Quality Assurance Procedures for Repair of Concrete Pressure Pipes with CFRP Composites

Murat Engindeniz[1], Rasko P. Ojdrovic[2], and Mehdi S. Zarghamee[3]

[1] Ph.D., P.E., M.ASCE, Senior Staff I, mengindeniz@sgh.com, 781.907.9110
[2] Ph.D., P.E., M.ASCE, Principal, rpojdrovic@sgh.com, 781.907.9231
[3] Ph.D., P.E., F.ASCE, Senior Principal, mszarghamee@sgh.com, 781.907.9203

Simpson Gumpertz & Heger Inc., 41 Seyon St., Bldg. 1, Suite 500,
Waltham, MA 02453

ABSTRACT

This paper proposes quality assurance procedures to be followed prior to, during, and after repair of concrete pressure pipes with carbon fiber reinforced polymer (CFRP) liners. A design framework for such repairs was recently proposed (Zarghamee et al. 2010). In this paper, the importance of and requirements for prequalification of the engineer, manufacturer, installer, and inspector; on-site verification of quality of construction, including material preparation, installation, curing, and post-installation inspection; and testing of CFRP are presented. The available guidelines for CFRP repair of other concrete structures are reviewed, existing requirements that are particularly important for repair of pipelines are highlighted, and modifications and additions to these requirements are discussed. Required physical and mechanical tests on the CFRP liner and associated testing standards are listed, and evaluation of the test results is presented.

INTRODUCTION

Since the 1990s, CFRP liners have been used to repair distressed prestressed concrete cylinder pipe (PCCP) where excavation is not economical or when time to repair is limited. In many projects, the savings in construction time provided by CFRP liners outweigh the lower cost of other repair methods. To further increase the speed of construction and to allow repair of small-diameter pipes where hand layup is not possible, robotic application equipments are currently under development.

Currently, ACI Committee Report 440.2R-08 (2008) provides general guidelines for design and construction of externally bonded FRP systems for strengthening concrete structures. While this report includes some guidance on quality assurance (QA) procedures, it requires that the details of such procedures be specified by a licensed design professional (referred to as Engineer herein) based on the complexity of the project. In addition, International Code Council Evaluation Service (ICC-ES) presents acceptance criteria for strengthening concrete and masonry structures with

FRP composites, which includes guidelines on qualification tests (ICC-ES 2010) and inspection and verification (ICC-ES 2008). Neither ACI 440.2R nor ICC-ES documents, however, is intended for repair of PCCP.

Successful execution of CFRP repair of PCCP requires proper implementation of the following: qualification of all involved parties (e.g., Engineer, Manufacturer, Installer, Inspector), selection of all components of the CFRP system, inspection of host PCCP, design that considers the condition of the host pipe and all associated limit states, surface preparation of inner-core concrete and joints, onsite verification of quality of construction by mockup testing, installation and curing of all materials, and independent inspection both during and after installation. The design is performed using the characteristic material properties calculated according to ASTM D7290 based on the test data provided by the Manufacturer prior to construction. Material properties of the field-applied CFRP are determined by testing CFRP witness panels made during construction.

To prevent inconsistencies in design, installation, and quality assurance procedures implemented in CFRP repair of PCCP that can potentially jeopardize the performance of such repairs, the American Water Works Association (AWWA) recently has undertaken the development of a standard in this area. To aid in this effort, we recently proposed a design framework (Zarghamee et al. 2010). The objective of the current paper is to supplement this effort by proposing QA procedures for CFRP liners to be followed prior to, during, and after the repair construction. The paper also is intended to provide guidance to owners, manufacturers, installers, and inspectors for preparation and execution of projects on CFRP repair of PCCP until standard procedures are developed. We review the currently available guidelines for QA of CFRP repair of concrete structures in general, highlight existing requirements that are particularly important for PCCP repair, and propose modifications and additions to these requirements for consideration for inclusion in the AWWA standard under development.

PROCEDURES PRIOR TO CONSTRUCTION

Responsibilities and Qualification of Involved Parties

Owner: The Owner provides all data relevant to the design of the CFRP liner as requested by the Engineer, such as pipeline properties, soil properties, design loads, and environmental conditions. The Owner also provides the Engineer with all submittals by the Manufacturer, Installer, and Inspector for review and awards the contract based on the results of this review.

Engineer: The Engineer is a licensed design professional who performs the design; prepares the repair drawings and specifications; approves the submittals by the Manufacturer, Installer, and Inspector; provides technical support and reviews the inspector's observations throughout the construction; reviews the results of tests on witness panels performed by an independent testing agency; and prepares a detailed report of all activities performed. ACI 440.2R states that the Engineer should be familiar with the properties and applications of FRP strengthening systems, but does not specify qualification requirements. For CFRP repair of PCCP, the Engineer should be experienced in the design of CFRP liners internally bonded to PCCP both as a standalone system and as a system acting compositely with the inner core of the host PCCP, as proven by successful completion of a minimum number of (say five) projects in the last five years. The Engineer should also be experienced in quality assurance inspections during and after installation of the CFRP liner and should be able to identify and specify corrective actions as necessary.

Manufacturer: The Manufacturer supplies all fabrics (or fibers) and resin systems, provides all material data required in the specifications as discussed later in this paper, and submits material safety data sheets and instructions for delivery, storage, handling, and application of all materials. ACI 440.2R requires that the submittals by the Manufacturer should include reference projects, but ACI does not detail this requirement. The Manufacturer should be specialized in the production of the materials to be used in the project with documented experience in a minimum number of (say fifty) successful field installation of CFRP systems, of which five should be PCCP repair projects.

Installer: The Installer performs the work according to all drawings and specifications issued by the Engineer and performs all corrective actions specified by the Engineer and Inspector. ACI 440.2R requires that the Installer submit documents of training received from the Manufacturer, project references (number not specified), evidence of competency in surface preparation techniques, quality control testing procedures, and daily logs and inspection forms. In addition, the Installer should be qualified based on submittal of documents indicating training of all crew members by the Manufacturer, agreement to have each area of work (e.g., surface preparation, material preparation, installation, and curing) supervised by a supervisor with a minimum of three years' experience and a minimum of a number of (say five) reference projects in CFRP repair of PCCP, OSHA (Occupational Safety and Health Administration) confined space training for all crew members, and agreement to have at least two quality control personnel on site at all times – one for operations inside the pipe and one for outside. The Installer should submit for the Engineer's and Owner's approval a detailed work schedule, a step-by-step repair procedure, and details of the curing equipment and schedule to be used.

Special Inspector: The Special Inspector (referred to as Inspector herein) is an independent inspector who reports to the Engineer and performs all special inspections required by the Engineer. The Inspector monitors and documents all phases of the construction of the CFRP liner for compliance with all repair drawings and specifications, and reports all nonconformances to the Engineer for disposition and corrective action as necessary. ACI 440.2R requires that the Inspector's submittals include a list of qualifications, sample inspection forms, and reference projects inspected, but ACI does not detail this requirement. For CFRP repair of PCCP, the Inspector should be qualified based on his/her knowledge of composite materials and their use as documented with training certificate or degree, a minimum number of (say five) reference projects on CFRP repair of pipelines in the last five years in which he/she acted as the Inspector, and OSHA confined space training.

Qualification of Materials

All materials to be used should be prequalified based on the results of laboratory tests. ACI 440.2R requires that the tensile properties reported by the Manufacturer be based on mean minus three standard deviations obtained from the results of a minimum of twenty tests. For CFRP repair of PCCP, the design should be based on "characteristics values" determined according to ASTM D7290, which also accounts for statistical uncertainty due to sample size. The CFRP laminate should be qualified based on the following:

- **Mechanical properties of the CFRP laminate listed in Table 1.** For acceptance, the characteristic values of the properties in Table 1 calculated according to ASTM D7290 should satisfy the values used in design. In cases where material data is submitted after the design phase, and the characteristic values are lower than the design values, the CFRP system can still be qualified if the design meets all limit states with acceptable factors of safety or if an alternate design can be developed with the submitted material.
- **Durability of the CFRP laminate based on environmental conditions in Table 2.** For acceptance, the laminate should exhibit retention of tensile strength and modulus according to Table 2 for exposure to water and temperature, as a minimum. (Percent retained strength or modulus is the ratio of the value obtained for conditioned specimens to the characteristic value for that property obtained for unconditioned specimens.) The laminate should also retain its tensile properties similarly for all other environmental conditions defined by the Owner, if any (e.g., exposure to sea water, sewage, chemicals).
- **Durability of the CFRP laminate based on creep rupture tests.** A minimum of eighteen specimens should be tested at the maximum operating temperature defined by the Owner by subjecting them to different stress levels less than the short-term tensile strength until failure, and the time to failure should be recorded. For acceptance, the extrapolated strength at fifty years on a log-log plot of stress versus time to failure should be greater than 55% of the characteristic tensile strength.

The resin system should be qualified based on the following:

- **Physical properties of the resin listed in Table 3.** For acceptance, the average glass transition temperature should be at least 40°F greater than the maximum operating temperature defined by the Owner, and the long-term water absorption should be less than 2%, with a coefficient of variation less than 10%. Coefficients of thermal expansion are required for use in design, but no limits are set for qualification.
- **Durability of the resin.** For acceptance, the resin should exhibit retention of its characteristic glass transition temperature for the water resistance test and the corresponding retention values in Table 2.

The Manufacturer should also provide test data indicating percent completion of cure versus temperature and duration and percent completion of cure (ASTM E2160) versus Barcol hardness (ASTM D2583). (Completion of cure is characterized by flattening of the exothermic portion of the thermogram obtained by differential scanning calorimetry (DSC).) The Manufacturer should also document compliance with testing requirements of NSF 61 (Drinking Water Components-Health Effects) unless this requirement is waived by the Owner.

Table 1. Mechanical property tests required for CFRP laminate.

Property	ASTM Test Method	Min. No. of Tests
Longitudinal tensile strength and modulus	D3039	10
Longitudinal compressive strength and modulus	D6641	10
Longitudinal flexural strength and modulus	D790	10

Table 2. Minimum environmental durability tests required for CFRP laminate[(1)].

Durability Test	ASTM Test Method	Test Condition	Test Duration (hrs)	Min. No. of Tests	Required % Retention of Characteristic Tensile Properties
Water resistance	D2247 E104	100% RH, max($T_{max}^{(2)}$, 125°F)	1,000 3,000 10,000	10 10 10	90% 85% 80%
Temperature resistance	D3045	max($T_{max}^{(2)}$, 125°F)	1,000 3,000	10 10	90% 85%

(1) This table should be extended as necessary to include all environmental conditions defined by the Owner (e.g., exposure to sea water, sewage, chemicals).
(2) T_{max} = maximum operating temperature defined by the Owner.

Table 3. Physical property tests required for resin.

Property	ASTM Test Method	Min. No. of Tests
Glass transition temperature	D4065	5
Water absorption	D570, Sec. 7.4	5
Longitudinal coefficient of thermal expansion	D696	5
Transverse coefficient of thermal expansion	D696	5

Inspection of Host PCCP

The design of the CFRP liner depends significantly on the condition of the host PCCP, which typically is established during condition assessment performed as part of failure risk analysis. If the condition of the pipe is not known, the Owner or the Engineer should perform an internal visual and sounding inspection of all repair pipes during the design phase and document all cracks, hollow-sounding areas, ovality, surface irregularities, and quality of the inner-core concrete. The quality of concrete surface should be determined by performing pull-off tests according to ASTM D4541 at representative locations. If the inner-core concrete is degraded (e.g., loss of cement paste due to exposure to acidic environment), this may result in poor bond to concrete, and petrographic examination may be needed to determine the cause and extent of degradation. The Engineer should use the collected data to determine the design approach (standalone CFRP liner or composite liner with inner-core concrete), the surface preparation needed, the need for special details at crack locations, and the effect of the existing imperfections on the strength of the CFRP liner (e.g., buckling). If internal inspection of pipes is not possible until mobilization for repair construction, each repair pipe should be inspected prior to commencement of repairs to confirm the Engineer's design assumptions regarding pipe condition and to make design revisions if necessary.

PROCEDURES DURING CONSTRUCTION

Surface Preparation

Surface preparation consists of roughening of all concrete surfaces to receive CFRP and preparation of joints for special CFRP termination details. All concrete surfaces should be roughened by hydroblasting, sand blasting, or other abrasive methods approved by the Engineer to achieve a minimum concrete surface profile of CSP 3 (ICRI Guideline No. 03732) free of loose or unsound materials and surface contaminants. Experience has shown that grinding with abrasive discs cannot provide an acceptable and uniform roughness and should be avoided. If surface preparation is performed during a CFRP installation in progress at another location in the pipeline, forced ventilation should be provided to keep moisture and dust away from the CFRP application area since such conditions can cause anomalies such as delaminations, voids, and amine blush, and also adversely affect curing of CFRP. Where removal of part of the inner-core concrete and/or the joint mortar is required, extreme caution should be used to avoid damage to the embedded steel cylinder. If punctured, the cylinder should be repaired by welding a steel piece over the punctured areas and inspected by a certified welding inspector.

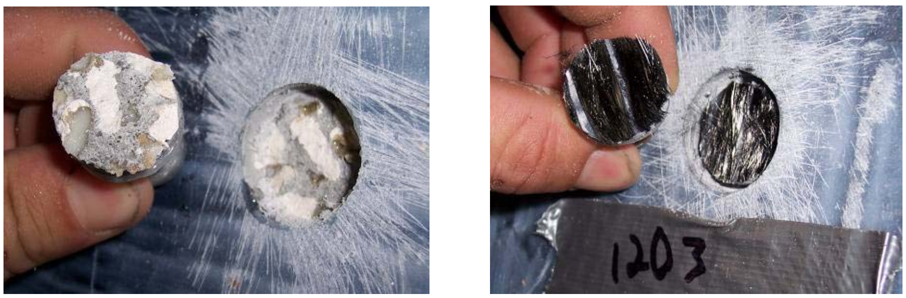
Pipes should be allowed to dry, and all dust should be removed by air blasting or vacuuming. The Inspector should inspect the concrete profile and the joint recesses after surface preparation and reinspect all surfaces for cleanliness just before commencement of CFRP installation.

Verification of Quality of Construction

The Installer should prepare approximately 2 ft by 2 ft mockup areas at a minimum of three locations in the pipeline selected by the Engineer and perform a minimum of three direct pull-off tests according to ASTM D4541 in each area in the presence of the Inspector for verification of the quality of construction. Mockup areas should be selected close to repair pipes to account for any variability of the quality of inner-core concrete and should be prepared using the same surface preparation, CFRP layup, and curing schedule to be used on the repair pipes. For pull-off strengths greater than 200 psi with cohesive failure in concrete (Figure 1a), the quality of construction is accepted. For lower strengths or failure at the concrete/CFRP interface or between the CFRP layers (Figure 1b), ACI 440.2R requires that the Engineer evaluate the results for acceptance. The following can be used as a guide for such an evaluation:

- Failure between CFRP Layers or at the CFRP-Concrete Interface with Pull-Off Strength Greater than 200 psi: Acceptable.

- Failure within Concrete (through aggregate) with Pull-Off Strength Less than 200 psi: Acceptable at the Engineer’s discretion if the CFRP liner is designed as a standalone system. Failure is due to low-strength or degraded concrete.
- Failure at the Concrete Surface (not through aggregate) with Pull-Off Strength Less than 200 psi: Rejected. Failure is due to poor concrete surface preparation, which should be improved, and new mockup areas should be prepared and tested.
- Failure between CFRP Layers with Pull-Off Strength Less than 200 psi: Rejected. Measures should be taken to improve the quality of construction and new mockup areas should be prepared and tested.



(a) Cohesive failure in concrete (b) Failure between CFRP layers

Figure 1. Pull-off testing on mockup areas.

Installation Procedure

All materials should be stored under environmental conditions recommended by the Manufacturer. ACI 440.2R requires that resin mixing be in quantities sufficiently small to ensure that all mixed resin can be used within the resin’s pot life, and does not reject on-site proportioning. For CFRP repair of PCCP, all materials should be brought to the site in preproportioned closed containers and mixed in complete batches for all applications as on-site proportioning increases the chance of error. For impregnation of fabrics, ACI allows in-place impregnation where saturating resin is applied to the repair surface and dry fabric is pressed into the saturating resin and allows the use of impregnation machines as an alternative. For CFRP repair of PCCP, all fabrics should be impregnated using an impregnation machine, and manual impregnation should not be allowed as it may result in insufficient impregnation and failure of the liner. Top-feeding impregnation machines that utilize the volume between two large drums as resin bath should be preferred to those that have a resin bath at the bottom through which the fabric is pulled, since the latter causes fast setting of the resin and requires frequent cleanup.

ACI 440.2R states that successive layers of saturating resin and fiber materials should be placed before the complete cure of the previous layer of resin, but does not discuss determination of degree of cure. Since achievement of “complete cure” for typical epoxy may take several weeks depending on the curing environment, we believe that such a long duration between successive layers of a CFRP liner for PCCP cannot be allowed. For CFRP repair of PCCP, all components of the repair system should be applied within the application time window recommended by the Manufacturer to avoid adverse effects on bond between the layers. Throughout the installation, the environment in the pipeline should be controlled, using methods approved by the Engineer as necessary, so that the ambient temperature inside the pipe is between 40°F and 90°F, the relative humidity is less than 90%, the concrete surface temperature is more than 5°F above the dew point, and the air is free of dust. Higher temperatures may shorten the pot life of materials significantly. Conditions such as low temperature, high humidity, and presence of dust or other contaminants may cause amine blush, also known as oiliness on the CFRP surface (Burton 2001). Such conditions also adversely affect curing and lower the glass transition temperature.

Typical installation steps for an individual standard pipe (i.e., no outlets or other features) should be as follows:

- Apply primer on all concrete surfaces.
- Fill all surface voids in the concrete and provide a smooth surface by applying thickened epoxy below springlines and tack coat above springlines. Tack coat, specially formulated for overhead applications, is used to prevent sagging and delamination due to the weight of the fabric, especially where more than two layers of CFRP are used.
- Install one layer of glass fabric (GFRP) to cover all exposed steel surfaces in the joint recesses at both ends of the pipe to avoid contact between subsequent CFRP layers and steel.
- Install the longitudinal CFRP layer(s) followed by circumferential layer(s), including a thin coat of thickened epoxy after each layer to aid in troweling and bonding subsequent layers.
- Install one layer of GFRP in the joint recesses at both ends of the pipe that is at least 2 in. wider than the steel expansion ring to be installed to prevent contact between the CFRP and the expansion ring.
- Apply a top coat approved by the Engineer that is formulated to improve durability under the special environmental conditions, if necessary (e.g., exposure to chemicals). Under usual conditions, a coat of the thickened epoxy can be used as top coat.

Once all applied CFRP and GFRP have become tack free, the stainless steel expansion ring with a 0.25 in. thick rubber gasket should be installed in the joint recesseses as recommended by its Manufacturer and pressured using a calibrated hydraulic jack to achieve a minimum radial interface pressure of 100 psi between the ring and the liner. All joint recesses should then be filled with epoxy mortar to cover the stainless steel rings and to provide a joint surface that is flush with the pipe surfaces on both sides.

In repairing a group of adjacent pipes, the repair schedule should be staggered such that no scaffolds are placed on freshly installed CFRP until it becomes tack free. The installation procedure should be the same as described above except that the stainless steel expansion rings are installed only at joints at both ends of the group and need not be installed at the intermediate joints. If the joints are tied, the longitudinal CFRP should be installed continuously across the joints as bonded to the concrete surface;

otherwise, an unbounded length centered at the joint should be provided to allow free movement of the two adjacent pipes. The Engineer should calculate the required unbounded length based on expected axial movement of pipes under hydraulic thrust, temperature variations, and other effects.

Inspection of Installation

All steps of installation, including material preparation, application of all layers of the CFRP system, termination details at joints, and curing, should be monitored and documented by the Inspector. Such inspections should extend to all shifts of work and not be “daily” as required by ACI 440.2R. The inspection checklist provided in ICC-ES AC178 Annex A can be used as a guideline and revised for inspection of repair of PCCP including those attributes presented in this paper. The following issues are of particular importance:

- The quality of construction should be verified by pull-off testing on mockup areas prior to commencement of actual CFRP repairs.
- The time elapsed between application of each layer of the CFRP system, including primer, tack coat, thickened epoxy, all fabric layers, and top coat, should not exceed that recommended by the Manufacturer.
- The Installer should prepare flat CFRP witness panels in the Inspector’s presence for tension testing by an independent laboratory after the construction. The number of panels made should be one per work shift per day and should not be less than three in any case. The panels should be made using the same materials and installation methods used on the repair pipes, and stored inside the pipeline or at a representative location approved by the Inspector until collected by the Inspector or the laboratory. The panels should be made using one layer of CFRP unless the Engineer specifies multiple layers. In specifying the number of layers, the testing capabilities of the laboratory should be considered.
- The curing schedule approved by the Engineer should be enforced as described in the following section.

Curing

All CFRP-applied areas should be cured using a curing schedule recommended by the Manufacturer in writing and approved by the Engineer prior to construction. Curing at elevated temperatures is strongly encouraged. This not only reduces the required curing time but also increases the glass transition temperature of the epoxy. The required percent cure of CFRP before refilling of the pipeline depends on the rate of development of the properties of CFRP (e.g., strength, durability), on which the data in the literature is scarce. In absence of such data, the Installer’s work schedule should allow sufficient time between completion of repairs and refilling of the pipeline so that CFRP completes at least 85% cure before being exposed to water based on the cure temperature versus time relationship provided by the Manufacturer, unless adequacy of lesser percent cure is proven by test data. While cure behavior is a product-specific property, the authors’ experience with certain products suggest that achievement of a percent cure of 85% may take up to a week at 70°F to75°F, but this duration can be reduced to around one day by curing at elevated temperatures (e.g., > 125°F). The Engineer should reject the work schedule if sufficient time for curing is not provided. If needed based on the work progress, the Engineer may specify a revised curing schedule during construction.

If elevated temperature cure is used, direct-fired gas or kerosene "salamander" type heaters should not be allowed. Only electric or indirect-fired heaters should be allowed. Exhaust fumes from vehicles or equipment should be kept away from all CFRP-applied areas during curing. If ambient temperature cure is used and the relative humidity is higher than that recommended by the Manufacturer, dehumidifiers should be used to control humidity.

The Inspector should verify the efficiency of the applied curing schedule by performing Barcol hardness test on randomly selected areas of each repaired pipe and using the percent cure versus Barcol hardness relationship provided by the Manufacturer. The Inspector should also verify curing of each resin type (i.e., primer, impregnating resin, tack coat, thickened epoxy, top coat) by randomly taking small samples of each material during every work shift, and keeping them in a representative environment until a Barcol hardness test indicates acceptable curing. Each sample should be traceable to the pipe that the material was used on. If specified by the Engineer, small samples of epoxy (on the order of milligrams) can be collected from the repair pipes after completion of the curing schedule and before refilling the pipeline back to perform DSC tests to ensure sufficient completion of cure.

PROCEDURES AFTER CONSTRUCTION

Post-Installation Inspection

The Inspector should inspect each repair pipe after the CFRP liner has become tack free to identify imperfections, such as voids, delaminations, wrinkles, and raised fabric edges, and to specify corrective actions to be taken by the Installer. A simple "coin tap test," which consists of dragging a coin or a small piece of metal across the CFRP surface and tapping at areas of change in sound, provides satisfactory results in identifying voids and delaminations. An automated version of this test is available (i.e., electronic tap hammer) but is not as practical. More sophisticated methods such as thermography also are available. The Inspector should specify corrective actions as follows:

- Small delaminations, less than 2 in.^{2}, each do not require corrective action, as long as the total delaminated area is less than 5% of the total laminate area and there are no more than ten such delaminations per 10 ft^2.
- Moderate delaminations, less than 25 in.^{2}, should be filled by low-pressure injection of a low-viscosity epoxy (e.g., impregnating resin).
- Large delaminations, greater than 25 in.^{2}, should be repaired by cutting away all delaminated layers in the affected area, and replacing them with a CFRP patch of equivalent number of layers and fiber orientations with an overlap of at least 12 in. the fiber direction of the patch. The overlap areas should be scuff-sanded and cleaned of all dust before applying the patch.

All joints filled with epoxy mortar should also be inspected after they have cured for any sagging or hollow sounding. A corrective action for hollow-sounding epoxy mortar is removal and replacement.

Testing of Witness Panels

The Owner should retain an independent testing laboratory to perform tension tests on coupons cut from the CFRP witness panels made by the Installer during construction to verify that the design tensile properties used by the Engineer based on the test data provided by the Manufacturer prior to construction were achieved in the field. The Owner may also allow the Installer to retain an independent laboratory and submit an official test report for the Engineer's review.

A minimum of ten coupons should be tested from each witness panel, and the tensile strength, chord modulus, ultimate strain, and failure mode should be reported according to ASTM D3039 except that the thickness of the panel should be taken as the nominal value and not the actual thickness. This is because the thickness of the panels may vary significantly based on the amount of resin used, which may result in misrepresentation of the actual material strength. Coupons can be tested with or without end tabs as long as failure at the grips is avoided.

The Engineer should identify all valid tests, analyze the test results statistically, and calculate the mean strength and modulus for each witness panel. Pooling of all test results into a combined data set should be allowed only if justified by statistical pooling methods. The mean strength and modulus should be greater than the characteristic values calculated based on the test data provided by the Manufacturer prior to construction and used in design. Otherwise, the Engineer should check the design with the calculated mean values and should recalculate the factors of safety for each limit state. If the revised factors of safety are still above those required by design, the CFRP witness panels should be approved.

CONCLUSIONS

The currently available design and installation guidelines and acceptance criteria for CFRP repair of concrete structures either assign the definition of detailed quality assurance procedures to a licensed design professional based on the complexity of the project (e.g., ACI 440.2R-08), or the detailed procedures that are specified are not necessarily intended to cover repair of PCCP (e.g., ICC-ES AC125 and AC178). Existing requirements that are particularly important in PCCP repair are highlighted, and modifications and additions are proposed herein for consideration in the development of the needed standard for repair of PCCP with CFRP liners.

REFERENCES

ACI 440.2R-08 (2008). *Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures,* American Concrete Institute.

ASTM D570. *Standard test method for water absorption of plastics*. ASTM International.

ASTM D696. *Standard test method for coefficient of linear thermal expansion of plastics between -30°C and 30°C with a vitreous silica dilatometer*. ASTM International.

ASTM D790. *Standard test method for flexural properties of unreinforced and reinforced plastics and insulating materials*. ASTM International.

ASTM D2247. *Standard practice for testing water resistance of coatings in 100% relative humidity*. ASTM International.

ASTM D2583. *Standard test method for indentation hardness of rigid plastics by means of a Barcol impressor*. ASTM International.

ASTM D3039. *Standard test method for tensile properties of polymer matrix composite materials*. ASTM International.

ASTM D3045. *Standard practice for heat aging of plastics without load*. ASTM International.

ASTM D4065. *Standard practice for plastics: dynamic mechanical properties: determination and report of procedures*. ASTM International.

ASTM D4541. *Standard test method for pull-off strength of coatings using portable adhesion testers*.

ASTM D6641. *Standard test method for compressive properties of polymer matrix composite materials using a combined loading compression (CLC) test fixture*. ASTM International.

ASTM D7290. *Standard practice for evaluating material property characteristic values for polymeric composites for civil engineering structural applications*. ASTM International.

ASTM E104. *Standard practice for maintaining constant relative humidity by means of aqueous solutions.* ASTM International.

ASTM E2160. *Standard test method for heat of reaction of thermally reactive materials by differential scanning calorimetry.* ASTM International.

Burton, B. L. (2001). "Amine-Blushing Problems? No Sweat!," Proceedings of the Fall 2001 Epoxy Resin Formulators' Meeting of the Society of the Plastics Industry. Baltimore, MD.

ICC-ES (2008). "Interim criteria for inspection and verification of concrete and reinforced and unreinforced masonry strengthening using fiber-reinforced polymer (FRP) composite systems (AC178)," International Code Council Evaluation Service, Inc.

ICC-ES (2010). "Acceptance criteria for inspection and concrete and reinforced and unreinforced masonry strengthening using externally bonded fiber-reinforced polymer (FRP) composite systems (AC125)," International Code Council Evaluation Service, Inc.

ICRI. *Selecting and specifying concrete surface preparation for coatings, sealers, and polymer overlays (Technical Guideline No. 03732)*, International Concrete Repair Institute.

NSF/ANSI 61. *Drinking water system components – health effects.* NSF International.

Zarghamee, M. S., Engindeniz, M., Erbay, O. O., and Ojdrovic, R. P. (2010) "Repair of Concrete Pressure Pipes with CFRP Composites," *Proceedings of 2010 ASCE Structures Congress,* Orlando, FL, pp. 1874-1884.