

Formulation of FRP Anchor Shear Strength Equation

Based on the failure modes of multiple specimens a behavioral model was developed allowing the design of additional anchor geometries for various FRP sheet-strengthening conditions.

Based on the observed failure modes of Specimens B-Z-2-5-4 and B-W-2-5-4, as discussed in section 4.6.2.2 and 4.6.2.4, respectively, it was assumed that an FRP anchor with a 2-inch (5.1 cm) splay diameter and an anchor diameter of ½-inch (1.3 cm) was strong enough to develop the force required to rupture a 2-inch (5.1 cm) width of FRP laminate. The failure mode of Specimen B-Z-4-5-4, which exhibited anchor shear, demonstrated that an FRP anchor with a 4-inch (10.2 cm) splay diameter and an anchor diameter of ½-inch (1.3 cm) was not strong enough to develop the force required to rupture 4-inches (10.2 cm) of FRP laminate. Using the FRP coupon tests discussed in section 4.3 it was determined that the FRP used in this experimental

program had an ultimate tensile strength of 3.51 kips/inch. Dividing the force necessary to rupture a 2- inch (5.1 cm) width of FRP sheet by the nominal area of a ½-inch (1.3 cm) FRP anchor yielded an FRP anchor average shear strength of 35.8 k/in² (246.8 MPa).

To determine the necessary anchor diameter for a 4-inch (10.2 cm) splay diameter, as used in Specimens B-Z-4-5-6, C-X-4-10-6, and C-Y-4-10-6, the average shear strength of the anchor of 35.8 k/in² (246.8 MPa) was used. The strength of the FRP sheet engaged by a 4-inch (10.2 cm) splay diameter was 14.04-kips (62.5 kN) based upon an ultimate tensile strength of 3.51 kips/inch as discussed above. Dividing the required FRP rupture force by the estimated average anchor shear strength and solving for the anchor diameter yielded an FRP anchor diameter of 0.707-inches (1.8 cm); therefore, it was decided to use an anchor diameter of ¾-inch (1.91 cm) for all tests involving a 4-inch (10.2 cm) anchor splay diameter.

The proposed anchor diameter formulation, which is based on an experimentally derived anchor shear strength previously discussed, has the following parameters (see Figure 5.1):

$$D_A = [5.1] \sqrt{\frac{4(S_A)(f_{fu})(t_p)(n_p)}{\pi (35.8)}}$$

where:

- D_A = FRP anchor diameter [in]
- S_A = anchor splay diameter [in]
- f_{fu} = FRP ultimate tensile strength [ksi]
- t_p = nominal thickness of FRP sheet [in]
- n_p = number of FRP plies

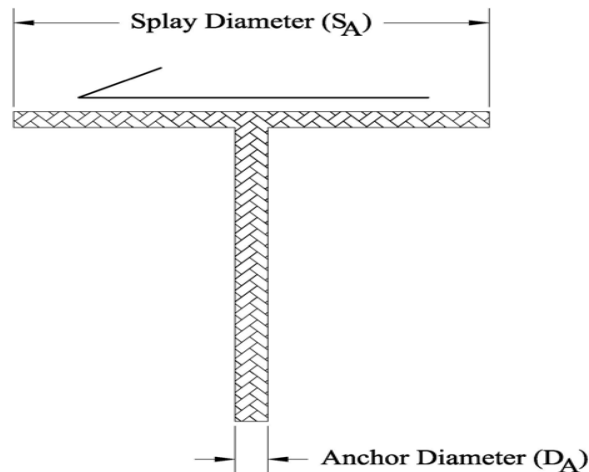


Figure 5.1 — FRP Anchor Shear Strength Parameters

To incorporate the shear strength equation it is necessary to select an anchor splay diameter, which will determine the effective width of FRP sheet engaged by an individual anchor. Once the force that each anchor needs to transfer into the substrate is determined, the required FRP anchor diameter is then calculated using equation 5.1. It should be noted however that equation 5.1 is only valid for FRP anchors ranging from

¼-inch (0.64 cm) to ¾-inch (1.91 cm) in diameter, as these were the FRP anchor diameters used in this research program. A discussion of the prevention of premature failure modes is presented in Chapter 7.

III. SUMMARY AND CONCLUSIONS

Summary

The objective of this research program was to study the effects of anchoring techniques of FRP sheets used to improve the performance of strengthened reinforced concrete members primarily in shear applications. Because the most common failure mode of FRP-strengthened reinforced concrete members is debonding, the goal of the research was confined to examine the effects of anchoring patterns to avoid or delay debonding of the FRP laminates from the concrete surface. No models characterizing the behavior of FRP sheets anchored to concrete were found in the literature. Tests were developed to study the gain in strengthening capacity of FRP sheets when anchored to the concrete surface using FRP anchors. The tests were also intended to provide an understanding of the various failure modes that occur when using this technique.

Six rectangular reinforced concrete blocks of a constant geometry and reinforcement were strengthened with carbon fiber reinforced composite sheets. Three series (A, B, and C) consisting of twelve total specimens were tested. Specimen group A, which was a control group, consisted of a total of 2 tests conducted on one block and had one ply of bonded FRP with no FRP anchors. The goal of specimen group A was to set a baseline for subsequent tests to establish the ultimate load when FRP debonding occurred and to establish the distribution of strains throughout the FRP bonded length and width during the debonding process. The goal of specimen group B, which consisted of a total of 7 tests conducted on four concrete blocks, studied the effects of using one row of ¼-inch (0.64 cm), ½-inch (1.27 cm), and ¾-inch (1.9 cm) diameter FRP anchors to study the efficiency of individual anchors to engage a given width of FRP material. An FRP anchor length of 2-inches (5.1 cm) was kept constant throughout all tests in this specimen group as anchor length was determined to be a non-

controlling factor because anchor pullout was not observed in any of the initial test specimens. The goal of specimen group C, which consisted of three tests conducted on two concrete blocks, studied the effects of using FRP anchors to fasten one ply of bonded FRP sheet having a 10-inches (25.4 cm) width. Concepts regarding FRP anchor diameter, FRP anchor splay diameter, FRP anchor length, FRP anchor spacing, and FRP bonded sheet length studied during the testing of specimen group B were applied to specimen group C to confirm that the theories developed in the experiments worked for a wider bonded FRP sheet.

The observed behavior was analyzed in terms of local response of the constituent materials and the global performance of the FRP anchorage system. The local performance was evaluated measuring strains developed in the FRP, load at the initiation of debonding, and ultimate load at specimen failure. The global performance of the FRP anchorage system was analyzed based on the observed failure modes. Based on the global performance of multiple specimens a behavioral model was developed allowing the design of additional anchor geometries for various FRP sheet-strengthening conditions.

A 2-D plane stress finite element model was developed using ADINA 8.3.3 to study the bond behavior between FRP sheets attached to the surface of reinforced concrete elements. In particular, two dimensional finite element models of Specimens A-0-0-10-0, A-0-0-5-0, and B-Y-2-5-4, were used to analyze the interfacial debonding behavior between FRP sheets bonded to the concrete surface. To validate the finite element models, comparisons were made between the finite element model and the test specimens regarding FRP strain profiles and ultimate load carrying capacity. A calibration formulation was proposed that calculated the maximum local slip, s_f , based on the bonded width of FRP sheet.

Global Response

Several fundamental characteristics were evident from the global response observed during the experimental investigation of fastening FRP laminates with FRP anchors. The overall effectiveness of FRP anchors was found to depend upon several factors, most noticeably the ratio of the FRP anchor splay diameter to FRP anchor diameter. This ratio governs the ability of the FRP anchor to engage a certain width of FRP composite sheet. Larger splay diameters engaged wider regions of the FRP sheets. Therefore, providing a large anchor splay diameter with a small anchor diameter caused failure in the anchor because the force being

transferred by the sheet into the anchor exceeded the anchor capacity. Conversely, providing a small splay diameter with a large anchor diameter was not efficient since the anchor shear strength was not fully mobilized. Small splay diameters, however, do not engage the entire FRP sheet width and lead to combined failure modes (localized sheet rupture and debonding of FRP sheet regions not engaged by the FRP anchor).

The overall effectiveness of FRP anchors was found also to be affected by the selected anchoring. Anchoring anchors longitudinally along the composite sheet was not necessary to develop higher sheet forces, but rather was important to increase ductility of the system before failure. Anchors placed across the width of the composite sheet were more efficient in developing higher forces in the anchored FRP sheet.

Spacing the anchors such that their splays nearly overlapped was very important as each anchor could engage a specific width of FRP sheet equal to the splay diameter of the FRP anchor. Spacing the anchors with a gap in-between anchor splays did not engage the composite sheet between the anchors resulting in composite sheet failure before development of the ultimate strength of the FRP anchors.

The length of FRP sheet bonded directly to the concrete surface behind the anchors also affected the effectiveness of the FRP anchor system. Providing a longer bond length of composite sheet developed a more ductile debonding process and increased the total force at specimen failure. The effectiveness of FRP anchors is dependent upon their ability to prevent FRP laminate debonding throughout the entire FRP sheet length. Only the anchored specimens that were able to prevent complete FRP sheet debonding were able to obtain approximately 70% or more of the ultimate strength of the FRP, with the exception of one specimen. The ability of FRP anchors to prevent debonding was affected by several parameters that caused premature failure modes associated to the anchorage system including anchor delamination, anchor pullout, and splitting failure between the FRP anchor and laminate sheet.

Local Response

The first major observation noted after examination of measured strains at different positions on the FRP sheet was the location of the maximum-recorded strain. It was expected that axial strain would be the greatest in the middle of the FRP laminate for specimens with no FRP anchors. However, it was illustrated that the location of the maximum strain occurred in a strain gage row near

the edge of the FRP sheet. For specimens with FRP anchors centered about the sheet centerline it was expected that the maximum strain would occur in the center of the FRP laminate directly in line with the FRP anchor, which was shown to be true. For specimens with FRP anchors that were not centered about the sheet centerline it was expected that the maximum-recorded strain would occur inline with the center of the FRP anchors and lower strains would occur in the centerline of the FRP sheet at the edge of an FRP splay region. As expected it was illustrated that the location of maximum strain for specimens with non-centered FRP anchors occurred in the edge strain gage rows, which were located closer to the center of the FRP anchor diameter than the center strain gage row that was located in the center of the FRP sheet outside of the anchor splay region.

The second observation was the variability in the

$$\frac{\epsilon_{max}}{\epsilon_{ult}}$$

recorded percentage of

$$\frac{P_{test}}{P_{ult}}$$

compared to P_{ult} . The wide variability in the maximum-recorded local strains was believed to be generated from local variation in local material properties of the FRP laminate and concrete substrate, or from localized FRP anchor effects. Variability in behavior introduced through the properties of the concrete substrate was believed to be the major contributor to strain variability. The concrete surface strength was highly variable due to irregular aggregate and paste distribution and also because of irregularities introduced during surface preparation of the specimens.

The third observation noted in the local response of individual strain gages was the inability to record FRP rupture strain, even in cases where FRP sheet rupture was observed. This phenomenon was believed to occur due to localized FRP material properties or the inability to record peak strain values using a discrete number of strain gages. It was noted that FRP rupture was observed for numerous specimens leading to the conclusion that the FRP rupture strain was reached, but not recorded. It was illustrated that FRP rupture occurred in localized locations causing the redistribution of forces inducing global FRP rupture or debonding.

Conclusions

FRP anchors are effective in fastening FRP laminates to reinforced concrete elements allowing for the development of the full rupture strength of the composite sheet. FRP anchors provide an additional strength to the FRP composite allowing for the development of the ultimate strength of the FRP sheet.

The effect of the FRP anchor geometry is an important parameter that governs the shear strength of FRP anchors. It was determined that FRP anchor length was not a governing parameter for the anchor length that was used in this research project. The splay diameter determines the effective width of FRP sheet engaged by an individual anchor and determines the required diameter of the FRP anchor to transfer the force generated on the FRP sheet into the concrete substrate. The FRP anchor diameter is directly related to the force being transferred from the FRP sheet into the concrete substrate. The FRP anchor diameter, therefore, has to be determined in accordance with the width of FRP laminate being engaged by each anchor splay. An FRP anchor shear strength of 35.8 k/in^2 (246.8 MPa) was calculated based on the global failure modes of multiple specimens, which can be utilized to select an anchor splay diameter, which will determine the effective width of FRP sheet engaged by an individual anchor.

Areas of Future Research

Given the variation in the recorded FRP sheet strain and the erratic propagation of the debonding crack front, it was difficult to evaluate the efficiency of an anchoring system based on the local response with a discrete number of strain gages. Therefore, further research into the development of design guidelines that is reflective of the global response of the specimen is warranted. Furthermore, to achieve this, a parametric study utilizing the percent of FRP rupture sheet strength obtained at failure as the dependent variable could be conducted. Further experiments utilizing the FRP anchor diameter and splay diameter as the independent variables could be investigated. The results of the parametric study would give extra insight into the cause of premature failure modes, the loads at which these premature failure modes occur, and would validate the derived FRP anchor shear strength.

Future tests consisting of unbonded FRP sheets fastened utilizing FRP anchors with a large splay to anchor diameter ratio forcing the anchor to fail in shear would allow for the direct formulation

of the FRP anchor shear strength provided that premature failure modes do not occur.

Additional control specimen investigations utilizing specimens without FRP anchors, constant FRP sheet bond lengths, and varying FRP sheet bond widths could be used to further validate the proposed finite element model calibration formulation.

Subsequent to the calibration of the control specimen's finite element models, further research into the constitutive behavior of FRP anchors is needed to properly model the FRP anchor region using interfacial shear-spring elements. The constitutive behavior of FRP anchors could possibly be determined by testing specimens with unbonded FRP sheets fastened to the concrete substrate utilizing FRP anchors, therefore isolating the behavior of FRP anchors.

Perhaps the most interesting area of future research would be conducted on specimens utilizing FRP sheets fabricated with FRP bundles that are woven normal to one another, unlike the FRP sheets used in this experimental program that consisted of longitudinal fiber bundles only. Interwoven fiber bundles would drastically change the behavior of an FRP anchor and might not limit the effective width of an FRP anchor equal to the splay diameter. Interwoven fiber bundles would also help prevent the premature splitting failure mode, which is discussed in further detail in the next section.

Prevention of Failure Modes

Several factors were noted during the premature failure of specimens utilizing FRP anchors with a $\frac{3}{4}$ -inch (1.91 cm) anchor diameter and 4-inch (10.2 cm) splay diameter that could be prevented.

During the installation of $\frac{3}{4}$ -inch (1.91 cm) FRP anchors it was observed that large openings existed in the FRP sheet behind the FRP anchor due to the spreading of the longitudinal FRP fiber bundles necessary to pass the FRP anchor through the FRP sheet (see Figure 7.1). It is believed that these sheet openings caused the splitting failure mode observed during the failure of Specimens C-X-4-10-6 and C-Y-4-10-6 as discussed in sections 4.6.3.4 and 4.6.3.5. It is thought that placing a transverse FRP sheet behind the FRP anchors during the installation of the FRP anchors subsequent to passing the FRP anchor through the FRP sheet and prior to impregnating the FRP anchor splay could help prevent the splitting failure mode by holding the longitudinal fiber bundles in this region behind the FRP anchors together.



Figure 7.1 — FRP Sheet Openings behind FRP Anchors

FRP anchors with a large splay diameter are more susceptible to the delamination failure mode since the anchor must transfer the force generated over a large width FRP sheet into the concrete substrate. In order to prevent the delamination failure mode observed during the failure of specimens with 4-inch (10.2 cm) splay diameters, it is believed that placing an additional transverse FRP sheet FRP over the FRP anchor splay region following impregnation of the FRP anchor splay would help prevent delamination between the FRP anchor splay and FRP sheet interface.

During the failure of Specimen C-X-4-10-6, as discussed in section 4.6.3.3, FRP anchor pullout was observed to occur. It is believed that anchor pullout occurred due to the inability of epoxy saturant to impregnate the entire anchor. Since the FRP anchor had a 3/4-inch (1.91 cm) anchor diameter it is believed that the FRP anchor only partially impregnated with epoxy saturant causing the premature failure mode. In order to prevent FRP anchor pullout it is believed that formulating a new method to construct FRP anchors where the FRP

sheet is impregnated before the FRP anchor is rolled and tied would ensure that the entire FRP anchor is saturated with epoxy and would help prevent FRP anchor pullout. Examination of the effects of different FRP anchor fabrication techniques on behavior of FRP-strengthened elements would therefore seem warranted.

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