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A Guide to the Use of Fiber Reinforced Polymers for Strengthening Department of Energy Facilities

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PART 1 Overview of Fiber Reinforced Polymer Capabilities

Purpose and Introduction

This document seeks to provide the reader with general information to support use of Fiber Reinforced Polymer (FRP) to strengthen Department of Energy facilities. Furthermore, it highlights requirements, concerns, and solutions developed form FRP application on two strengthening projects in PF-4 and one project at the Radioassay Nondestructive and Testing (RANT) facility at Los Alamos National Laboratory. The projects in PF-4 are believed to represent the first application of FRP inside an operating nuclear facility in the United States.

The projects mentioned were for structures constructed of reinforced concrete. While lamination of FRP to concrete is a common rehabilitation practice, concrete is not the only substrate that may receive FRP strengthening. It is also possible to strengthen masonry, timber, steel, tanks, and pipes with FRP. Content that follows provides more detail on the types of systems that may be reinforced with FRP. This document does not cover every possible application of the product, since the field is still developing.

Terminology used here follows the definitions in ACI 440.2R – A Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. In addition, the document is written from an engineering and construction prospective. The document focuses on the use of Carbon Fiber Reinforced Polymers (CFRP), because the projects at LANL employed this product. The document also focuses on concrete structures since this material is associated with a large part of the DOE building inventory.

Moreover, the reader is encouraged to validate statements and references in this document. While every effort was made to insure correctness of content, it is possible that advances in the technology will obsolete some of the statements and concepts presented here. Furthermore, ACI 440.2R-16 was on the cusp of emergence at completion of this document. This document considered the advances in technology associated with ACI 440.2R-16 where applicable.

Lastly, the content in this document considers products offered by BASF Corporation, since the projects at LANL used products from BASF. Other manufacturers supply FRP products similar to BASF. Other suppliers of FRP include Fyfe, Quakewrap, Sika, and Simpson Strong-Tie. LANL selected BASF due to the fit of their technical expertise with the rigors of the rehabilitation projects in PF-4.

What is FRP?

A basic definition of Fiber Reinforced Polymer (FRP) is a composite material comprised of fiber (aramid, carbon, or glass – being the most common) and polymer resin commonly referred to as epoxy. FRP is a generic term for Aramid Fiber-Reinforced Polymer (AFRP), Carbon Fiber-Reinforced Polymer (CFRP), and Glass Fiber-Reinforced Polymer (GFRP). FRP used for strengthening civil structures traces its roots to the mid-1980s with the first installations occurring in Europe and Japan. Today, thousands of rehabilitation projects around the globe have employed these composites to add strength to concrete, masonry, timber, and steel structures.

The motivation to develop FRP for civil structures was to provide an alternate to conventional strengthening methods. Some of the conventional methods include steel plates epoxy-bonded to concrete, steel plates bolted to concrete, and steel plate jacketing of round, square, and rectangular concrete columns. The obvious disadvantage of conventional methods is that they are heavy and difficult to install. In addition, once steel yields, it will stretch with little strength gain. However, FRP is linear-elastic to failure. It has roughly the same tensile modulus as steel; thereby, making it a nice alternative to steel.

FRP products are available in primarily two forms. These are wet-layup and pre-cured. During the wet-layup process, installers saturate dry fibers with epoxy resin (Figures A1 and 9B to 17B). Mixing of the resin takes place immediately prior to saturating the fibers. Then fiber installation follows the saturation process. Prepreg systems use rigid FRP shapes (typically thin and flat plates) that are epoxy bonded to the substrate. These systems have lower versatility than wet layup systems; however, the quality control is better.

A final form of FRP strengthening is near-surface-mounted (NSM) bars or rods. In this case, cured bar or round stock FRP is bonded into shallow grooves cut into the concrete cover provided over conventional reinforcing steel. Typically, these bars are ¼ inch or smaller in width or diameter and installed in grooves that are ½ inch wide by ½ inch deep. NSM bars can provide a very practical solution for strengthening unreinforced or reinforced concrete or masonry elements. NSM bars can be an excellent option where abrasion damage to wet-layup FRP is a concern. Figure A2 depicts the installation of NSM bars into a concrete diaphragm. Figure A10 depicts NSM bar installation into timber.

The fibers in the FRP composite are brittle. In the case of CFRP, the fibers can be ten times stronger than steel in tension and are linear-elastic to failure. As an example, MasterBrace FIB 600/50 CFS[1] composite (fiber and epoxy resin) has an ultimate strength of 550 ksi at 1.7% strain. By comparison, A615 grade 60 steel yields at about 65 to 70 ksi and 0.2% strain. However, these materials have roughly the same tensile modulus (E_t). E_t for steel is 29,000 ksi and E for the composite is 33,000 ksi. The bare MasterBrace FIB 600/50 CFS fibers have a tensile strength of 720 ksi. Glass fibers are not as strong as carbon; however, they are more ductile. Appendix A of ACI 440.2R-08 gives a rough comparison of fiber material properties.

The epoxies used to saturate the fiber (known as the saturant) are very elastic. When combined with the fiber, the resultant composite becomes more flexible than the original fibers alone. This is because the fiber density is less in the composite comprised of fiber and epoxy. Substrate preparation epoxies are sometimes referred to as the primer and putty. The primer prepares the substrate to receive both the high viscosity leveling epoxy (putty) and the final bonding epoxy or the saturant.

Because of the brittle nature of the composite, a design must include adequate margin on failure. Margin will vary with application. The design team may consider inclusion of the appropriate margin in the design criteria[3] documentation following discussion with the independent reviewer and fiber manufacturer. ACI 440.2R was written with the commercial building industry in mind. Therefore, it may be necessary to tighten up strain limits noted in ACI 440.2R to meet performance goals associated with nuclear and high hazard structures.

Suppliers of FRP Systems

BASF, Fyfe, Quakewrap, Sika, and Simpson Strong-Tie provide FRP systems. There are likely other companies; however, these five represent the major suppliers.

The material suppliers may provide design services or work with an independent engineering firm that specifies the design. However, a skilled and knowledgeable engineer can perform most design work through utilization of ACI 440.2R. In some cases, the cost of the fiber may include an allotment for design services. However, for special installations like in PF-4, the design cost will exceed customary levels. Therefore, the design team may wish to consider ways compensate the manufacturer / designer for work that exceeds customary measures.

These companies may provide installation services or they may work with licensed contractors capable of preforming the fiber installation. The installation process is part art and part science. Therefore, it is important to use installers trained and certified to install the chosen product.

The resulting strength of the composite will vary from manufacturer to manufacturer. Subsequently, it is important to research the systems offered relative to the project requirements. Also, the technical skill will vary among manufacturers. This aspect can be very important for difficult projects like those in PF-4.

Some manufactures have ICC-ES reports for their products. Others don't. One of the manufacturers listed qualified their product to an aerospace standard based on testing applicability. These aspects become irrelevant for FRP systems due to the proprietary nature of the design. Furthermore, the Commercial Grade Item Dedication (CGID) process can be used to qualify any product. Therefore, it is recommended to consider the appropriateness of product application rather than focusing on the type of external certification associated with its use and installation.

FRP Applications

Perhaps the most common application of FRP is to strengthen concrete structures. However, it is also possible to strengthen masonry, steel, cast iron, and timber with FRP. The strength of the substrate will often dictate the fiber type. Generally, retrofits of timber and masonry structures may employ glass fibers. Rehabilitations of concrete and steel structures may use carbon.

In the case of concrete structures, there are varieties of ways to strengthen them with FRP. It is permissible to add flexural strength to a concrete beam through application of wet layup, NSM bars, or precured FRP. Fiber applied to the tension face of the beam would represent the typical flexural installation. Furthermore, two-sided, three-sided, and full-perimeter overlays may be used to increase shear capacity of beams and T-beams. It is possible increase shear strength of diaphragms with one and two sided overlays. Jacketing of a column with FRP will increase the compression capacity. This rehabilitation method will drive up the compression capacity on an interaction diagram over all eccentricities less than the balance eccentricity, but will not act to increase the tension capacity of a reinforced concrete column. Lastly, some have postulated that FRP could be used to prevent cracking of concrete at anchorages to concrete. In this instance, preclusion of substrate cracking would act to drive up the anchorage capacity.

Before emergence of modern seismic codes, hollow clay tile and unreinforced concrete masonry units were a popular material for shear walls. As we know, these systems are inherently non-ductile and exist throughout seismically active regions of the world. It is permissible to strengthen these systems for shear with one and two sided FRP overlays (generally with GFRP). Generally speaking, one-sided overlays apply to walls less than eight inches thick. One-sided applications are advantageous where it is not desirable to destroy architectural finishes or where access limitations prevent a two-sided installation. In addition, it is possible to strengthen masonry beams and columns in a manner similar to concrete elements. ACI 440.7R is a companion document to ACI 440.2R that specifically addresses design and construction considerations for strengthening masonry structures with FRP.

The use of FRP in steel structures is more limited; however, still possible. Typical applications include adding tension capacity to beams and pressure elements (pipes, cast-iron-pipe fittings, and pressure vessels) and to buried pipe through internal and external overlays.

There may be situations where external anchoring of the FRP is desirable. Anchors can act to provide continuity of structural load paths and act to improve reliability. ACI 440.2R is investigating rules for the design of anchorage; however, the no codified methodology exists today. The projects in PF-4 employed anchorage and utilized published research to facilitate this process. See the LANL calculation in reference 5 for a detailed procedure on the design of FRP anchorage.

The reader should exercise caution when using FRP reinforcing. For example, it is possible to reinforce an element in flexure so that it may carry more load. However, be aware that too much flexural reinforcing could render the member under reinforced for shear. In this example, brittle shear failure will replace ductile flexural failure.

Examples of FRP Used in DOE Facilities

LANL's PF-4 laboratory is a two-story reinforced concrete building roughly 250 feet on a side. Construction of this structure took place in the mid-seventies. The LANL SAFER project identified structural deficiencies in the PF-4 superstructure following an increase in the seismic hazard at LANL. For a variety of reasons, facility management chose to use FRP to strengthen structurally deficient concrete T-beams and columns. Detail work on the columns started in 2012 and in 2014 on the T-beams. Note that a detailed description of these projects is not given here due to the sensitive nature of these projects. Please see the references that pertain to these projects for additional detail.

The subject columns are eighteen-inches square and captured elements with deformation capacity limited to a short portion of their height. With a thirteen-ply circumferential FRP jacket over the section free to displace (Figure A3), the compression and deformation capacity of these elements was increased. This jacket resulted in roughly a three times gain in compressive strain over the unconfined system. Subsequently, the increase in compression capacity enlarged the column interaction diagram over all eccentricities less than the balance eccentricity. Obviously, the increase in compression strain acted to drive up the axial compression and moment capacity of the elements. The outcome of increasing the section compression and moment capacity is to drive up the displacement capacity of the column elements. See references 6, 7, 9, and 22 for the specifics of this project.

Some T-beams in PF-4 do not have enough capacity to give reasonable margin on shear capacity under Performance Category 3 vertical seismic loading. Due to the nature of these beams, FRP was an obvious choice for adding capacity. Because T-beams are rectangular beams integral with a concrete diaphragm, it is only possible to place FRP on the web. This aspect limits FRP placement to two or three sides of the beam web.

In the case of the PF-4 beams, a three-sided, three-ply overlay of CFRP on the webs of these members gave them 120 kips of additional shear capacity[5]. Figure A4 depicts the final installation. End anchorage exists at the terminating ends of the CFRP (Figure A15). The anchorage will act to add margin in the event of loading past the theoretical point of fiber debonding. Furthermore, the anchorage will insure integrity of the system past the strain corresponding to loss of aggregate interlock (about 0.4 percent). In the completed installation, the overall shear strength becomes a sum of the concrete capacity plus the steel stirrups plus the CFRP overlay. See reference 8 for the drawings associated with this project.

Because PF-4 is a nuclear facility, it was considerably more difficult to perform the FRP installations. Non-standard conditions include work in a radiation environment, higher standards for design and installation, higher requirements on reliability, CGID of materials, and stringent testing and inspection of the installation. Additional complexities are discussed later in this document.

LANL also used FRP to strengthen a roof diaphragm at the Radioassay and Nondestructive Testing Facility (RANT) at TA-54 during a seismic upgrade project. This structure is eighty feet square and thirty-six feet tall. Precast concrete wall and double-tee roof beams comprise the RANT structure. Precast structures are inherently non-ductile and often fail under earthquake displacements at the element-to-element connections. Therefore, through the integration of an FRP overlay onto the roof diaphragm, it was possible to stitch the existing double-tee beams together into a composite diaphragm system.

Design work began on this project in 2016. The overall rehabilitation was accomplished through an FRP reinforced double-tee roof diaphragm, new concrete collector elements at the diaphragm perimeter, and special concrete shear walls supported on drilled piers. Load transfer from the FRP into the collector was accomplished with headed steel studs attached to a continuous steel plate. The plate was bonded to the FRP with epoxy and the collector was cast on top of the plate. This stud plate element will act to transfer diaphragm demand into the collector.

The FRP overlay provided significant cost savings and reduced mass over a formerly proposed lightweight concrete topping placed on the existing double-tee roof structure. Furthermore, through the use of FRP, it was possible to locate the laminate around existing rooftop mechanical equipment. This layout concept precluded the need to relocate the mechanical equipment and the ducting resulting in a significant cost savings. Relocation was required to avoid overloading the roof diaphragm under dead load from the topping and MEP. Lastly, the use of FRP reduced the construction schedule also contributing to cost savings.

The FRP layout at RANT[30] consisted of laminating the material to the existing double–tee roof beam diaphragm. Because of the one-half inch joints between the existing double tees, it was necessary to fill these joints with epoxy sealant. The intent of the sealant was to prevent side-to-side compressive or racking movement of the beams. Subsequently, forty-five degree "X" plies of FRP were placed at eight feet on center over the joints to force the beams to act collectively as a diaphragm element and further prevent beam-to-beam racking. Finally, placement of a tick-tack-toe pattern of FRP laminate spaced at four feet on center increased the in-plane shear capacity of the composite diaphragm element. At the perimeter of the diaphragm, the design employed headed stud steel plates adhered to the new FRP with MasterBrace[1] SAT 4500 (saturant). The saturant epoxy has a shear bond capacity that exceeds 2.3 ksi per ASTM C882 insuring a capacity well exceeding demand. This stud plate in turn bears on the concrete in the collector beam located at the diaphragm perimeter.

It is important to note that steel and FRP must be isolated from each other due to galvanic action. Therefore, the stud plates used at RANT were placed on a 50 mil thick pad of MasterBrace[1] F 2000 (putty) prior to bonding with saturant. This layer will act to isolate the two dissimilar components. GFRP is an insulator. Therefore, one could place a layer of GFRP under the steel plate in lieu of the epoxy layer to isolate the plate and the CFRP.

Advantages of the Use of FRP

Rehabilitation of structures is often expensive. However, there are many reasons to retrofit structures. For example, it may be too expensive to replace a deficient structure in its entirety. It may be operationally disadvantageous to remove a structure from service and replace it.

FRP is an expensive material. But, when compared against the alternatives of poorer or inadequate performance or structural collapse from earthquake, the cost may become reasonable. Dry fiber costs of FRP can be around fifty dollars per square foot.

FRP has the benefit of being a low-weight solution. One layer of fabric and saturant weighs roughly two-ounces per square foot. Most installations don't exceed four layers. The light nature of this product also facilitates installation ease. FRP installation is similar to the process of wallpapering. Compare these qualities against conventional strengthening with steel plates, concrete toppings, and shotcrete overlays. These materials will add significant dead load demand to a structure; thereby driving down the benefits from retrofit.

In addition, a typical FRP overlay will add less than a quarter of an inch to the dimensions of a structural element. Four layers of material and saturant will measure about one-eighth of an inch thick. Therefore, this material won't impact the final appearance of a structure. Finishes that cover structural elements can be removed and replaced in-kind following installation of the FRP.

FRP is easy to handle. Typically, the product will arrive at the jobsite in twenty-inch-wide rolls. The fiber behaves like nylon fabric when unsaturated. Following saturation, the material is sticky, yet remains flexible for about forty-five minutes. Initial cure time depends on the ambient temperature at the installation site and of the components in the mixture.

FRP is versatile. The wet layup process allows strengthening of variable shapes and sizes.

The epoxy resins associated with the FRP emit low levels of volatile of organic compounds (VOC). Therefore, installation of the product will not generally pose an inhalation hazard to the installers. However, the only access to the PF-4 roof girders was through a non-permitted confined space. This work required supplemental ventilation because the VOC could build up in the confined spaces surrounding the roof girders.

Disadvantages to the Use of FRP

FRP is not the perfect material for structural retrofits. However, there are few disadvantages associated with this product.

FRP can debond from a structure if moisture or vapor gets trapped behind the product. Moisture intrusion is primarily a concern in external applications. However, water can enter a structure through cracks or a poor roofing membrane and enter interior structural elements. This can moisten the substrate enough to cause debonding of FRP strengthened elements. For moisture induced debonding to occur, the moisture must be trapped behind the FRP. Therefore, in instances where the FRP does not fully encapsulate an element, moisture can escape at joints in the FRP reinforcing. It is also possible to add weeps (typically shallow grooves cut into the concrete) behind the FRP to allow moisture to escape from full encapsulation type installations.

FRP is combustible. The material will increase the combustible loading of a facility. Intumescent coatings can be used to coat the final installation and reduce the combustible potential of an FRP installation. Furthermore, the material will lose strength if the temperature surrounding the FRP warms to the glass-transition temperature. See the section on Exposing FRP to Heat for more detail on the glass-transition temperature. Typically the glass transition temperature is about 160 degrees Fahrenheit. Therefore, this material is not suited for high temperature installations.

The use of FRP strengthening is a relatively new concept. Some may consider this a disadvantage. However, as noted above, the material traces its origin to installations in the mid-eighties. Hundreds of projects around the globe employ this material every year. The material is new in the nuclear industry and nuclear codes do not address FRP installations. However, as demonstrated at LANL, it is permissible to use FRP to strengthen structural elements in nuclear facilities.

Substrate preparation can be a formidable effort. Installations over deteriorated concrete, can require significant effort to restore the substrate to a suitable condition before applying the FRP. In addition, the substrate must be smooth. Therefore, it may be necessary to add leveling epoxies to smooth discontinuities in the substrate surface. The accepted levelness is 0.04 inches. In addition, cracks larger than 0.01 inches wide must be filled with epoxy prior to installation of the FRP. Without proper preparation, cracks of this nature can move following application of the FRP and damage or tear the installation.

FRP will fail in a brittle manner. The failure will either be debonding or fracture. Anchoring of FRP will provide additional margin on the design and prevent catastrophic strength loss from debonding. FRP will creep under sustained loading. However, ACI 440.2R provides limitations on capacity to preclude this mode of failure.

An additional disadvantage pertains to installation in high-security facilities like PF-4. It is not typical to find certified-FRP installers that possess security clearances. For the projects in PF-4, LANL facility management decided that it would be too cumbersome to provide one escort for each uncleared, certified installer. So, LANL facility management decided to hire Hydra-Crete[12] to train Q cleared painters to perform the installation work. The training burden was not great. It only took two days of off-site training to certify the painters on FRP installation.

As noted above, it may be necessary to perform a CGID to qualify FRP material. This aspect added cost to the installation at LANL. Initially, the team selected Southwest Research Institute (SWRI) to perform the testing associated with the CGID. However, after the testing became routine, SWRI declined to perform any additional testing. At this point, project management hired Nutherm to perform the additional testing required for the CGID. Nutherm subcontracted their work out to a third party testing laboratory located in Georgia. Although, Nutherm claimed that their subcontractor ATS was NQA-1 compliant, the results produced by ATS were the subject of continuous scrutiny. Eventually, the poor performance lead to the termination of the contract with Nutherm and ATS.

How Does FRP Strengthen Structural Elements?

FRP can only carry tension loadings parallel to individual fibers; therefore, this limits its application. Load transfer takes place in one of two ways, which are bond and contact critical applications. A bond critical application requires load to transfer from the substrate across an epoxy resin layer and then into the FRP. The epoxy resin must carry shear from the substrate and deposit that load into the FRP. These types of installations can be prone to debonding failures if the load in the FRP exceeds the debonding threshold.

On the contrary, in contact critical applications the FRP confines the substrate and can drive up its compressive and shear properties. In this case, the fiber jackets the structural element around its perimeter. The jacket acts similar to hoops of reinforcing steel that confine the core of a concrete element. The fiber laps back onto its self; therefore, strains of one percent can be reached in the fiber. It is not possible to reach the ultimate strain due to reduction factors associated with environmental conditions and guidelines on maximum strain. Debonding is not a concern with contact critical installations.

Flexural reinforcing added to the tension face of a concrete beam is an example of a bond critical installation. In this case, the debonding strain will control the capacity of the FRP. Circumferential jacketing of a concrete column is an example of a contact critical installation. In the former condition, one must consider strain compatibility to design the reinforcing. In the latter condition, the FRP-tension ring confines the concrete from compression failures and acts to drive up the compressive capacity of the element[13].

The addition of FRP can provide additional shear strength to an element. In this case, ACI 440.2R recommends circumferential installations, but provides guidance for two and three sided applications. ACI 440.2R-16 will provide guidelines for one sided applications associated with diaphragms and walls. One, two, and three sided installations are bond critical. Such installations may require FRP-based anchorage at terminating ends of the fabric. This was the case for the

PF-4 roof T-beams. The independent reviewer at Degenkolb insisted on anchorage to improve the system reliability. The provisions of ACI 440.2R rely on bond formulations to define the loading transferred into the concrete substrate in two and three sided installations. Therefore, the need for anchorage will depend on the nature of the installation and the desired margin on the installation. Special FRP anchorage and anchorage details were developed during the course of the rehabilitation of the PF-4 roof girders. Guidelines for these details were not available in codified literature and were developed with the assistance of Degenkolb Engineers.

There are additional ways to strengthen structural elements with NSM FRP bars. NSM bars are applicable to installations attempting to add additional shear or flexural capacity. Due to the rigidity of these elements, it is unlikely that these elements could be used in contact critical type applications.

ACI 440.2R places limitations on the maximum achievable strength gain from application of FRP laminates. This is to protect against failure of the original structure in the event of damage to the FRP strengthening. Equation 9-1 of ACI 440.2R-08 states that the design strength of the existing structure should exceed 1.1 times the dead load plus 0.75 times the live load supported by the strengthened structure.

ACI 440.2R-08 also notes that documentation exists for flexural strengthening between ten and one-hundred and sixty percent of original capacity. However, ACI 440.2R states that forty percent is a more reasonable limitation on permissible gain in flexural strength. The shear strength gain on the PF-4 roof girders was thirty-eight percent. The increase in compression strain capacity following installation of FRP on the PF-4 short columns was 3.3 times. The increase in compressive strain allowed the elements to achieve three-quarters of an inch displacement over their roughly fifty-inch height.

PART 2 Specifying Fiber Reinforced Polymers in DOE Facilities

Process Overview

Like many construction activities, the process of strengthening with FRP follows a basic process. Usage conceptualization is the starting point for any FRP installation. A facility customer needs to identify a desire to improve a structure. At this point, the project team will form to support the need.

FRP installations are primarily focused on structural engineering. On most projects, the structural upgrade will impact architectural finishes, and mechanical, electrical, and plumbing systems. Therefore, it is important that the initial project scoping consider the impact on all associated systems.

A typical installation in a DOE facility may have a project team comprised of the Owner, FRP specialty engineer, and the independent reviewer. The architect, structural engineer, and MEP engineers are likely employees of the Owner. Because engineers experienced with design of FRP systems can be rare, a specialty-engineering firm or the FRP manufacturer will likely specify the

FRP reinforcing. Additionally, because FRP design is part science and part art, it is common for an engineering firm who specializes in FRP design to specify the FRP. However, it is permissible for the Owner's structural engineer to specify the FRP using ACI 440.2R. On the projects in PF-4, LANL elected to hire Degenkolb Engineers as the independent reviewer because they employ staff knowledgeable in the design of FRP.

The LANL structural engineer controlled the design process through the use of design memorandums approved by the independent reviewer. The memorandums served as the basis for the FRP design, installation, and testing. The LANL structural engineer completed design work outside the FRP specification. BASF Corporation used the design memorandum as input to the FRP design. Following generation of the FRP designs, the LANL structural engineer checked the FRP design and Degenkolb Engineers provided the independent review. Degenkolb Engineers also provided the independent review of all structural engineering services outside the scope of the FRP design.

The FRP design represented a reasonably small portion of the projects in PF-4. However, both projects in PF-4 and the one at RANT required significant expertise on the part of the BASF FRP designer. The remaining portions of the project included work to support the CGID, anchor design, anchor fabrication and anchor testing, pre and post-installation testing, coordination, and design modifications. The paragraphs that follow discuss required activities to support the full project scope.

Design of the FRP

Although ACI 440.2R provides guidelines for the design of FRP systems, due to the fact that this is a niche technology, expertise in the design of these systems is not common. Furthermore, specification of FRP systems is typically performed by specialty engineering firms or by individuals employed by the fiber supplier. For these reasons, it could be necessary to hire an engineering entity that specializes in the design of FRP. However, structural engineers knowledgeable in FRP systems can perform most design work through utilization of ACI 440.2R. In the case of the seismic upgrades in PF-4, LANL elected to hire BASF Corporation to produce the designs due to the technical superiority they demonstrated with preliminary design concepts.

LANL controlled the design process through the issuance of design memorandums. BASF produced the design in accordance with the PF-4 Design Criteria memorandum. This document specified the pertinent input parameters, code guidelines, ASTMs, and LANL specific criteria relevant to the FRP design. Degenkolb Engineers independent reviewed this document and provided input to its composition. A primary consideration for this document was the specification of seismic criteria absent in ACI 440.2R-08. Significant content on system capacity limits came from ACI 318[10] and ACI 349[11]. Note ACI 440.2R-16 will contain guidelines for design of FRP subject to seismic loads.

Once BASF produced the design that complied with the Seismic Design Criteria for Strengthening the Type V Columns in PF-4[3], LANL verified the calculation, and Degenkolb Engineers provided the independent review. BASF served as the designer for this portion of the calculation only.

It is important to note that ACI 440.2R provides design examples to assist with specification of FRP. See Chapter 15 of 440.2R-08 and Chapter 16 of ACI 440.2R-16.

Special Design Considerations – Anchoring FRP

The art of FRP design is an evolving field. While ACI 440.2R seeks to specify guidelines to insure the safe and reliable design and installation of FRP, it does not include rules that address the level of redundancy typical in nuclear facilities. Therefore, situations arose on the PF-4 seismic upgrade projects where the independent reviewer required non-codified redundancy in the design.

The addition of FRP to the PF-4 roof girders increased their shear capacity. Because the roof girders are structurally classified as T-beams, it was not possible to install FRP (wrap) around their perimeter. This characteristic necessitated a three-sided, bond-critical installation. In a bond-critical installation, load is transferred from the fiber into the substrate over a finite width and length of the fiber[14]. The load does not transfer over the full bond area between the fiber and the substrate. Once debonding begins, it will likely continue until the FRP fully delaminates under constant loading. This makes debonding potentially a catastrophic failure mode.

One can conceptualize debonding of FRP similarly to the act of pulling a film or piece of tape off a surface. In the case of peeling tape off a surface, note how the adhesive at the debonding front is the only area carrying load. Maeda's[14] work demonstrates the mechanics behind this process.

To add margin into the design, our independent reviewer at Degenkolb was adamant that we provide anchorage at the terminating ends of the FRP plies. The intent of the anchorage is to arrest catastrophic debonding in the case of beyond design-basis-load application. Using the analogy of the adhesive tape again, the anchors will perform the same function as pressing on one end of the tape and then applying a load to the free end of the tape. If one presses hard enough on the free end, it is possible to pull hard enough on the tape to cause tensile rupture. This is the intended function of the FRP anchorage, to preclude a debonding failure before tensile rupture in the fiber.

Academicians have studied the effect of anchorage on FRP laminate systems. Some proposed the use of anchorage for precluding debonding failure in FRP used for flexural and shear reinforcing. These studies often demonstrate that the full fiber capacity can be reached through the addition of FRP anchorage. However, the guidelines in ACI 440.2R place sufficient limitations on the bond capacity to afford most installations adequate safety margin without anchorage. ACI 440.2R accomplishes this goal by limiting the maximum strain. The ACI 440 committee formed a task group in spring of 2016 to address the addition of anchorage design rules in to the ACI 440 guidelines.

MasterBrace[1] FIB 600/50 CFS carbon fiber fabric comprised the anchors used in PF-4. The design was based on the cone-bond theory[15, 16] associated with adhesive anchors embedded in concrete. The anchor design criteria memorandum[29] encapsulates the actual design methodology used for these anchors. Assignment of the anchor embedment and diameter followed the methodology in these references. The anchors used in PF-4 were three-quarter inches in diameter and had a nine-inch embedment depth. These size characteristics are larger than those tested by researchers in references 15 and 16. In addition, the design load imposed on the PF-4 anchors will exceed documented research by a factor of two.

For these reasons, LANL elected to proof test the proposed anchors. The testing demonstrated that the anchors are capable of supporting thirteen kips of tension load required by design. The tests were not run to failure. The probable upper bound capacity of the anchors is near thirty kips. The biggest problem with the tests was transferring the load from the testing device into the carbon fiber anchor tail that stuck out of the concrete. Several iterations were required before it was possible to load a sample to thirteen kips. Figure A12 depicts the testing apparatus, carbon fiber anchor, and concrete test block. The intent was to simulate testing performed in reference 16.

Recall the girders in PF-4 received a three sided FRP installation. The vertical FRP will carry tensile load in a manner similar to steel stirrups. The philosophy used for the FRP anchors in PF-4 is that they act in tension to resist loading following a debonding failure. The anchors are bonded into the beam webs perpendicular to their height with fans spayed out onto the vertical FRP. Some may argue that the anchors will act in a pryout failure mode. However, due to the lack of research to validate this failure mode, the anchors were designed as if they could only support tension loading. Furthermore, this failure mode is common to mechanical anchors that are rigid along their length. The FRP anchors are much more flexible in shear than a headed steel stud; therefore, only tension behavior was considered.

The anchor fan details are likely as important as the anchor embedment details. Several researchers[17, 18] have studied this characteristic. The fan must have enough area to develop the imposed load and bond to the composite, much like a reinforcing bar must have enough length to engage the concrete matrix. Also, adjacent fans should overlap each other. Researchers suggest placing a reinforcing strip, orientated with their fibers transverse to the fan length, over the anchor sites to account for unresolved transverse stresses that can develop in the anchor fan. Lastly, it is important to provide at least a one-half inch radius on the anchor hole to mitigate concerns associated with stress concentrations imposed by a sharp concrete edge. References 5, 6, 17, and 18 discuss these details and others.

The fiber-to-fan lap considered a usable shear bond stress of 2 ksi in the saturant. BASF suggests that their saturant can support up to 2.3 ksi in shear as demonstrated by ASTM C882[19]. However, to add conservatism into the process, our reviewers at Degenkolb suggested reducing the capacity by ten percent. Additional details on determination of FRP lap capacity are defined in reference 5. The same limits on strength may be used to design FRP to FRP splices. An additional consideration is that the C882 test does not exactly replicate the lap-to-lap installation. Therefore, some judgment is necessary to insure accuracy in application of results. The newest standard that attempts to define FRP-to-FRP lap shear strength is ASTM D7616[19]. However, this does not exactly replicate typical lapping conditions. Therefore, one needs to use judgment in interpretation of results from both ASTM C882 and D7616.

The anchorage design considered two strain levels. The first was associated with the strain at which the concrete would lose aggregate interlock. This strain is 0.4 percent. Subsequently, the anchor embedment was evaluated for a beyond design basis strain of one percent. Consideration of this strain level demonstrated that the anchors would not fail under a beyond design basis seismic event. At one-percent strain, both the concrete and steel stirrups will no longer be acting to share load, only the carbon fiber will be capable of resisting load.

Column strengthening with FRP is a common way to add strength and ductility to overloaded column. In the case of columns that support seismic loading, some researchers and practitioners view the need for FRP anchors similar to the requirements for cross ties in conventionally reinforced concrete. Application of this methodology to the PF-4 columns demonstrated that the columns were narrow enough so that they did not require anchors. However, it could be prudent to use anchors on wider columns to restrain the FRP jacket similar to how cross ties restrain hoop steel in columns supporting seismic loading. The vertical and horizontal spacing of the anchors should follow the recommendations for cross ties in the seismic provisions in ACI 318 and ACI 349.

Special Design Considerations – Attaching Structural Steel to FRP

On occasion there will be a need to integrate FRP with structural components at the limits of the FRP. An example of this would include transfer of load in a diaphragm rehabilitated with FRP to the structure's main lateral system. A similar application includes strengthening of connections between tilt-up wall panels and the same FRP reinforced diaphragm. Lastly, consider the case of developing flexural reinforcing on shear wall elements into foundations. All cases require a transfer element or system to integrate dissimilar materials.

The obvious way to make a connection may be with the use of FRP anchors. While this is possible for uniaxial loading, transverse loading on FRP anchors may quickly lead to brittle failure of the anchor stem associated with shearing of the fibers. The solution for connections that require ductility or that must handle multi-directional loading is to use structural steel bonded to FRP.

As mentioned above, the RANT project at LANL involved strengthening of a double-tee roof diaphragm with FRP reinforcing. This roof reinforcing had to be integrated with a new concrete collector element at the diaphragm perimeter. As noted above, saturating epoxy was used to bond a shear stud plate to the FRP. Following installation of this plate, the one-foot square collector element was cast directly over the FRP and stud plate at the diaphragm perimeter. The collector-stud-plate element will deliver seismic load into the new concrete shear walls associated with the seismic rehabilitation.

Epoxy is very good at transferring load in shear between elements. This is evident from the robust load transfer mechanism between FRP and concrete substrate. For example, in the case of shear reinforcing on the web of a T-beam, tensile load in the FRP is transferred across the bond length (usually less than two inches in length) in shear and correspondingly deposited into the concrete substrate. Negligible shear deformation occurs in the bond film between surfaces.

A similar shear mechanism can be used to transfer load from FRP into steel anchor plates or other structural shapes. The designer may rely on the shear capacity of the saturating epoxy or high viscosity putty to transfer load between FRP and steel. The shear capacity of BASF MasterBrace[1] SAT 4500 is 2.3 ksi per ASTM C882. BASF recommends the use of a lower bound shear capacity of 1 ksi for their MasterBrace[1] F 2000 (putty). The manufacturer of competing FRP composite systems should be able to define these magnitudes in accordance with ASTM C882 or D7616.

A designer may also wish to transfer load from a structural steel shape to the FRP in bending across an epoxy bond. A physical example is an edge angle attached to the edge of a flange of a double-tee beam. The span of the edge angle would be parallel to the beam span. Such an edge angle could act to restrain an exterior wall system at the roof diaphragm level.

Installations using this load transfer mechanism are not known to exist in civil construction. However, this idea was attempted on RANT and discontinued to avoid the research effort. The specific application included the need to bond an L6x4 angle to the edge of a two-inch thick, double-tee beam flange. The connection was intended to transfer seismic demand imposed by ten-inch thick, precast concrete panels back into the FRP reinforced diaphragm.

Saturating epoxies and high viscous epoxies can exhibit strains of more than two percent to failure. In addition, these materials have reasonable capacities at these strains. The concern is setting reasonable strain limits to insure adequate load transfer in flexure across the bond surface. For the edge angle connection discussed here, the proposal was to limit flexural strains to 0.2 to 0.3 percent in the epoxy to insure elongation similar to that experienced in steel as it approaches yield. The properties at this strain level could be combined with the section modulus of the bond surface (over one leg of the angle) to yield bending capacity. At higher strain limits, peal failure could control connection capacity. No ASTM exists to define peal strength of this kind of connection.

In the cases noted above, it is necessary to isolate the steel and carbon fiber due to galvanic corrosion potential. Section 9.3 of ACI 440.2R-08 discusses this issue. Therefore, it is recommended to apply a 40 mil layer of epoxy between the steel and carbon fiber to eliminate concerns about galvanic action between mating surfaces. Alternatively, one could achieve isolation with plies of glass or aramid fiber placed between the carbon fiber and steel element.

It is important to note that the automotive, marine, and wind power industries use the adhesive bond to transfer load from carbon fiber products to steel and aluminum components. These industries recognize the several advantages offered by adhesive connections over conventional mechanical fasteners. These connections improve manufacturing efficiency, preclude stress concentrations, and prevent tear-out type failures common in bolted connections[33, 34]. Furthermore, these adhesives make connections and construction possible that would not be with mechanical connections. Lastly, ACI 440.2R-16 provides some ideas pictorially in Chapter 13 for load transfer between FRP and concrete elements.

Exposing FRP to Radiation

An obvious question at this point would be how does radiation influence the strength of FRP? LANL is fortunate to have the services of Los Alamos Neutron Science Center (LANSCE) at its disposal. LANSCE scientists Bjorn Clausen, Charles Kelsey, and Michael Mocko performed an experiment on January 28 and 29 of 2014 to evaluate material property degradation of the FRP following fifty years of radiation exposure[26]. The exposure simulated the summation of 10 mrad per hour of dose over a period of fifty years. This dose is roughly equivalent to 5000 rad. Twenty-six FRP coupons received this exposure.

Following exposure, the coupons were sent to SWRI for tensile testing in accordance with ASTM D3039. The results from these tensile tests demonstrated that there was no tensile strength degradation for the exposure.

A publication from NASA[25] notes that epoxy resins used for space vehicles did not experience significant strength degradation until receiving $1x10^9$ rad of dose. Therefore, FRP has viability for strengthening of structural elements in many areas of nuclear power plants and other radiological structures.

Exposing FRP to Heat

It is advisable to consider the thermal environment that surrounds the FRP installation. Temperatures common to those that support human life are acceptable to FRP. However, in locations where sustained temperatures exceed 140 degrees Fahrenheit, the thermal effects on the FRP cannot be denied. This temperature represents roughly the glass-transition temperature for FRP. This threshold is the point where the FRP begins to soften from thermal loading.

Since epoxy resins are heat sensitive, the epoxy in the composite will soften as temperature rises. Significant strength loss occurs when the temperature exceeds the glass-transition temperature. For FRP the point of substantial loss of strength is at about 180 degrees Fahrenheit. The actual temperature and severity of strength degradation will vary between manufacturers. Therefore, use this number as a guide rather than an absolute. See ASTM D4065[19] for the procedure to determine the glass-transition temperature of a FRP composite.

Any installation may experience heat from fire during the lifetime of the installation. Extreme heat events like fire can be detrimental to an FRP installation. Coating the FRP with intumescent paint or covering it in drywall will not provide sufficient insulation to prevent the FRP from reaching its glass-transition temperature. A common application for intumescent paint is to coat architecturally exposed structural steel (AESS). The coating will balloon to several times its original thickness when exposed to fire-level heat. Subsequently, this expansion will act as thermal insulation to protect the steel substrate from damage associated with a heating event. The expansion generally occurs at temperatures exceeding 300-degrees Fahrenheit. Thus, they do not expand until after the FRP exceeds its glass-transition temperature.

The FRP strengthening on the PF-4 roof girders has an intumescent coating. The accident scenario for this installation is a post-earthquake fire. The intumescent coating could act to reduce the combustible loading inside PF-4, but will not protect it from degradation during a fire.

Commercial Grade Item Dedication of FRP

Since the supplier of the FRP products used at LANL were not on the facility Institutional Equipment Suppliers List (IESL), it was necessary to commercially dedicate the FRP. This was the first time anyone item dedicated FRP. Therefore, the process presented some hurdles.

The initial issue pertained to selecting the proper critical characteristics. On a fundamental level, it was necessary to validate the strengths of the primary components in the composite system. These components are the primer, saturant, and the carbon fiber. The putty does not have a safety function. First, the team selected tensile modulus, rupture strain, and rupture stress of the composite, and flexural modulus of the saturant as metrics. Procedures in ASTM D3039 were used to evaluate the first three metrics. The manufacturer provided reference values for these items on their material data sheets.

Subsequent testing results demonstrated that it was not possible to demonstrate a reasonable match for the reported flexural modulus. SWRI performed the flexural tests and reported values all over the map. Upon further review and understanding of the material in use, the team determined that flexural modulus really did not provide any data relevant to the CGID of the FRP. Therefore, the team disregarded the flexural tests results.

At this point, the team went back to the drawing board. Using the failed flexural tests as a guide, the team kept the tensile modulus testing and elected to validate primer functionality through post-installation testing per ASTM D7522. The purpose of testing per ASTM D7522 is to demonstrate proper installation of the FRP laminate through localized destructive testing. This test subjects a local area (scored through the FRP and into the substrate) of the installation to direct tension loading. In order for a sample to pass this test, the failure must occur through the concrete matrix. If the failure were to occur in the primer, it would invalidate the primer capacity and installation procedure. Further details of this procedure exist in the section on installation testing.

Therefore, a CGID should focus on the metrics necessary to validate the final installation. Through trial and error, the team determined the best way to validate the installed composite was through pre and post-installation testing of the composite coupons per D3039 and installation testing per ASTM D7522.

Note that in July of 2016, the team learned that BASF has NQA-1 program. LANL hopes to use their 2015 NIAC audit to qualify future orders of fiber and saturant. This process will allow LANL to get BASF onto the IESL. The intent is for BASF to submit Certificates of Certification for their fiber and saturant with each purchase order. Validation of the primer will be through testing per ASTM D7522.

Reporting of Tensile Properties for the Composite

In some instances, the project team may wish to validate the manufacturer's reported material specifications on the composite through sample testing. This methodology can be used to support the CGID. In the case of the projects in PF-4, testing of the composite per ASTM D3039 supported metrics associated with the CGID. Figure A18 shows a typical coupon and A11 depicts the test setup. The metrics for the CGID included tensile modulus, rupture strain, and rupture stress. Reporting of tensile properties is not a simple matter. There are several ASTMs used in industry for tensile testing and a myriad of methods used to report tensile properties. It is important to specify how the testing lab is to define strength and modulus for this material.

Some manufacturers report their strengths considering an average epoxy thickness imparted on a test coupon. Also, it is possible that the testing lab will report results based on measured thickness of the test coupon. This will generate strengths all over the map, because the epoxy thickness on a sample can vary significantly. Do not accept values reported in this manner. Also, note that the epoxy thickness will have little influence on the tensile strength of the specimen.

The manufacturer should specify a thickness of their product per ply. For the product used in PF-4, the manufacturer reported a thickness of 0.013 in/ply. The manufacturer should use ASTM D3776[19] options A or C to determine the areal weight in the ply thickness evaluation. Areal weight is the weight per unit area of a single ply of fiber. Areal weight divided by the density per ASTM D3800[19] will yield the average thickness. Note that in some situations the purchaser may wish to specify that the manufacturer report areal weight per option A. Through this option, the purchaser will get an average ply thickness per roll of fiber. Option C only considers a small swatch in the thickness determination. This option will not produce thicknesses that are representative of a lot of material. In addition, option A may be more appropriate for determining design material thickness.

It could be advantageous to specify the design material thickness in the specifications and or documentation that supports the CGID. Make this specification with input from the fiber supplier. Both of our testing consultants on the projects for PF-4 were unfamiliar with testing per ASTM D3039. This caused problems with reporting of test results. SWRI tried to measure the thickness of the bare carbon fiber with a micrometer. This method will not produce the correct result. Because the carbon fiber is an assemblage of filaments, the sample will soften and flatten under force applied by a micrometer. The procedure in the paragraph above must be employed to arrive at the correct thickness.

Tensile testing often follows one of two ASTM standards. These standards are ASTM D3039 and ASTM D7565[19]. The former standard provides guidance for determination of values in load per unit area. The latter ASTM provides guidance for determination of values in load per unit width. D3039 is a general purpose standard for testing composites; whereas, D7565 applies more to FRP used for strengthening of civil structures. ASTM D7565 may be the most appropriate standard for confirming manufacturer's reported strength, since it eliminates the thickness from the evaluation. However, it is permissible to use ASTM D3039 if desired. ASTM D7565 refers to D3039 for coupon and testing specifics.

Interpretation of Tensile Test Results and Testing Problems

It can be difficult to interpret the tensile test results. ASTM D3039-08 provides detailed views of failure modes in Figure 4. Ideally, the failure mode should be type XGM. Other failure modes can be an indication of undesirable testing configurations. For example, the presence of external drilling moment acting on the coupon may cause mode SGM. This could indicate misalignment of the grips on the testing machine. Other undesirable modes include LIT, GAT, LAT, and DGM. Figure A19 depicts an XGM failure and Figure A20 depicts undesirable failures.

In general, it is desirable to eliminate any source of bending imposed on the coupon during the tensile test. This is because bending could contribute to premature failure of a coupon. Front-to-back misalignment of the grips will also induce bending in the sample. See ASTM D3039 and ASTM E1012[19] for recommendations on testing machine setup and calibration. Also, these references provide guidance on ways to determine if a coupon is properly aligned or unintentionally loaded in bending.

Additional aspects that may influence results include:

- Method of gripping the sample. Incorrect gripping can lead to premature coupon failure typically notable by a near grip failure mode. See ASTM D3039 section 6.2.
- Coupon thickness and width. The coupon should be of uniform width and thickness. Thickness variation can lead to unintended stresses in the coupons during testing.
- Loads imposed by large strain gauges. D3039 suggests using glue on strain gauges to prevent unwanted loads on the coupons. See the section in this document on The Extensometer for additional information
- Nicks, delamination, and damage on the coupon
- Calibration of testing machine
- Method of reporting strength and modulus
- Experience of the testing lab with performing the D3039 test
- Exclusion of grips or use of incorrect grips on the tensile specimen. Figure A16 depicts an example of the proper grips for tensile testing.
- Gripping misalignment. ASTM D3039 discusses these issues in sections 6.3.

In some instances, testing results that fail to meet the specification may still be adequate. This is because the design will only consider a fraction (roughly a quarter) of the total material capacity. If the results are within an acceptable tolerance of the correct tensile modulus, but fall below the specified ultimate strain and stress, it is important to consider how the results may still be valid. Also note, that it is inappropriate to compare the results of one sample against the performance goal. ACI 440.2R suggests averaging results across twenty samples and comparing the average against the performance goal. Whereas, D3039 requires a minimum of five samples. ASTM E122 provides guidance on determining required sample size based on precision required.

For example, consider the case where a coupon test of carbon fiber demonstrates a tensile modulus of 33,000 ksi and matches the specification. However, the failure stress and strain are less than the manufacturer's specified limits of 550 ksi and 1.7 percent, respectively. If the results demonstrate sufficient margin on the design requirements, then the results are likely acceptable. Some suggest that an acceptable margin on all values is minus ten percent. Also keep in mind the usable strain limit is a maximum of 0.4 percent for shear applications, one percent for confinement of concrete, and roughly one percent for flexural applications (reduced for bond) per ACI 440.2R. It is difficult for anyone other than an expert in the D3039 tests to achieve the strength and stain values reported by the fiber manufacturer.

Alternatively, the team may wish to specify testing criteria that are below the manufacturer's specified properties. The properties listed by the manufacturer represent results achieved by experienced testing laboratories under perfect testing conditions. The values that result from testing are largely influenced by the skill of the technician that performs the tests. The fiber manufacturer will use one who is an expert in performing D3039 tests, most testing laboratories do not possess the necessary expertise in the D3039 test method. This is even true for NQA-1 certified testing laboratories. Therefore, it is recommended to specify acceptable range on the desired properties rather than insisting that the coupons meet every material criterion listed by the manufacturer for their fiber. Subsequently, this could simplify the CGID process, yet still yield accurate and valid results.

Moreover, section 4.3 of ACI 440.2R-08 recommends that the manufacturer report the ultimate tensile strength and strain as the mean minus three standard deviations. This same section recommends that the manufacturer report the tensile modulus as the chord value over strains of 0.3 to 0.6 percent. Since ACI 440.2R recommends considering an average of twenty samples, it is necessary to evaluate the average of tensile and modulus tests against the manufacturer's published data. The design team should inquire on the material strength reporting methods used by the FRP manufacturer.

Lastly, it is important that the testing laboratory provide the stress-strain plots for the coupon testing. These plots will provide the reviewer additional insight into the results of the coupon testing. In addition, the plots can demonstrate potential sources of error in the testing program, such as coupon slippage.

The Extensometer

The extensometer or strain gauge used for the ASTM D3039 testing is an important component. Nutherm who performed testing for LANL on the PF-4 seismic upgrades project, used an Epsilon 3542 extensometer. Figure A17 depicts this gauge attached to a composite coupon. This gauge is typically used for testing plastics and other materials that exhibit large strains prior to failure. It is important that the strain gauge accurately capture behavior over the strains experienced during coupon testing. The strains associated with testing of carbon fiber coupons are generally less than two percent. A more appropriate strain gauge for this test is the Epsilon 3442.

An additional consideration is how much the extensometer weighs and how the lab supports the device during testing. The extensometer (and anything hanging from it) can imposed significant drilling moment on the test coupons if it is heavy (more than an ounce) and if it reacts on the coupon at distance. Drilling moment from the Epsilon 3542 supported at six inches from the coupons was believed to have contributed to testing inaccuracies for some of the PF-4 test coupons.

Furthermore, the extensometer classification is an important criteria. ASTM D3039 section 7.3.2 recommends the use of class A gauges when testing stiff material. The alternative class is B-1, which this class of gauge may introduce significant fixed error when testing stiff materials. Consult with the testing lab on this issue prior to testing or consider inclusion of this information in to project specifications.

Alternatively, one may wish to consider using glue on strain gauges in lieu of a mechanical extensometer or employ more advanced methods of measurement such as the DIC technique. These types of gauges are not commonly used for the D3039 tests. However, one advantage is that this mechanism will not impose bending moment into the specimen because it is adhered to the specimen. In addition, use of glue on strain gauges can help to trouble shoot poor testing results. Through placement of these gauges on both sides of the specimen, the lab can compare strains between gauges to determine if the grips are misaligned. This is because the presence of bending moment will induce different strains into gauges on opposite sides of the coupon. ASTM D3039 lists other advantages of using glue on strain gauges.

Reporting Tensile Modulus

One desirable form of data from the ASTM D3039 test is tensile modulus. The engineer may wish to specify how the testing laboratory reports this quantity. Since FRP is brittle to failure, a coupon test should exhibit one slope up to failure. The slope represents the tensile modulus. However, the coupons can exhibit slight ductility at the approach of the failure strain. This ductility should be excluded from the reported values.

The testing lab should report the chord modulus as defined in D3039. This corresponds to the slope of the stress-strain curve between 0.001 and 0.003 in/in of strain. Furthermore, the stress-strain curves should be concave down so that the chord modulus pertains to the maximum value over a test. Curves that are concave up (suggesting stiffness gain with applied load) will result in a chord modulus that represents the minimum stiffness. Curves with this shape can be an indication of slippage in the griping system.

It is important to review the stress-strain curves provided by the testing laboratory. Valid tests will exhibit the plot quality defined in ASTM D3039. However, stress-strain curves from the lab may not indicate this exact behavior. Detrimental qualities evident in these plots include:

- Curves that are concave up in shape.
- Stair-stepping in the diagram. Drops in strain at a constant load can be an indication of this characteristic. This characteristic may be because of slippage of the coupon at the grips or due to slippage of the stain gauge. Figure A21 depicts this type of plot and behavior.
- Curves that do not originate from the origin of the plot. This quality can be an indication of poor calibration of the testing apparatus.

For the reasoning noted above, it is recommended to specify the exact method of reporting results associated with the D3039 testing.

PART 3 Installing Fiber Reinforced Polymers in DOE Facilities

Preparing to Install FRP and Substrate Preparation

Installation is perhaps the most complicated activity of an FRP structural upgrade. The complicating factor is the addition of the material into an operating facility. There can be considerable impact to in place systems with emphasis on Architectural and Mechanical. Additional costs associated with moving of existing obstructions (Figures A5A, A5B, and A5C) can substantially add to the overall project cost. Generally, the installation cost is small in comparison with the cost of moving obstructions and substrate preparation.

On most projects, it is necessary to expose the structural frame to facilitate the installation. This can involve removal of interior and exterior architectural finishes, relocation of mechanical equipment, and any other in-place building components. When planning a project, the team should consider the costs associate with removing obstructions that prevent access to the system receiving strengthening. Figure A5A depicts ventilation ducting that must be removed to permit access to the web of a T-beam in PF-4. In this Figure, the vertical segment of the duct prevents access to the beam web. The duct happens to carry a contaminated source. Figure A5B shows other obstructions to the T-beam webs. This Figure depicts issues associated with vertical clearance and obstructions from horizontal members framing into the T-beams.

As an example, the installers of the CFRP in PF-4 could complete the strengthening effort on one girder in one month. Of this time, it took roughly three days to install the strengthening. Moving obstructions, establishment of ventilation, surface preparation, and replacement of finishes consumed the remaining time.

The installers of the FRP in PF-4 required a minimum of twelve inches of horizontal clearance between obstructions and a vertical surface receiving FRP. However, in some situations (locally around conduits and pipes) the required distances can be substantially less. The minimum clearance between a horizontal surface receiving FRP and the nearest obstruction should not be less than three inches. LANL found that the FRP installation is very simple following relocation of obstructions.

Typically, a specialty contractor will install the system. However, for projects like the ones in PF-4, it may be prudent or required to train cleared DOE personnel to perform the installation. The escort requirement in PF-4 (cleared to uncleared) drove the decision to train LANL painters to install the FRP reinforcements.

Following exposure of the structural elements, it is necessary to prepare the substrate to receive the FRP. For a concrete structure, this can be a formidable effort. If the structure was not properly maintained, the concrete may be deteriorated. Corrosion must be removed from the reinforcing steel and spalled concrete replaced prior to installation of FRP. ICRI[20] documents contain the required guidance for repair of deteriorated concrete and corroded reinforcing steel. The smoothness of the concrete must meet ICRI profiles CSP 3 minimum and CSP 4 maximum.

Even well maintained structures will require some preparation. For example, the PF-4 T-beams represent a well maintained structural system. Prior to installation of the FRP, all cracks larger than 0.01 inches wide required filling with epoxy-crack injection. Figure A22 depicts a typical crack requiring injection. Figure A23 depicts the injection sites and ports. Preclusion of this step could allow movement of the element on either side of the crack and subsequently lead to a shearing failure of the FRP reinforcement.

In addition, it is necessary to round corners of elements to a minimum one-inch radius. In some instances, at anchorage holes for example, a one-half inch radius is acceptable. Note ACI 440.2R recommends a minimum one-half inch radius on all corners. However, it could be appropriate to use one inch radiuses in nuclear facilities. Rounding of the corners will improve system performance by eliminating stress concentrations associated with right-angled corners. Sharp corners can impose stresses in the FRP system that contribute to premature failure.

The primer is the first epoxy applied following substrate preparation. The primer epoxy prepares the substrate to receive putty and saturant. Following cure of the primer, it is often necessary to sand outgassing bubbles that may have formed during the curing process. This act can be performed using 100-grit sandpaper.

It is also necessary to remove of high spots and fill of low spots in the substrate. The concrete must be regular to not more than 0.04 inches of variation. ICRI guidelines #310.2R and #320.2R define preparation requirements. Large imperfections or holes from D7522 testing can often be filled in the concrete with a high viscosity epoxy called the putty. Putty has roughly the same consistency as moisturizing lotion. Following cure of this epoxy it may be necessary to level the cured product through grinding with a masonry disc or through sanding with 40 grit sandpaper. Some holes may require filling through application of concrete patching material.

Appendix B depicts a series of photographs that define the overall installation process. These photographs are a pictorial representation of the training that LANL painters received prior to installing CFRP in PF-4.

An additional complicating factor on the PF-4 roof girders and columns was the presence of Plasite paint (epoxy) coating on the concrete. Pre-installation testing per ASTM D7234[19] demonstrated that the Plasite paint had adhesion strength sufficient to force either a mode A or B failure in the concrete exceeding 500 psi in most locations. Note that both of these modes are similar to mode G per ASTM D7522. If the Plasite demonstrates good adhesion, it should be roughened with 40-grit sandpaper prior to applying primer. In situations where a coating does not have good adhesion, it will be necessary to remove the coating prior to installation of the FRP.

A component of the installation preparation can include determining the soundness of the substrate. ACI 440.2R recommends that the substrate be able to support a minimum of 200 psi direct tension induced from testing per ASTM D7234 (for coatings on concrete) and ASTM D7522 (for direct testing of the installed laminate). Furthermore, the failure must be of cohesive nature and in the concrete. The desired failure modes are A or B per ASTM D7234 and G per ASTM D7522. Figure A6 depicts the desired failure and Figures A7 and A8 depict undesirable failures. It is permissible to have a combination of failure modes as long as the majority of the failure is in the preferred mode. The idea is that you want the concrete substrate to be the weakest link in the load path. The modes noted will demonstrate failure through the aggregate and hardened cement. Interpretation of test results requires judgment.

With these tests, it is imperative to use 50 mm or two-inch diameter test dollies. Figure A24 and A9 depict test dollies from ME Taylor Engineering and DeFelsko, respectively. The ASTMs noted also support the use of 20 mm diameter dollies; however, test dollies of this size will not properly engage the concrete matrix. Improper engagement can lead to invalid test results. For example, the 20 mm diameter dollies will not sufficiently engage the matrix and failures will generally pull off in modes other than A or B (ASTM 7234) or G (ASTM 7522).

An additional consideration is to insure that the dollies are centered on the test location. Epoxy (2000 psi and stronger) is typically used for adhering the dollies to the test site. While permissible, duct tape may be used to secure the dollies during cure of the epoxy. In some instances, poorly adhered duct tape will not prevent the dolly from slipping during epoxy cure. This could lead to improper loading of the test site during the adhesion test and could invalidate the test.

LANL leveraged personnel trained in additive manufacturing to print installation devices that insured the dolly would remain exactly centered during epoxy curing. Staff from Applied Engineering Technology (AET-1) developed and printed installation aids for both dollies used. See Figure A25 for a photo of the DeFelsko installation aid. Following substrate validation, it is permissible to install the FRP.

To facilitate the pre-installation and post-installation testing, the LANL team developed a document known as the Testing Criteria Document[4]. This document outlined all the necessary steps for successful testing and acceptance. The independent reviewer at Degenkolb also agreed with the content in this document prior to implementation.

Installing the FRP

The installation of the fiber and associated epoxies (primer, putty, and saturant) is an art more than pure science. The process is akin to wallpapering. In wallpapering, the installer must apply an adhesive to the wall before the wallpaper will stick to a wall. Similarly, the FRP fiber must receive the saturant before it will adhere to the substrate. The act of applying the bonding epoxy to the fiber is known as saturating the fiber. In this step, a mixed, two-part epoxy is worked into the fiber by mechanical means to form a composite matrix of fiber and epoxy. Although, automated mechanical equipment may be used to speed up the fabric saturation process, manual means were used in PF-4. Restriction of access and contamination concerns drove the decisions to use manual saturation.

During saturation, it is imperative that the enough saturant is applied to the fabric. Experience and training demonstrated that it is not often possible to judge the adequacy of the saturation process by mechanical measurement. Rather, the installers need to develop an eye for how much saturant to apply. Therefore, installer training and experience is imperative. Inadequate saturation can lead to between ply failures during post-installation testing per ASTM D7522. Generally speaking, the upper bound on saturant application is 50-mil per ply per side. Allow the installers to decide how much saturant to apply as long as they do not exceed this threshold.

Following preparation of the saturant, it has a workable life of roughly forty-five minutes. The pot life will depend on the ambient temperature around the installation site. Also, note that the saturant can self-combust. Therefore, limit saturant quantities to the amount usable in the product’s pot life.

The first step in the installation process commences with the installers applying an 18 to 22 mil layer of saturant to the prepared substrate. The saturant is applied with conventional painting rollers. Next, the installers “lay up” or apply a ply of fiber. Subsequently, the fiber is rolled into the saturant with a serrated metal roller. See Figures A10, 17B, and 18B for photos of these rolling implements. Following the rolling-in process an additional layer of saturant is applied. This process may continue uninterrupted until four layers of fiber and the associated saturant are applied. After application of the fourth layer, it is recommended to allow the materials to cure for twenty-four hours before adding additional saturant and fiber. The recommended limit will insure that the installation does not sag under its own weight prior to curing. Moreover, in top-side diaphragm applications the thickness of the uncured materials can inhibit placement.

After the composite cures, it is necessary to roughen the surface of the cured composite before application of additional saturant. LANL found that lightly sanding with 100-grit sandpaper added sufficient roughness to the cured composite to facilitate proper bond between the cured system and additional saturant. Following the roughening process, it is desirable to clean the surface to remove dust. It is permissible to use Acetone for this process. Acetone helps expedite dust removal. However, in areas with combustible loading sensitivity, it is acceptable to wipe the surface many times with a clean, wet rag. Wiping must continue until all dust is removed.

Following each successive cure, it is necessary to inspect the cured composite for out-gassing bubbles and delaminations. Remove outgassing bubbles with light sanding. Delaminations may develop during the installation process from trapped air or from gasses developed during curing. In addition, young concrete will outgas and likely cause such delaminations. Therefore, the installers should inspect the previous day's work for these types of problems prior to adding additional saturant and fiber.

Repair of the delaminations is usually a simple matter. It usually involves drilling a small hole into the delamination and injecting the resulting void with saturant. Larger holes may require removal of the debonded section and replacement with additional fiber and saturant. The LANL project documentation defines the recommended repair process for small, medium, and large delaminations.

Installation of anchorage will usually follow installation and cure of the primary reinforcing material. However, the installation personnel must locate reinforcing steel (with GPR or other means) prior to fabric installation and subsequently layout the anchor sites. This will prevent conflict between anchor holes and reinforcing in the substrate. Drilling of holes for FRP anchors follows the same process as for conventional adhesive anchors. The caveat is that the beginning of the hole must have a minimum one-half inch radius to prevent stress concentrations from developing in the anchor fibers.

The state of the art in anchor fabrication leaves the process up to the installer. Commercial entities are starting to fabricate FRP anchor for purchase; however, not many companies perform this service. Reference 27 defines the known suppliers of FRP anchorages. This reference lists LANL as a supplier, because the project team developed a process to fabricate FRP anchors from MasterBrace FIB 600/50 CFS and MasterBrace SAT 4500. Details of this process are in the PF-4 roof girder strengthening project documentation[5]. LANL controlled the anchor fabrication and inspection process through the CFRP Anchor Fabrication Testing Criteria memorandum[32].

Published literature[17, 28] suggests that it is possible to insert saturated and uncured pigtail anchors into predrilled holes. Following insertion, the hole is backfilled with saturant and allowed to cure. LANL found that it is not possible to use this installation method for large anchors like the ones used in PF-4. In PF-4, anchors with cured embedments were inserted into holes partially filled with saturant. Following insertion, the remaining parts of the anchors were saturated and the fan section was splayed out onto the primary shear reinforcing. The researchers in references 17 and

28 use this same basic process for creating the fan following insertion of the pigtail into the anchor hole.

The last step in the anchor installation process is to splay the anchor fans out over the primary reinforcing material. The fan will spread out over an angle of roughly sixty degrees[17, 18].

Researchers[16, 17] recommend to apply a reinforcing strip over the anchor fans and corresponding holes following installation of the anchors. The strip is generally only one ply thick and roughly sixty percent of the anchor fan length. Center the strip on the anchor holes. These criteria may not be applicable to fans that span three-hundred-and-sixty degrees. Therefore, the reader may wish to conduct a search on the recommended properties of anchor fans in such applications.

Installation Testing

ACI 440.2R recommends testing to validate the system installation. Two parts comprise the recommended testing. First, the installation crew should fabricate witness panels for testing in accordance with ASTM D3039. Secondly, the installers must validate the laminate bond strength onto the substrate through post-cure testing. The tests are in accordance with ASTM D7522. The former test should validate the strength of the resulting composite. The latter test will validate the integrity of the layers comprising the composite and the bond to the concrete substrate. The design team for the seismic upgrade projects at LANL controlled the post-installation testing process through the Testing Criteria for the PF-4 Roof Beam Strengthening memorandum[4].

During fiber installation, the installers need to assemble witness panels for tensile testing per ASTM D3039. Reference 21 defines the assembly process. This process involves field assembly of FRP panels comprised of saturant and fiber. The saturated fiber panels are generally twelve-inches by twelve-inches and one ply thick. Following a seven-day cure period, qualified personnel will cut the coupons from each panel. The coupons should be roughly three-quarters inch wide by ten inches long. Refer to ASTM D3039 for additional details on coupon assembly. Since the coupons will serve to validate the installation, it is imperative to use proper technique to manufacturer, cut, and prepare the coupons.

Some suggest that the witness panels do not accurately represent the installed FRP. Rather the witness panels represent the capabilities of the installation crew to make witness panels. Therefore, keep this aspect in mind when specifying witness panel criteria and when interpreting test results from these panels. Test results from the witness panels are a guide to capacity rather than an absolute.

Moreover, D3039 specifies acceptable variability in the coupon thickness. Several test coupons failed to meet the stringent thickness limits in D3039 on the LANL projects. It is again important to consider the minor impact that this variability has on coupon strength. The epoxy will be the only component that contributes to sample thickness variability. Additional epoxy will act to drive strength down, but by a minor amount. Therefore, inclusion of samples that do not meet the thickness limitations will likely have no impact on coupon capacity. In addition, consider that the sample are field assembled under variable conditions. It is extremely difficult to meet the thickness tolerances in D3039 when constructing panels in the field.

One caveat to the thickness variability is that significant variation can result in application of unintended secondary moment on the coupon. Therefore, coupon thickness variation is acceptable within reason. See ASTM D3039 for more information.

It is desirable to assemble test coupons at intermittent intervals during the installation. In the case of the PF-4 column strengthening, witness panels were assembled at twenty-five, fifty, seventy-five, and one-hundred percent installation on each column. For the girder upgrades, the assemblies took place at fifty and one-hundred percent of installation on a given girder.

The second component of installation validation is through ASTM D7522. This is a locally destructive test. The test validates the complete installation of the FRP laminated onto the substrate. The basic process involves scoring the cured FRP with a two-inch diameter core drill. Preferably, the coring site is far from the edge of the installed FRP. The core must penetrate the concrete substrate to a depth of between one-quarter and one-half inch. Sites without proper core depth can lead to inaccurate failure modes. The composite must cure for seven days prior to performing these tests.

Since ASTM D7522 is a locally destructive test, most FRP designers require that the tests take place in a sacrificial FRP swatch rather than on the final installation. LANL recommends this procedure. Installation of the swatches should take place periodically during the actual installation. In addition, these swatches should be large enough to insure that they are representative of the final installation.

Initially, LANL specified swatches that were too small. This lead to inaccurate testing results because it was not possible for the installers to properly roll the saturant into the fiber without the swatch sliding around on the substrate. The initial swatch size was six inches square with the maximum number of plies required by design. However, accurate results were only obtained once the swatch grew in size to roughly ten by twenty-four inches. LANL had to test the final installation in a few instances because of the errors associated with small swatches. The Final CFRP Testing Preparation, Testing, and Repair memorandum[31] addressed how to facilitate testing on the final installation.

Following the coring operation, a two-inch diameter aluminum dolly is epoxied to the core site. Typically, the epoxy will be an industrial grade with tensile capacity exceeding 2,000 psi. Once this epoxy cures, the test dolly is subjected to tensile force with a special testing apparatus. ACI 440.2R requires that the failure pressure exceed 200 psi and that the failure be mode G per ASTM D7522. Mode G is a cohesive failure in the concrete substrate. Ideally, the fracture plane will pass through aggregate in the concrete. Any test site that fails at greater than 200 psi and in predominately mode G is acceptable, and validates the installation. Following the test, the hole may be filled with putty and patched with plies of FRP if desired.

LANL’s independent reviewer at Degenkolb required that the D7522 tests in PF-4 fail in mode G and above 480 psi. Ironically, this corresponds with the capacity of the DeFelsko Posi-test adhesion device[23]. This failure stress did not have any basis or relate to the design capacity of the installed FRP. However, the independent reviewer felt that this stress level better corresponded with appropriately sound concrete in a nuclear facility.

Apparently, an old military standard is the basis for the 200 psi threshold. That document defined tensile strength of concrete to be roughly ten to fifteen percent of the compressive strength. Therefore, the opinion of the ACI 440 committee and the author of ASTM D7522 was that concrete suitable to receive FRP laminate should have a tensile strength per ASTM D7522 of at least 200 psi. Note, cracking of concrete and corrosion of rebar will lead to pull off strengths below 200 psi; thereby, substantiating the need for substrate repair prior to installation of the FRP.

It is imperative to use two-inch diameter dollies. ASTM D7522 allows three-quarter inch dollies; however, these dollies will not sufficiently engage the concrete matrix. The quality could result in irregular failure modes not consistent with the desired mode G. The team on the PF-4 upgrades projects observed these irregular failures during the column-strengthening project. Through experience the team learned that two-inch diameter dollies are the only ones that will sufficiently engage the concrete matrix and support acceptable test results.

An additional consideration is proper affixing of the dolly during cure of the bonding epoxy. This is especially important for dollies installed on vertical surfaces. It is necessary to define a method for installers to use that will insure the dolly does not slide or tip before the epoxy cures. The installers who secured the test dollies in PF-4 used duct tape and similar adhesives to prevent sliding and or tipping of the dollies during epoxy cure. However, in some instances this method allowed the dollies to move. During pull-testing, slight misalignment can cause the dolly to impose tension and bending moment on the test site. This type of loading can result in a combined failure mode and thereby result in an invalid test.

To assist with proper dolly alignment, the team engaged the services of LANL's Applied Engineering Technology group (AET-1). AET-1's additive manufacturing group developed installation aids with 3D printing technology. These aids insured perfect alignment of the dolly on the scored concrete and prevented slippage during cure of the bonding epoxy.

LANL used two adhesion-testing apparatuses for performance of the D7522 tests. The first was a DeFelsko – PosiTest[23] and the second was from ME Taylor Engineering called the Patti Micro[24]. The capacity of the DeFelsko unit is 480 psi on a two-inch diameter dolly. However, the Patti Micro can impose 850 psi on the dolly through use of an F-20 piston. The team's experience with these devices demonstrated that the DeFelsko was well suited for production. However, the Patti Micro seemed better suited for research applications. This unit was more fragile and difficult to operate when compared to the DeFlesko - PosiTest. Figures A13 and A14 depict the Patti Micro and DeFelsko adhesion testing devices, respectively.

Through use of the Patti Micro it was possible to demonstrate failure stresses above 600 psi on some tests. Over 157 total tests (pre and post installation), the mean failure stress was 440 psi with a standard deviation of 76 psi. Unfortunately, no exact method exists to correlate in-situ strength of the concrete with the results of the D7522 tests. However, the specified twenty-eight day strength of the concrete in PF-4 is 4000 psi. Inclusion of strength gain with age, could lead to compression strengths in excess of 5000 psi today.

Definition of Terms

ACI – American Concrete Institute

ASTM – American Society of Testing Materials

Beam – Intended to mean primary structural member which some would call a girder

CGID – Commercial Grade Item Dedication

DOE – Department of Energy

FRP – Generic name for AFRP, CFRP, and GFRP

GPR – Ground Penetrating Radar

ICRI - International Concrete Repair Institute

ISEL – Institutional Supplier Equipment List

LANL – Los Alamos National Laboratory

MEP – Mechanical, Electrical, and Plumbing equipment

OSHRM – Office of Seismic Hazards and Risk Mitigation

NIAC – Nuclear Industry Assessment Committee

NSM – Near Surface Mounted

RANT - Radioassay and Nondestructive Testing Facility

SWRI – Southwest Research Institute

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Appendix A – Figures

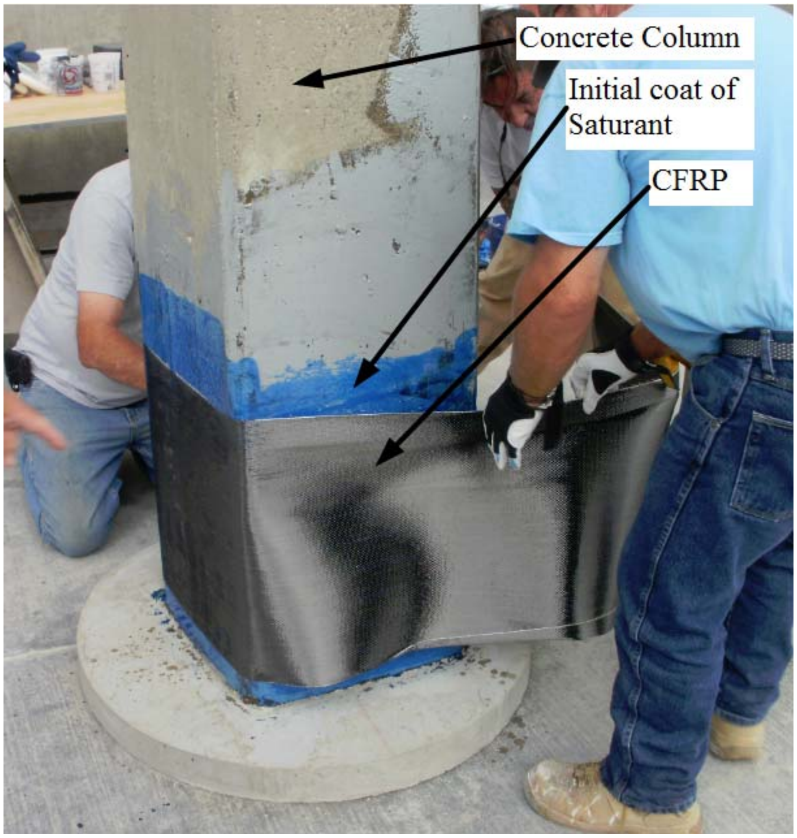

Figure A1 – Wet Layup Process

Figure A2 – Near Surface Mounted (NSM) FRP[1]

Figure A3 – Circumferential Jacketing of Columns in PF-4

Figure A4 – CFRP Reinforcing on Web of PF-4 Roof T-Beam

Figure A5A – Obstructions at Girder to Receive FRP

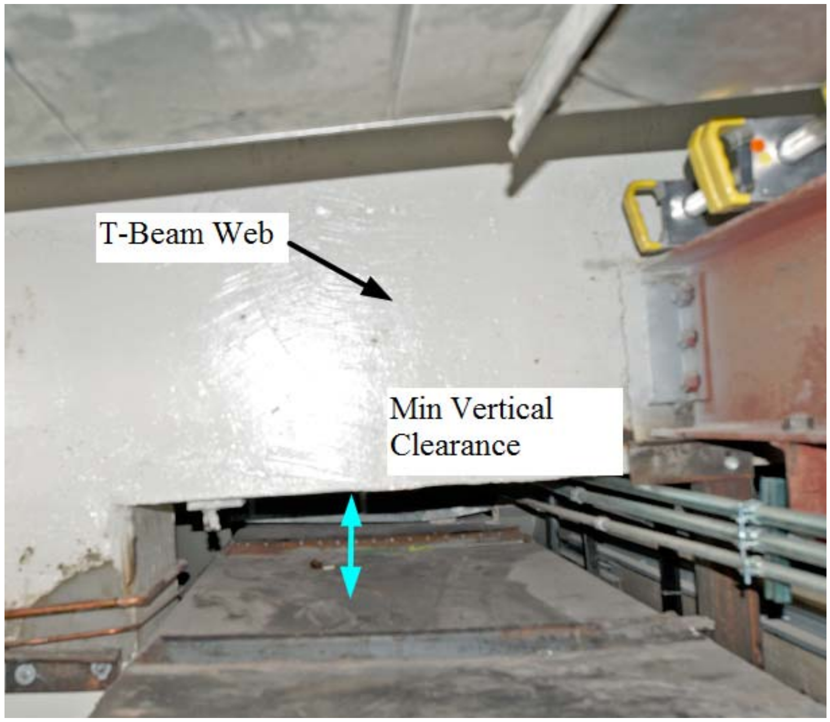

Figure A5B – Obstructions at Girder to Receive FRP

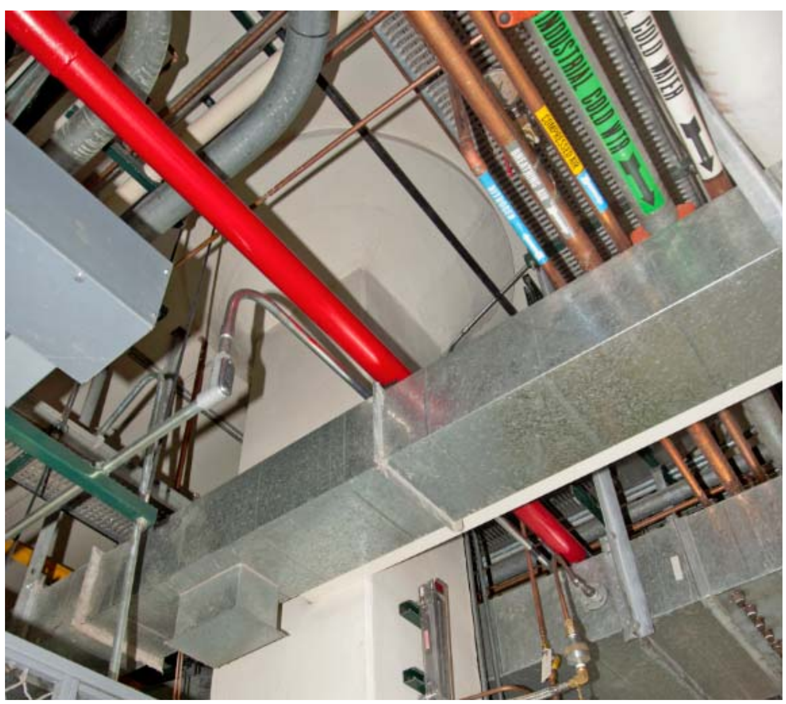

Figure A5C – Obstructions Around a Column to Receive FRP

Figure A6 – Patti Micro Dolly and Concrete Failure Mode G

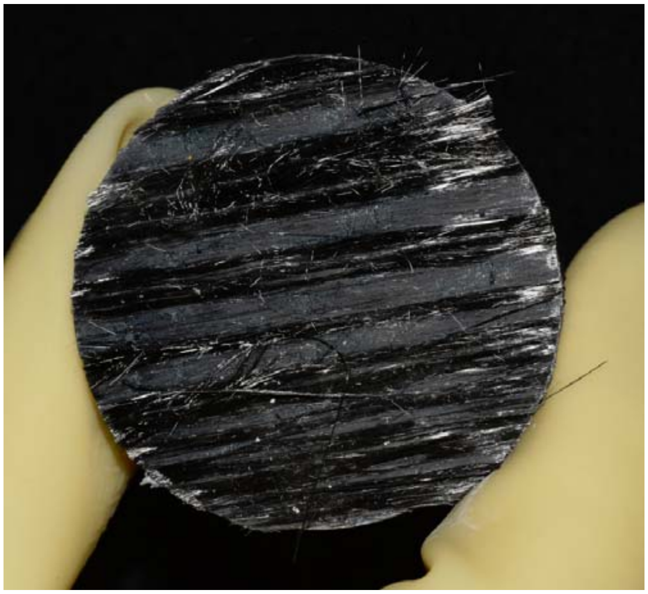

Figure A7 – Patti Micro Dolly and Through Fiber Failure - Mode B

Figure A8 – Patti Micro Dolly and Failure at Plasite to Concrete Interface - Mode A

Figure A9 – DeFelsko Dolly and Concrete Failure Mode G

Figure A10 – NSM in Timber Beam[1]

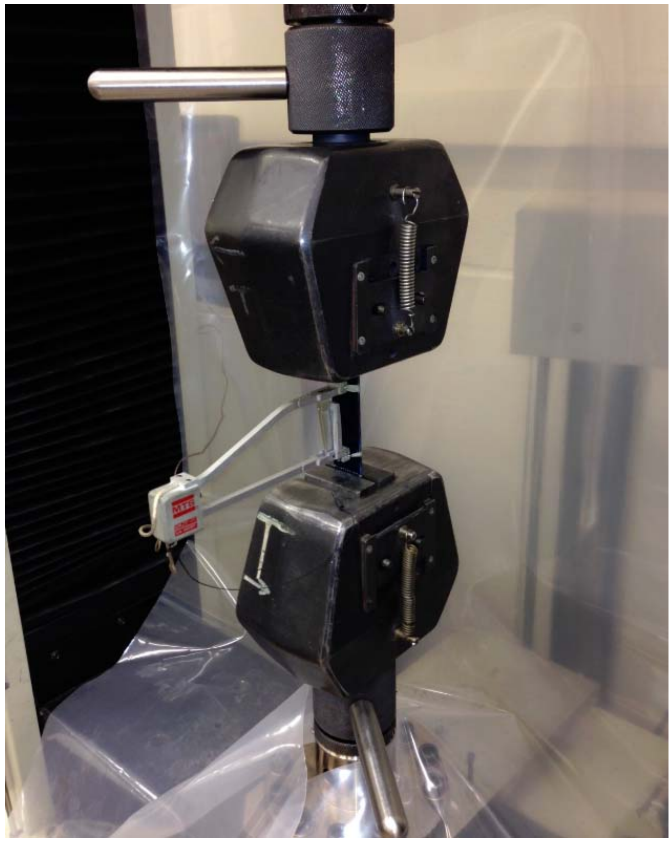

Figure A11 – Tensile Testing Per ASTM D3039

Figure A12 – Tensile Testing of FRP Anchor at LANL

Figure A13 – ME Taylor Engineering Patti Micro and F-20 Piston Adhesion Tester

Figure A14 – DeFelsko PosiTest AT-A Adhesion Tester

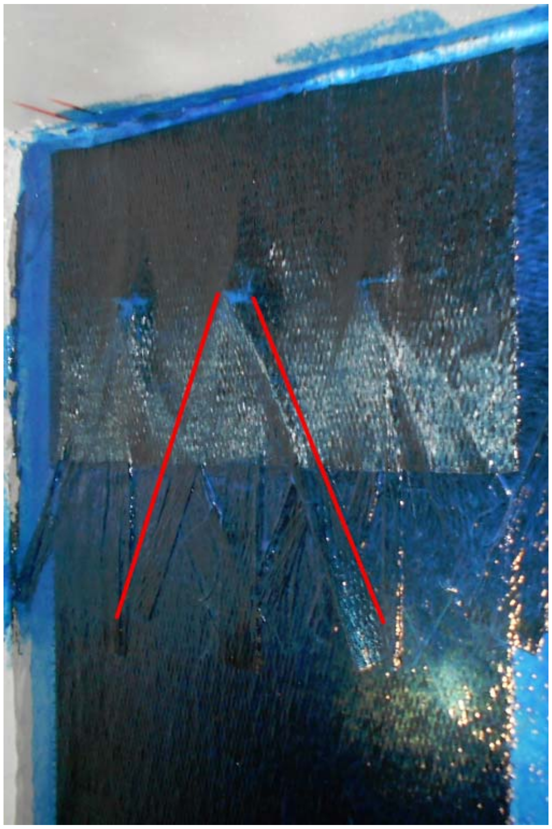

Figure A15 – FRP Anchor in Roof Girder

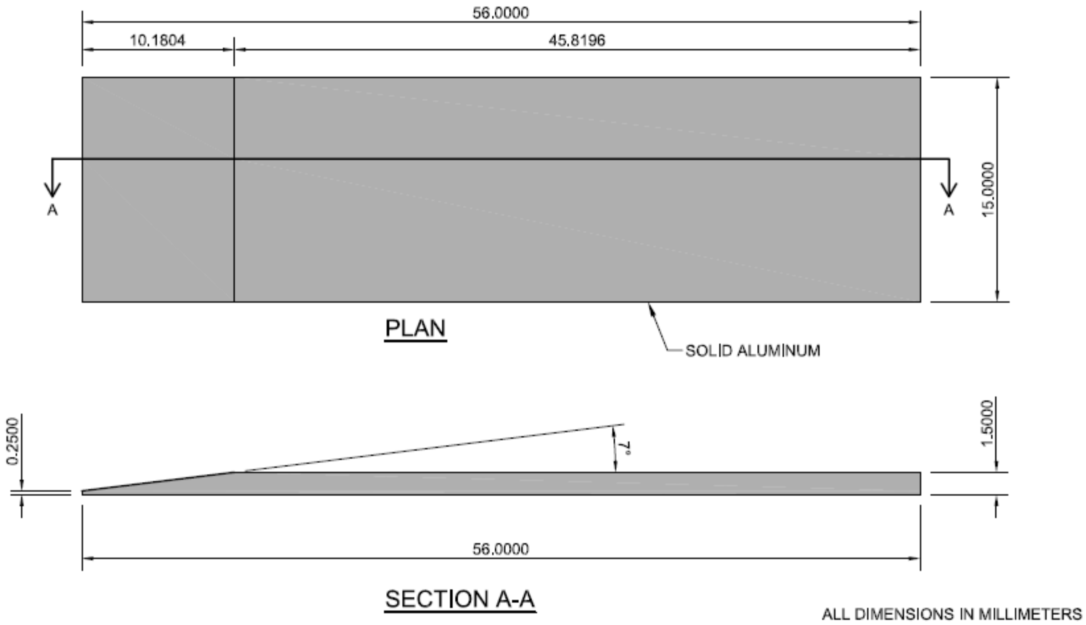

Figure A16 – Recommended Grip Geometry[1]

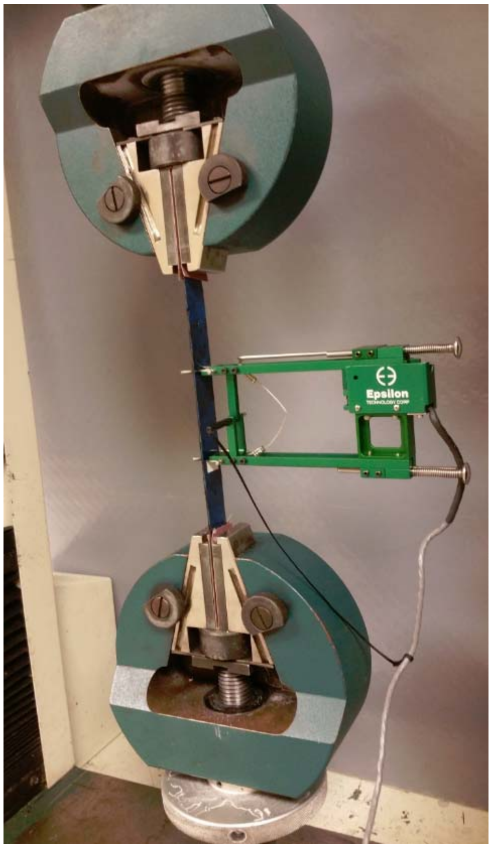

Figure A17 – ASTM D3039 Coupon Test with Epsilon 3542 Extensometer

Figure A18 – ¾" Wide by Ten Inch Long Coupon for ASTM D3039 Test

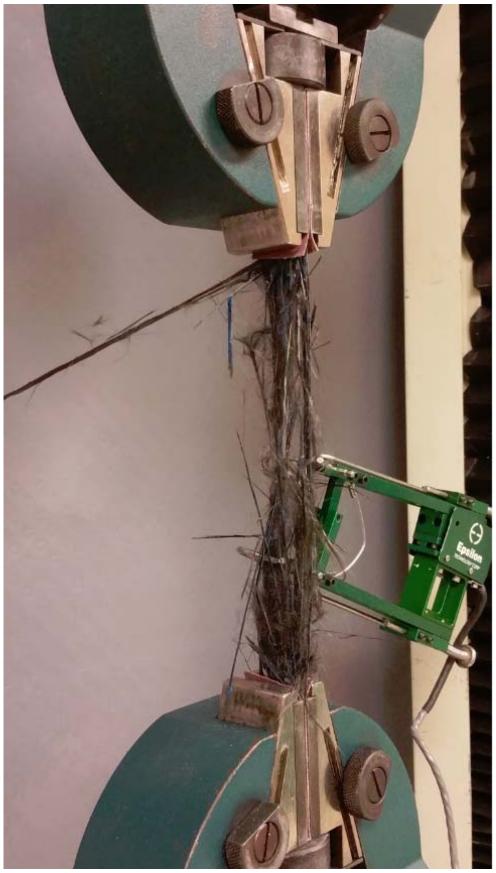

Figure A19 – Coupon Failed in XGM Mode

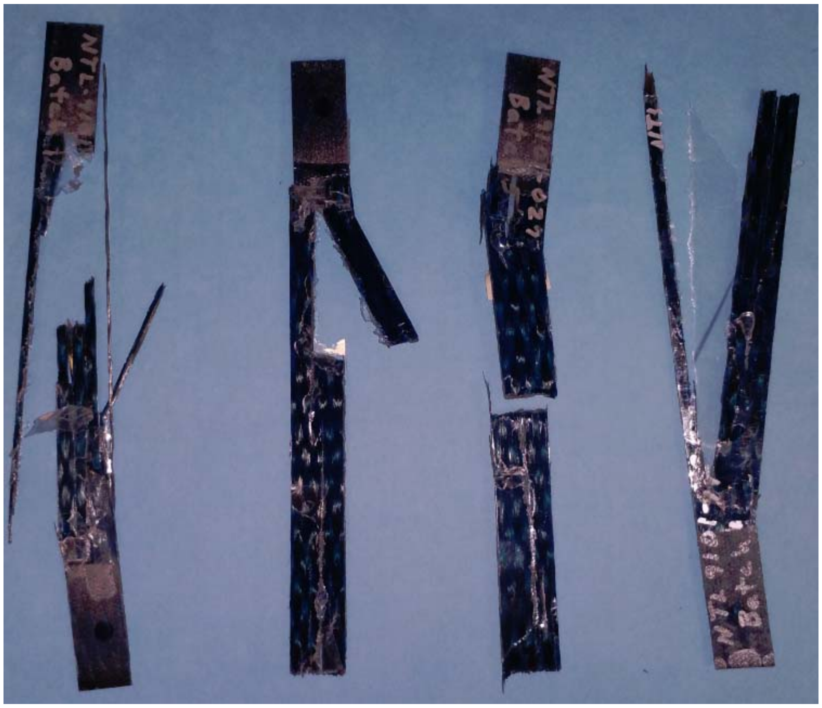

Figure A20 – Undesirable Failure Modes

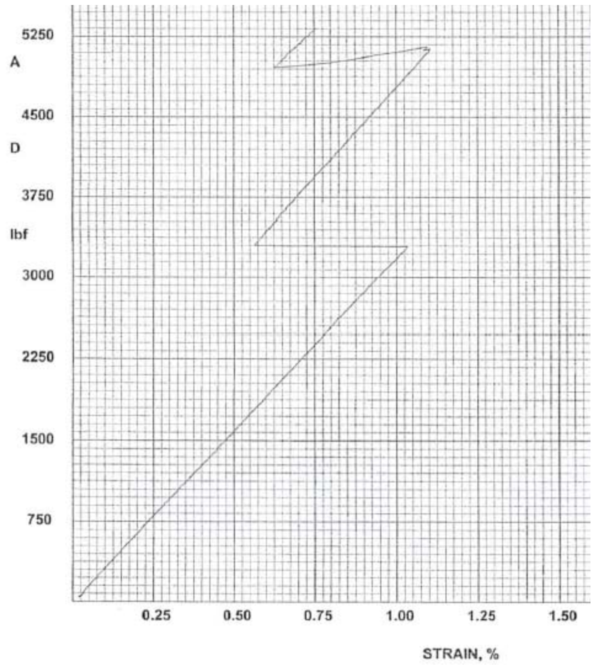

Figure A21 – Stress-Strain Curve Depicting Non-Ideal Results

Figure A22 – Typical Crack in Concrete Substrate

Figure A23 – Epoxy Crack Injection

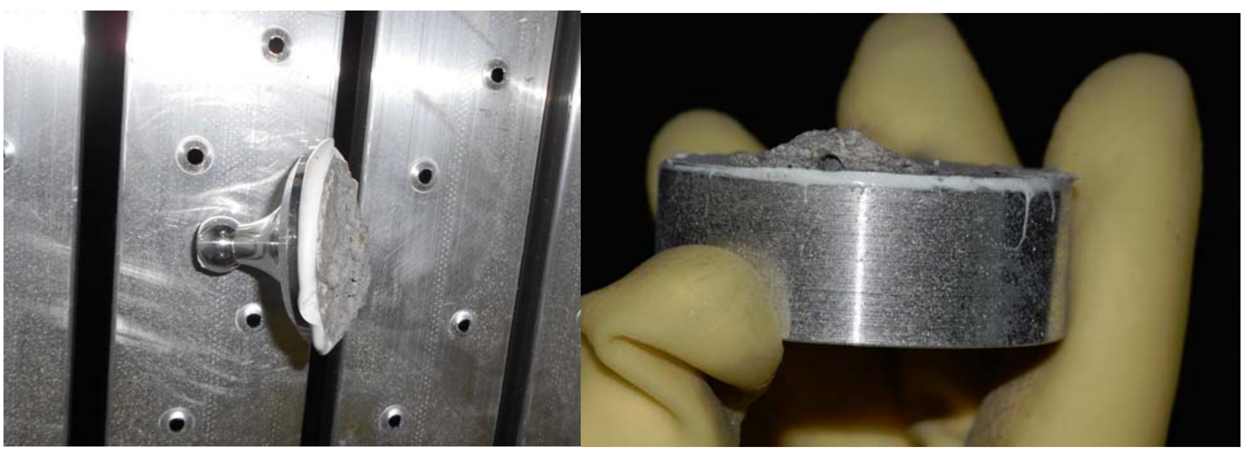

Figure A24 – DeFelsko and ME Taylor Engineering Dollies

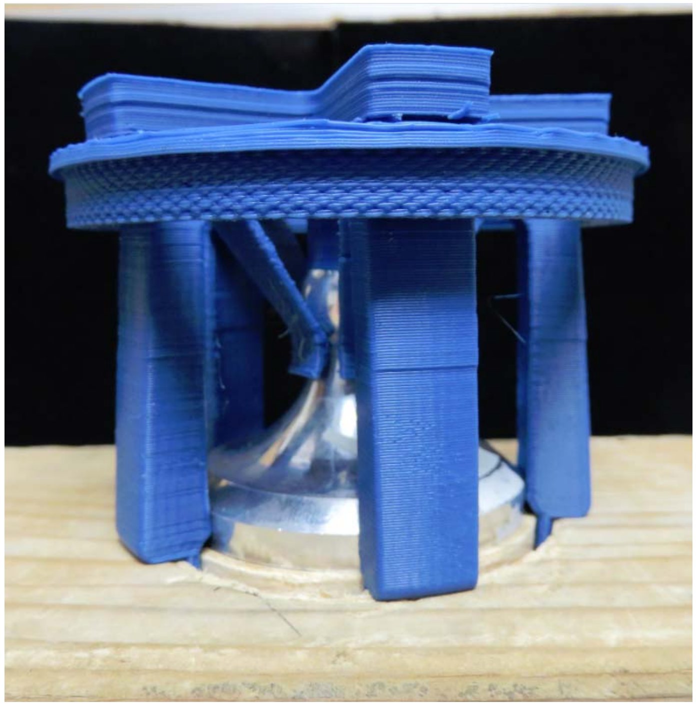

Figure A25 – DeFelsko Dolly Installation Aid

Appendix B – FRP Installation Process

The following figures depict the basic process for installation of FRP onto concrete substrate. Eric MacFarlane took these photos at Hydra-Crete in Albuquerque during LANL sponsored training in July of 2013. These photos depict BASF, Hydra-Crete, and LANL employees.

This training took place under optimal conditions. Hydra-Crete cast the concrete specimens specifically for the training session. On the day training started, the specimens were four days old. Therefore, the samples outgassed more that would be typical for older concrete and testing per ASTM D7522 resulted in capacities below normal (Figure 26B). The training initiated at the step of system application for one ply of FRP; therefore, these figures preclude grinding of the concrete.

Figure 1B – Exposed Structural Elements

Figure 2B – Mixing of the Primer

Figure 3B – Preparing to Apply Primer

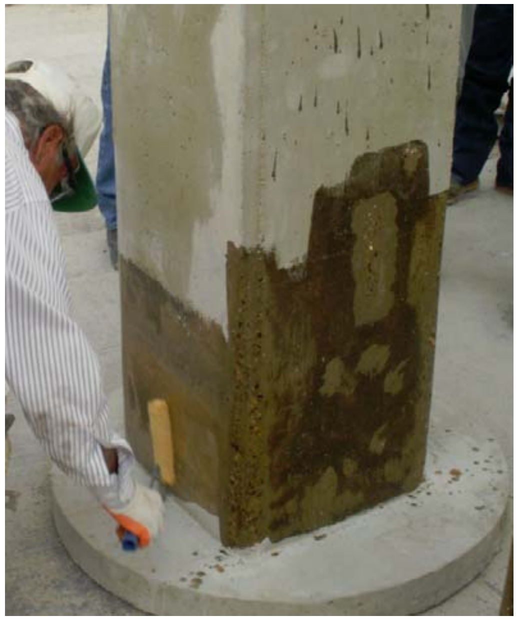

Figure 4B – Primer Application

Figure 5B – Outgassing Following Primer Application

Figure 6B – Preparing to Apply Putty

Figure 7B – Putty Application

Figure 8B – Oozing of Putty

Figure 9B – Mixing of the Two-Part Saturant

Figure 10B – Preparing to Apply the Saturant

Figure 11B – Saturant Application

Figure 12B – Carbon Fiber

Figure 13B – Carbon Fiber Installation

Figure 14B – Cutting of Carbon Fiber with Scissors

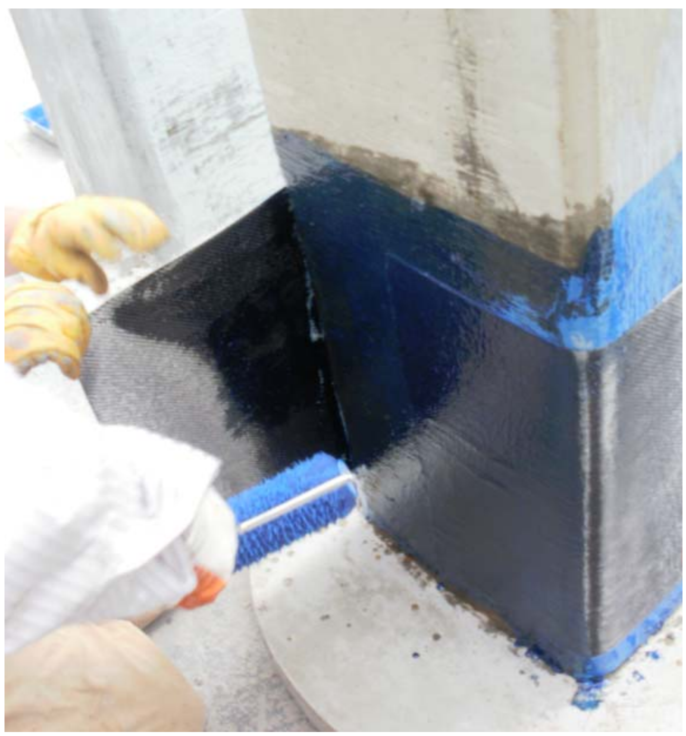

Figure 15B – Saturant Application at Termination of Carbon Fiber

Figure 16B – Positioning the Carbon Fiber

Figure 17B – Rolling Carbon Fiber into Saturant

Figure 18B – Serrated Metal Rollers for Installation Process

Figure 19B – Sanding of Outgassing Bubbles on Cured FRP

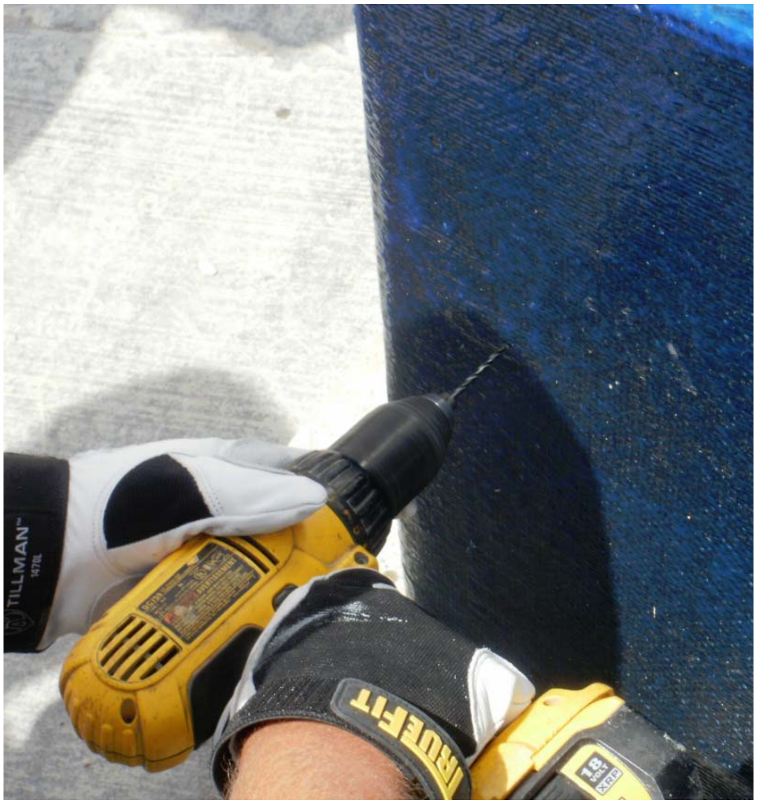

Figure 20B – Drilling of Void Pocket in Cured FRP

Figure 21B – Syringe for Injecting Void Pocket with Saturant

Figure 22B – Preparing a Cored FRP Sample for ASTM D7522 Testing

Figure 23B – Dolly Installation for ASTM D7522 Testing

Figure 24B – Preparing to Perform ASTM D7522 Post-Installation Testing

Figure 25B – Installation of the Loading Fixture for ASTM D7522 Test

Figure 26B – Dolly Following Failure

Appendix C

LANL Team Members for FRP Installations in PF-4

LANL Professional Staff and Researchers

Larry Bronisz - Additive Manufacturing Specialist of AET-1
Bjorn Clausen - Los Alamos Neutron Science Center of MST-8
Judith Eglin – Project Program Director of IMP
Larry Goen – Seismic Program Manager and Engineering Services Division Leader of ES-DO
Charles Kelsey – Los Alamos Neutron Science Center of P-27
Eric MacFarlane – Engineer of Record of the Office of Seismic Hazards and ES-EPD
Leslie Martinez – Project Manager of PM7
Darren Meadows – Quality and Performance Assurance of QPA-IQ
Michael Mocko - Los Alamos Neutron Science Center of P-27
James Narum – Project Engineer of ES-55
Michael Salmon – Office of Seismic Hazards Team Leader of AET-2
James Thompson – Additive Manufacturing Specialist of AET-1

Consultants to LANL

Will Gold – Fiber Designer of BASF Corporation
Insung Kim – Design Independent Reviewer of Degenkolb Engineers
Charles Popelar – Southwest Research Institute
Tom Sterbis – Nutherm International
Loring Wyllie – Design Independent Reviewer of Degenkolb Engineers

Material Installers and Construction Management

April Herrera of LOG-CS
Johnathan Lujan of LOG-CS
John McEvoy of LOG-CS
Keith Padilla of LOG-CS
James Rowe of LOG-CS
Johnny Torres of LOG-CS
Adrian Toscano Diaz of LOG-CS
Michael Tousley – project superintendent of MOF-CM-CS
Daniel Waters of LOG-CS
Kenneth Witt – painter foreman of LOG-CS