Fifteen Years of Lessons Learned: Design and Construction of CFRP Liners for Large Diameter Pipelines

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ABSTRACT

Strengthening of pressure pipelines using carbon fiber reinforced polymer (CFRP) materials has been an accepted repair method since the late 1990's. CFRP composites are high strength, non-corrosive and durable materials and can add considerable structural capacity which makes them very suitable for pressure pipeline strengthening. However, there are several keys to success and best practices with regard to material selection, design, construction and quality control. There are lessons learned through installations which have taken place over the past fifteen years. These include adoption of criteria for material selection, new design philosophies, termination end detailing and critical points during the construction process. This paper provides state of the art information regarding materials, design considerations, installer experiences and current best practices. Field case studies provide a comprehensive review of the use of CFRP composites.

1. BACKGROUND

Over the past fifteen years inspection methods for large diameter pipelines have evolved to include more accurate methods, failure risk analysis and repair prioritization. These advancements have provided utility owners with critical information regarding the exact location of distressed pipes and caused an increase in demand for targeted rehabilitation technologies. Based on this repair prioritization information, utilities have taken proactive steps in advance of failure to replace or repair the distressed pipes with an unacceptably high risk of failure. There are several repair options for concrete pressure pipes which include encasing the degraded pipe in a reinforced concrete block, post-tensioning by wrapping tendons around the pipe, or relining the pipeline. Relining is typically performed by utilizing CFRP or by steel slip lining.

CFRP was first used in the United States for the internal rehabilitation and strengthening of Pre-Stressed Concrete Cylinder Pipe (PCCP) in the late 1990s. The use of internally applied CFRP is applicable to pipelines 30 inch diameter and above because manned entry is required into the pipeline for application of CFRP materials. Following the initial installations, and an evaluation period, various municipal pipeline owners and power generation stations began to use CFRP lining for PCCP on a regular basis. By the mid- 2000s, installation of CFRP on the interior of PCCP had become a widely acceptable repair and strengthening system for PCCP.

CFRP lining system design principles have also evolved since the first repairs took place in the 1990s, and through testing and experience, improvements in design concepts have led to an increase in the long term performance expectations for CFRP systems (McReynolds et al, 2013). There is currently no standard for design and installation of CFRP lining repairs of pipes. There is an American Water Works Association (AWWA) subcommittee which is in the process of developing a standard which addresses design, materials, installation, and quality control for CFRP upgrade (repair, strengthening) of PCCP (ANSI/AWWA CFRP). The design principles described below are in line with the standard being developed by AWWA.

In the past 10 years CFRP has been adopted for use in many other types of pipe structures as well including steel, mortar lined steel and polymer pipes. This paper focuses on the use of CFRP for PCCP, as that is its most common pipeline application.

2. MATERIAL SELECTION

A typical CFRP lining system consists of a primer, thickened epoxy, epoxy, reinforcing fabric, and top coat. The most effective epoxy systems for long-term civil infrastructure rehabilitation applications, such as rehabilitation of PCCP lines, are ambient cure thermoset epoxy systems. In order to minimize environmental hazards present inside the pipeline during application of the materials, epoxy systems which are made of 100% solids and are Volatile Organic Compoud (VOC) compliant are utilized. The primer layer of epoxy applied to the pipe consists of a low viscosity epoxy as shown in Figure 1 which penetrates into the concrete substrate, providing an adhesive bond for the thickened epoxy and saturating layers as well as subsequent layers of the CFRP system. The thickened epoxy system is made up of either a specially formulated higher viscosity epoxy system or made up of the saturating epoxy and silica fume which have been mixed together in accordance with the manufacturer’s recommended procedure. The thickened epoxy filler is used to even out the concrete substrate, fill voids and it is also used in between layers of CFRP to ensure intimate contact of the CFRP system at all locations within the CFRP liner.

The top coat of the CFRP is typically made of thickened epoxy, with or without a pigment added for ease of identification of repaired pipe segment(s). In environments where high concentrations of H_2S or aggressive chemicals are utilized, a top coat with high chemical resistance is used. In circumstances where the CFRP system is applied externally to exposed piping, a UV resistant top coat is recommended. In cases where potable water is conveyed by the pipeline system, industry standard is that all materials utilized in the CFRP liner repair have been tested to be in compliance with ANSI/NSF 61, which is the nationally recognized health effects standard for all components, devices, and materials which come in contact with drinking water (ANSI/NSF, 2013).

Figure 1. Application of epoxy primer

2.1 Types of FRP composites used

There are a wide variety of reinforcing fabrics available, however for internal repair of pipelines best practices include only the use of unidirectional carbon fiber fabric as structural reinforcement. In order to resist all of the design loads acting on the pipeline, separate sheets of unidirectional carbon fiber reinforcing fabric are applied to the interior of the pipeline with the direction of the fibers oriented in either the longitudinal or the circumferential direction to provide the necessary strength. Carbon fibers have the potential for electrical conductivity; therefore, to avoid galvanic corrosion of steel in proximity to carbon fibers, a glass fiber fabric is used for isolation of any steel substrate from the CFRP system.

2.2 Material performance requirements

Unlike traditional construction materials such as concrete and steel, for CFRP liner systems, the selection of appropriately functional and durable CFRP materials is placed on the owner or engineer. Numerous materials available in the market have different short and long term properties in the exposure environment, and it is the responsibility of the owners, engineers and material suppliers to perform the necessary tests to demonstrate that the materials have the necessary reliability and durability. Material resistance adjustment factors, used in design along with load factors, need to be based on the sufficiently large number of test samples tested in accordance with a number of short and long term test methods. If unsuitable FRP materials are installed, this could result in a substantial reduction in the service life of the pipeline(s) where CFRP is installed.

One industry certification aids owners and engineers is the inclusion of a valid International Code Council (ICC) Evaluation Service Report (ESR) as a requirement for FRP materials. ICC developed a set of minimum durability and performance criteria for CFRP materials which must be adhered to in order to receive ICC approval and a valid ICC report. ICC's Acceptance Criteria 125 (AC125) and AC178 establish the minimum acceptable durability criteria, structural performance, and inspection criteria for any CFRP system to be considered suitable for structural rehabilitation applications. To obtain a valid ICC Report, materials must maintain minimum percent retention of properties when they are tested after 1,000 hour, 3,000 hour, and 10,000 hour exposure to various aggressive environments including water at different temperatures, saltwater, alkali solutions, and dry heat (ICC 125, 2010 and ICC 178, 2010). Specifications which protect owners and engineers, ensuring properly tested CFRP materials are installed, require a valid ICC report be provided as part of the bid submission.

More extensive durability testing beyond the 10,000 hour exposure tests required by ICC AC125 are available for selected CFRP materials. For instance, a recent study was released which highlights an 8-year (70,000 hour) durability study completed by the Metropolitan Water District of Southern California (Sleeper et al, 2010). In this study, an inspection of CFRP lined PCCP was performed approximately eight years after the installation of the CFRP lining system. The visual and sounding inspection indicated no damage in the form for delaminations, bubbles, cracks, or edge lifting. Observations from the same inspectors who were present during the initial CFRP lining installation noted that the CFRP was in comparable condition to the originally installed system. In addition to the results of the in-service CFRP inspection, coupons made from the same CFRP system installed in MWD's pipeline were tensile tested after eight years of exposure to tap water in environmental chambers. The tensile test results indicated minimal change in the structural performance of the CFRP system, as measured through tensile strength, tensile modulus and breakage strain, after being continuously immersed in tap water for a period of over eight years (Sleeper et al, 2010). The results of this durability study indicate strong potential for the CFRP lining system to perform well as a long-term solution for pipeline rehabilitation.

3. CFRP LINER DESIGN

The circumferential design of a CFRP liner is based on the combined effects of gravity loads and internal pressures consisting of pipe and fluid weights and earth load that will be imparted to the lined pipe as the host pipe continues to deteriorate and experiences degradation. For a distressed or degraded PCCP, the CFRP liner can be designed as a composite system with the inner concrete core or as a stand-alone system which does not rely on the host pipe for resisting any of the design loads.

Levels of degradation of the host pipe at the time of installation are discussed below, and in most cases, the host pipe is expected to continue to deteriorate with time such that the CFRP system needs to be designed for the expected host pipe condition at the end of the service life.

- Non-Degraded Pipe. The CFRP liner for a non-degraded pipe, requiring strengthening due to increased load (e.g., pressure, earth load, live load), is designed by considering the composite action of the CFRP with the entire pipe wall thickness.
- Degraded Pipe. A degraded pipe consists of PCCP with broken wires, but with an inner core that is circular and may have some minor cracking that can be repaired.
- Severely Degraded Pipe. Severely degraded pipe consists of PCCP with broken wires, multiple wide cracks in the concrete core as well as a significantly deformed and uneven internal surface with ovality or waviness imperfection.

CFRP repair of degraded PCCP is designed to provide strength, durability, and reliability throughout the service life of the repaired pipe when the pipeline is subjected to long-term and short-term loads. The CFRP system, as shown in Figure 2 is to have adequate reliability such that the probability of failure of the repaired pipe resulting from the variations of loads and resistance is similar to the probability of failure associated with the use of more traditional structural repair materials or pipeline replacement.

Figure 2. Completed CFRP lined section prior to removal of scaffolding

3.1 Structural behavior of CFRP liner for degraded PCCP

While applied loads do not change significantly over time, the moment capacity of the pipe reduces as the repaired pipe degrades due to increase in the number of broken prestressing wires and cracking of the core. The structural system of the pipe changes from a relatively rigid pipe at the time of internal repair, to a more flexible, fully deteriorated pipe resulting in increased deflections and pipe ovaling. The CFRP system has to be capable of accommodating such deformations.

The design of the CFRP liner is based on the loss of all prestressing wires which results in a flexible pipe design for the liner. In addition, the design accounts for the bending of the CFRP lining due to differential stiffness along the length of the pipe encountered during the degradation process, as there will be localized wire breaks (in the form of bands) which cause differences in stiffness along the length of the pipe. Like other flexible pipe designs, the CFRP liner relies on the stiffness of the soil to resist the external loads. Adequate geotechnical data at the site is needed to support selection of the constrained soil modulus for design of the CFRP liner (AWWA M45).

3.2 Design limit states

As part of the process of CFRP lining design, multiple limit states must be addressed. For a stand-alone CFRP liner design, the limit states addressed are as follows:

- Rupture of CFRP circumferential and longitudinal laminate in tension, compression, flexure, or shear.
- Circumferential or longitudinal buckling of the CFRP laminate.

When the inner concrete core is taken into account in the CFRP design, the following additional limit states are addressed:

- Rupture of the CFRP laminate in tension or combined tension and bending.
- Buckling of the CFRP laminate bonded to concrete inner core.
- Debonding of CFRP from the concrete inner core under one of the following circumstances:
    - Shear between the CFRP and the concrete inner core.
    - Excessive radial tension.
    - Concrete core crushing from gravity loads, in absence of internal pressure.

All applicable limit states must be accounted for in the CFRP design in coordination with appropriate loading combinations and material adjustment factors such that a conservative CFRP lining design is developed.

4. CFRP LINER INSTALLATION

CFRP repair of large diameter PCCP lines require extensive planning, especially in municipal areas where traffic control and other complications persist. Dewatering and access to pipeline segments to be repaired are typically coordinated by the Owner. Prior to the pipeline shutdown period crews arrive at the site; set up fencing and material, equipment, and storage areas, temporary office facilities as necessary, lay-down areas, and saturator and material mixing areas; and have all required materials and equipment staged at the pipeline work locations. A typical enclosed mixing area is shown below, in Figure 3. The mixing and storage areas for materials must be maintained at a minimum temperature of 40F.

Figure 3. Typical enclosed material mixing area

Safety is an important aspect of these projects, given that the work takes place in a confined space with limited access and egress availability. Ensuring that crews within the pipe have adequate air supply is one portion of the safety approach. Dehumidification air-blowing units are installed at the appropriate locations, as shown in Figure 4, to ensure a constant supply of clean dry air for ventilation purposes and also to assist in drying the segments to be strengthened following the surface preparation operation.

Figure 4. Dehumidification unit

4.1 Installation procedure

General work activities associated with the PCCP strengthening system installation that occur outside of the pipe include the preparation and mixing of the epoxy system and the saturation of glass and carbon fabric sheets prior to mobilizing the saturated sheets into the pipe for technician installation. Saturation takes place using specialized mechanical saturation equipment, as shown in Figure 5. Fabric saturation is a critical step in the process and it should be even through the fabric thickness such that there are no dry fabric spots.

Figure 5. Mechanical saturator

General work activities associated with the CFRP system installation that will occur inside of the pipe include joint preparation, surface preparation of the inner core, installation of the CFRP system, and installation of the end terminations.

4.2 Surface preparation

Surface preparation is one of the most important aspects of the CFRP installation process. Concrete surfaces are to be prepared to an ICRI profile of CSP-3 or greater to create an open pore structure and to remove all protrusions, sharp edges, and surface contaminants. Joint areas are also prepared during surface preparation. The steel surfaces at termination detail areas in the joints are prepared to a near-white or white metal finish, which requires abrasive blasting of the steel substrate to achieve the necessary profile.

Surface preparation can be performed by ultra-high pressure water blasting, abrasive blasting or pneumatic sponge-blasting. If water blasting is selected, it is recommended that 40,000 PSI equipment, operating at 30,000 to 36,000 PSI is utilized to ensure proper profile of the concrete substrate is accomplished. Use of low pressure may result in inadequate surface preparation and low bond strength. Abrasive blasting is another effective method for surface preparation and standard techniques apply, to the specified surface profile. Special precautions regarding mitigating airborne particulate levels are taken for this type of blasting in a confined space. An alternative method of abrasive blasting with environmental benefit is sponge-blasting, as shown in Figure 6. Sponge media is open-celled, water based polyurethane impregnated with abrasives.

Figure 6. Sponge-blast set-up on pipe interior

On impact with the surface, the sponge particles compress and slide across the surface producing a scrubbing action, more similar to a sanding effect, but eliminating the harsher and dusty negative effects associated with conventional grit blasting. The abrasive particles achieve the desired surface profile and the media rebounds at quite low velocity as the media converts the majority of its energy into work at the surface. The sponge blast media generates less than 10% of the airborne dust levels normally experienced with conventional grit blasting medias, allowing for improved safety during surface preparation.

4.4 Installation of saturated carbon fiber system

Following the surface preparation and prior to CFRP installation, portable scaffolding is erected, as needed, spanning the pipe section to be lined. This gives the crew the ability to apply the CFRP liner to all areas of the pipe section without the need to walk on the pipe. Best industry practice to ensure a successful installation is that the application take place continuous in a manner which avoids contact with the CFRP after installed until cured.

The saturated carbon fiber is applied to the inside surface of host pipe in a wet lay-up process. Dry layup process should not be used as it may result in unsaturated fabric and debonding. The wet-out fabric is pressed to the inside surface of the host pipe to achieve intimate contact. Any entrapped air between layers is released or rolled out without wrinkling of carbon fibers. Figure 7 below shows the first layer of longitudinally applied CFRP being installed inside the pipeline.

Figure 7. Installation of longitudinal layer of CFRP

The installed carbon fiber fabric should be oriented in the directions indicated on the design drawings, with no greater than 5 degree misalignment of the fabrics from the specified direction. When the CFRP is not properly aligned, the affected layer of CFRP system needs to be removed and replaced prior to curing. If the CFRP layer cannot be removed without affecting the integrity of the surrounding carbon fiber, an additional layer is overlaid onto the off axis fibers to restore the laminate structure to its intended directional strength requirements.

4.5 Termination of carbon fiber system

The termination points of the CFRP liner are designed such that internal water pressure is not able to migrate behind the inner core. If the CFRP is not properly sealed at termination points and pressure is allowed to build up behind the inner core, the CFRP lining will be stress-free and structurally ineffective. Designs which include termination details with the CFRP extended into the next pipe section will allow water pressure to build up behind the inner core when the adjacent pipe degrades and hence this termination detail is no longer used.

The length of the bond between CFRP laminate and the steel substrate in the joints is designed so that the maximum axial force in the CFRP in the longitudinal direction from all loading conditions will not cause shear bond failure or tension failure. To prevent galvanic corrosion, the CFRP is constructed on GFRP applied to steel surface. The procedure used for preparation of termination detail must avoid damage to the steel cylinder. Any damage, including gouges and punctures, needs to be repaired prior to CFRP system installation. Installation of the CFRP system into the joint region is shown in Figure 8.

Figure 8. Completed termination detail

5. QUALITY CONTROL BEST PRACTICES

The overall quality of CFRP liner repairs is governed by quality and conservatism of design, quality and durability of materials used, experience of workers and supervisors involved in installation, and quality of installation that includes surface preparation, mixing of epoxy, wetting carbon fiber fabric layers and installation of wetted layers and curing. Quality of CFRP installation is insured by inspection throughout the installation and inspection of the finished system. A trained Quality Control supervisor needs to observe all aspects of the onsite preparation and material application.

The CFRP installer should provide for inspection hold points to allow inspection of the workmanship of in-process construction. Inspection hold points are critical breaks in activities to inspect the workmanship of in-process construction. The following steps should be independently observed by the Owner's inspector:

- Verify construction according to drawings and specifications
- Verify materials and storage conditions (expiration dates, storage temps)
- Document condition of host pipe
- Verify surface preparation and pipe cleanliness prior to CFRP installation
- Verify joint preparation
- Observe testing of mockup panels per ASTM D4541 bond testing
- Document proper control of air flow, temperature, and humidity
- Observe material preparation (fabric/epoxy weight ratios, saturator gaps)
- Observe application of CFRP (layer orientation and sequence, timing)
- Observe installation of CFRP termination details
- Observe preparation of witness panels for ASTM D3039 tensile testing
- Document curing of the CFRP system (85% cure before service)
- Perform post-installation inspection (when CFRP system is tack free)

Due to the complexity of the CFRP lining process, owner's inspector overseeing QA/QC for CFRP lining systems should have extensive experience in this field to ensure appropriate oversight.

5.1 Adhesion (bond strength) testing

In order to validate the adequacy of the surface preparation and the adhesion strength of the carbon fiber strengthening system, the installer is to perform adhesion tests on the prepared concrete substrate adjacent to repair. These areas are to be cleaned, prepared, and covered with CFRP system test patches with minimum dimensions of 2 ft x 2 ft. The patch, as shown below in Figure 9, consists of two orthogonal layers of CFRP. Three adhesion tests are performed and reported in accordance with ASTM D4541. The remaining adhesion test panels are finish coated and remain in place for future testing purposes as needed.

Figure 9. ASTM D4541 bond test typical patch

5.2 Tensile testing

In order to verify the material properties of the field applied CFRP system are in line with the properties used in the design, tensile tests are performed in accordance with ASTM D3039 on test panels which are field fabricated using the carbon fiber fabric, epoxy and saturation equipment used in the production runs for the field-installed CFRP lining system. These panels are made with minimum dimensions of 12in. by 12 in. and are prepared on a smooth flat surface overlaid with plastic (polyethylene or vinyl) sheeting (Figure 10).

Saturating epoxy is used to prime the surface, followed by the saturated CFRP fabric, and finally topped with more saturating epoxy. A cover of plastic sheeting is placed over the panel and the panel squeegeed to remove any bubbles and other surface irregularities to insure a smooth flat surface. The panel is labeled with time, date, sample panel number, fabric lot numbers, and epoxy batch numbers. It is then stored in a clean and dry place to cure. Two test panels are typically fabricated per day of installation of the CFRP system in the field. A minimum of 10% of all fabricated samples are typically tested at an independent testing laboratory. The test lab will perform tensile tests with the fibers oriented in the strong direction for each tensile test panel in accordance with ASTM D 3039 and provide tests results for tensile strength, tensile modulus and related specimen thickness, and percent elongation.

Figure 10. ASTM D3039 Tensile Testing panel preparation

6. CONCLUSION

The design and construction practices for CFRP liners have made significant advances throughout the past 15 years, and this paper describes the current state-of-the-art and best practices. Use of CFRP materials has become a standard repair method for owners of large diameter pipelines, and it is anticipated that CFRP will continue to be more prevalently used for pro-active renewal of critical pipe line systems. The repair system is comprised of materials that need to have tested short and long term properties with known material strength reduction factors, design that has to take into account existing and future pipe condition and all associated design limit states, experienced installers, and experienced construction quality control.

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