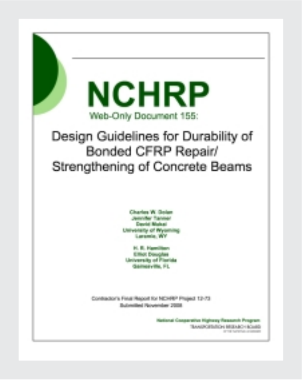

NCHRP

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Design Guidelines for Durability of Bonded CFRP Repair/Strengthening of Concrete Beams

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ABSTRACT

This research provides a methodology for evaluation of durability related strength loss of bonded carbon fiber reinforced polymer (CFRP) systems applied to concrete beams. The report addresses test methods to establish a durability strength reduction factor, identification of corresponding field exposure conditions affecting durability, and suggestions for the application of the durability strength reduction factor for design of field applications. The durability strength reduction factor is a measure of the loss in strength over time due to environmental exposure. It is defined as the ratio of the flexural strength of a 4 in. x 4 in. x 14 in. concrete beam reinforced with CFRP exposed at 140°F and submerged in water or 100% relative humidity for 60 days to the flexural strength of a control specimen. The resulting durability strength reduction factor may be used to evaluate CFRP system performance.

Two field environments are suggested: Wet and Air. In a Wet environment water accumulates at the bond surface. This is the default condition and corresponds to test results in submerged water at 140°F for 60 days. An Air environment allows drying between wetting episodes so water cannot accumulate on the bond surface. This condition corresponds to test results in 100% relative humidity at 140°F for 60 days.

EXECUTIVE SUMMARY

This research provides a methodology to evaluate durability of bonded Carbon Fiber Reinforced Polymer (CFRP) repair and strengthening of concrete beams. The methodology is based on use of a durability strength reduction factor, ϕ_d, to describe durability related strength loss of CFRP systems. The report presents suggested test procedures, including test specimens and exposure protocols, to establish the durability strength reduction factor. The test method evaluation program led to the definition of field exposure environment. Definition of a field environment allows the durability strength reduction factor to be used in conjunction with existing load and resistance factors to evaluate the effects of durability strength loss in field applications.

The strength of CFRP composites bonded to concrete deteriorates when exposed to hygrothermal conditions. The deterioration occurs principally on the bond plane, which is the interface between the epoxy adhesive and the concrete. The exact mechanism of the deterioration is not well known; however deterioration is accelerated under elevated temperature, immersion in water or sustained loads. Tests on a several CFRP systems indicated that the procedures in this report were capable of differentiating a wide range of responses of deterioration of CFRP systems subjected to the test procedures. Environmental exposure conditions and test procedures assure uniform reporting and evaluation of durability strength reduction factors to field application environments. The methodology presented in this report allows engineers to obtain standardized comparisons of alternative CFRP systems, apply the strength reduction factors to field applications, and to make decisions on the applicability of a CFRP system for a given environment.

Two exposure environments: Wet and Air are recommended for design. The Wet environment is characterized by the extensive exposure to and accumulation of moisture at the epoxy-concrete interface and is the default environment for selection of durability strength reduction factor for use in design. The Air environment is characterized by an ambient environment in which water does not accumulate at the bond surface. Selection of the Air environmental exposure condition requires confirmation to assure that water does not accumulate on the bond surface and the report recommends comparison of the Wet and Air tests to further assess the selection of a field exposure environment.

The durability strength reduction factor is defined as the ratio of the flexural strength of exposed test specimens to the flexural strength of control specimens. The durability strength reduction factor may be established experimentally for any CFRP composite system and concrete strength. The durability strength reduction factor may be used a) in conjunction with the AASHTO resistance factor to provide design values for the reduced CFRP strength due to environmental exposure, b) to qualify a specific CFRP system, c) to compare durability strength reduction factors to those provided by system suppliers, or d) to confirm compliance with project specifications. These recommendations are for strength deterioration of the bonded CFRP system applied to concrete beams and do not address strength loss due to deterioration of the underlying concrete or corrosion of steel reinforcement.

The test exposure for a Wet environment submerges the test specimen in 140°F water for 60 days. Test exposure for an Air environment is 60 days at 100% relative humidity at 140°F. In lieu of other considerations, the Wet environment is recommended as the default condition. If an Air environment is selected, the Wet environment tests are recommended to provide the engineer with a basis to evaluate the exposure selection. The research recognizes that 140°F is a high exposure temperature; however, the 60-day exposure at this temperature correlates with the long-term lower bound response of specimens exposed to lower temperature conditions.

The test specimen is a 4 in. x 4 in. x 14 in. beam, tested in three-point bending (flexure) on a 12 in. span length. The specimen is prepared by providing a full-width half-depth saw cut approximately 0.1 in. wide at mid-span. Application of a CFRP system and surface preparation is in accordance with NCHRP reports 514 and 609.

1. INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

Bonded Carbon Fiber Reinforced Polymer (CFRP) composite systems are widely used to repair or strengthen bridge structures. Their light weight and ease of field application make them an attractive alternative to traditional strengthening or replacement of bridge beams. Short-term laboratory test results of CFRP application demonstrate that improvement in flexural or shear strength is possible with these materials. (ACI 440) Concurrently, there is little comprehensive information on the deterioration of CFRP strengthening systems in field environments nor is there information allowing the estimation of the service life of these materials. A summary of relevant research on durability of CFRP systems is given in Chapter 2.

Research Objective

The objective of this NCHRP 12-73 Project was to develop test methods to evaluate the durability of CFRP used for repair or strengthening of concrete beams. A CFRP system consists of the carbon fiber fabric or pre-cured CFRP laminate, the epoxy adhesive and associated primers and sealers. The CFRP system is typically supplied as a system, that is, the carbon material and adhesives. Application of bonded CFRP systems is addressed in NCHRP Report 514 and the manufacturers’ literature.

The research objective was met by defining a durability strength reduction factor, ϕ_d, which is applied to the strength calculations of CFRP systems used to strengthen or repair concrete beams. Definition of moisture conditions for design environments and draft specifications defining procedures for establishing the durability strength reduction factor are provided. These recommendations result from an extensive testing program. The procedures may be applied to any bonded CFRP system to establish durability strength reduction factors for design or for manufactures to improve CFRP systems. The durability strength reduction factor applies only to the CFRP component and is not applicable other mechanisms such as corrosion of steel of reinforcement or concrete deterioration.

A second portion of this research examined procedures for estimating service life associated with the strength loss of the bonded CFRP. In both the literature review and in the experimental work conducted in this project, the degradation of the CFRP specimens submerged in water occurred in days or weeks depending on the temperature. Service life is expected to be in years or decades. Therefore, in lieu of prediction of service life, the research recommended two exposure conditions that are dependent on the water content in the environment that affects CFRP in service conditions. The strength reduction factors derived from the test procedures recommended in this report represent lower bound values and are suitable for the life of the structure.

Research Approach

The research approach included a review of relevant literature and factors affecting durability, defined a test procedure for establishing a durability strength reduction factor, conducted exposure tests, and assessed the test results. Attachments A and B contain test specifications to determine the durability strength reduction factor, ϕ_d, for any given CFRP system and specifications for mixing epoxies for the test specimens.

2. ENVIRONMENTAL FACTORS AFFECTING DURABILITY

Research has been performed on CFRP durability, but the majority of studies have been performed on constituents of the CFRP system, mainly neat resin samples and carbon fiber-epoxy composites. Durability of CFRP bonded concrete beams has not been studied extensively. Based on the literature review, major environmental factors affecting CFRP durability are moisture, temperature, chemicals in the water, UV radiation and fatigue.

MOISTURE AND TEMPERATURE

Moisture and temperature have been regarded the most important factor affecting CFRP durability. Lefebvre et al. (1991) and Au et al. (2006) reported that a critical relative humidity (RH) value in epoxy resins or CFRP composites existed beyond which durability degradation occurs. Quantifiable identification of critical parameters affecting durability was not provided. Wolff (1993) reported combinations of time, temperature, stress, chemicals, cyclic loads or moisture cause increasing problems with durability of FRP composites. Karbhari et al. (1997) reported that interfacial fracture energy decreased with exposure to water in CFRP composite bonded concrete beams. Toutanji and Gomez (1997) observed a pronounced bond strength reduction in CFRP composite systems subjected to wet/dry cycling. Tu and Kruger (1996) and Aiello et al. (2002) concluded that water immersion led to bond strength degradation for epoxy bonded concrete. Malvar et al. (2003) conducted CFRP to concrete pull-off tests and found that bond strength of CFRP composite systems decreased at high temperature and relative humidity (RH). Grace and Singh (2005) reported that reinforced concrete beams with externally bonded CFRP plates exhibited an average of 33% reduction of load capacity after 10,000 hours of 100% humidity exposure. Chun and Karbhari (2005) attributed the degradation of pultruded E-glass vinylester composites to plasticization, hydrolysis, fiber-matrix debonding and microcracking mechanisms caused by water ingress and temperature aging. Abanilla and Karbhari (2006a, 2006b, and 2006c) concluded that moisture uptake and other environmental factors deteriorated the strength characteristics at the matrix and interface levels for FRP systems. Wan et al. (2006) demonstrated that water presence in CFRP composite systems resulted in an adhesive failure along the primer-concrete interface. Au and Buyukozturk (2006) concluded that 100% relative humidity exposure resulted in a 50-60% loss in fracture toughness at the epoxy-concrete bond surface in CFRP composite systems.

CHEMICAL SOLUTIONS

Chajes et al. (1994) reported that exposure to chlorides in both wet/dry and freeze/thaw environments reduces flexural specimen strength, and that the wet/dry condition was slightly more severe. Chin et al. (1998) reported a 40% tensile strength reduction in dogbone specimens of isophthalic polyester and vinyl ester resins after immersion in alkaline solution (pH 13.5). Sen et al. (1999) observed a 0 to 55% strength loss and a 0 to 45% loss in bond strength for CFRP wet-layup systems bonded to concrete and subjected to cyclic sea water exposure. Hawary et al. (2000) reported a 25% decrease in bond strength due to tidal saltwater exposure over 6, 12, and 18 months for epoxy bonded concrete specimens. Toutanji and Gomez (1997) observed a 5-30% loss in flexural strength after 75 days of wet/dry exposure in simulated saltwater of CFRP and GFRP wet layup bonded concrete beams.

UV RADIATION

Several investigators (Liao et al. 1998; Wolf 1993) reported ultraviolet radiation deterioration increased in conjunction with moisture. They attributed observed strength reduction to increased creep strain of the FRP. Haeberle et al. (2002) reported that UV exposure caused surface cracking of carbon fiber vinylester resin matrix coupons. Liau and Tsent (1998) reported that the UV exposure caused crack initiation in CFRP specimens, eventually reducing the strength due to stress concentrations. Hulatt et al. (2002) found that stress at failure increased after exposure of CFRP pre-impregnated coupons to 2000 hours of UV radiation according to ASTM G 53.

FATIGUE

Reifsnider et al. (1983) investigated the long-term fatigue behavior of composite materials and established concepts and models to interpret the damage states during cyclic tension and compression of composite materials. Hayes et al. (1998) investigated effects of moisture on the fatigue behavior of glass-vinyl ester composite and reported that quasi-static tensile strength was reduced by 26% at a moisture concentration of 0.95% by weight and this reduction was not recovered when the material was desorbed. Kitane et al. (2004) reported an insignificant degradation in stiffness of FRP system after 2 million loading cycles. Brena et al. (2002) reported beams reinforced with CFRP composites subjected to cyclic loading exhibited little fatigue deterioration under service conditions. Georgiou et al. (2005) investigated fatigue and monotonic strength of RC beams strengthened with CFRP laminate and reported the ultimate deflection and strain of CFRP was slightly decreased, but the ultimate load was not affected by cyclic fatigue loading.

TIME FRAME FOR CFRP ACCELERATING AGING

A goal of accelerated aging testing is to reduce the time required to characterize long-term behavior. Au et al. (2006) conducted a 3D diffusion simulation study and peel testing. Au observed that specimens with CFRP bonded to concrete and subjected to 8 weeks of continuous moisture exposure at 122°F resulted in the fracture toughness degrading to a steady value, which was validated by peel testing. Au further reported that previous studies found that accelerated aging tests could be terminated in a 60-day timeframe because equilibrium states were reached. The Arrhenius equation was suggested as a method to correlate real time and accelerated aging (Zhou and Lucas 1998). The equation is a power curve and the deterioration in strength is correlated through curve fitting test data. Zhou and Lucas reported that the equation was valid for continuous behavior, e.g., moisture migration into a CFRP system.

FINDINGS FROM LITERATURE REVIEW

Four findings from the literature review influenced the development of a design methodology. They are: moisture critically affected the performance of bonded CFRP systems; elevated temperature accelerated deterioration; strength losses of up to 60% could be expected; and accelerated aging results within a 60-day time could be expected.

The literature review presented conflicting findings. This was attributed to the materials used in the various test programs. An underlying assumption was that all epoxies behave in a similar manner. The literature review suggested that this is a false premise and each CFRP system must be assessed individually.

3. EVALUATION APPROACH AND EXPOSURE CONDITIONS

This chapter addresses test and environmental exposure procedures to evaluate the durability of the CFRP bonded to concrete. . Commercially available CFRP systems and epoxies formulated by the research team were used to further evaluate that the test specimen and procedures were capable of differentiating performance and provide insight to CFRP durability. Specimens were fabricated and tested independently at two locations. Group 1 is at the University of Wyoming and Group 2 the University of Florida. The two groups allowed direct comparison of systems exposed to common conditions and variations in test procedures to evaluate overall performance. When variations in test results affected the conclusions and recommendations, the differences in Group 1 and Group 2 specimens are discussed in detail.

The definition of a durability strength reduction factor is to allow engineers to extend the test methods to evaluation of field applications. The AASHTO LRFD design method uses load and resistance factors to specify required strength of structures. The resistance factor, ϕ, accounts for variation in initial material properties and sectional dimensions. The resistance factor does not account for changes in these properties over time. To account for the loss of strength of CFRP systems due to environmental effects, a durability strength reduction factor, ϕ_d, is introduced. The factor ϕ_d is applied only to the CFRP system contribution to the design strength calculations. Thus:

$$\Sigma\gamma_i Q_i \leq \phi\,\phi_d\,R_n$$

where γ_i is the load factor, Q_i is the force effect, ϕ is the resistance factor, ϕ_d is the durability strength reduction factor, and R_n is the member resistance.

SPECIMEN EXPOSURE CONDITIONS

The exposures used to condition the beam specimens are summarized in Table 1. These conditions provided controlled accelerated aging and real time tidal and solar exposures. Control specimens were cured in ambient laboratory (dry) conditions and were tested at 28 days. A small number of control specimens were kept in ambient laboratory conditions and tested at the conclusion of the environmental exposure tests. These specimens had the same or higher flexural strength than the original control specimens.

Submerged exposure conditions consisted of continuous immersion of multiple specimens in temperature controlled water for the specified periods. The Group 1 specimens were submerged in elevated temperature water baths in which heat was supplied through a commercial screw plug immersion heater. The Group 2 specimens were exposed using 120-qt insulated coolers connected to a pump and a household water heater via 5/8-in. diameter heater hose. While exposure systems used for Group 1 and Group 2 specimens differed slightly, they provided essentially the same exposure conditions.

The continuous exposure to elevated temperature water baths provided a severe aging condition that resulted in substantial strength degradation of bonded CFRP composites in a relatively short period. Because these materials may perform adequately in high humidity without immersion, specimens were exposed to 75% and 100% relative humidity (RH) to evaluate the effect of a moist environment on the CFRP composite. For comparative results, specimens were also submerged in room temperature water. Additionally, moisture uptake of concrete was measured by examining slices from the concrete beams exposed to the same relative humidity (RH) and room temperature submerged environment as the beam specimens.

Other investigators (Lefebvre et al. 1991; Toutanji 1999; Abanilla et al. 2005) reported that mechanical strength degradation of FRP samples saturated with epoxy resin was partially reversible or insignificant after drying. Therefore, the effect of wet/dry cyclic exposure conditions and the effect of drying after long-term exposure of CFRP systems were investigated.

The remaining exposures included salt and high pH solutions, sustained loads combined with hygrothermal exposure; UV light cycled with immersion; and fatigue resistance after exposure. Moisture penetration was also accelerated using a pressure vessel rather than immersion to accelerate the effects of moisture by using pressure.

Real time solar and tidal exposures were conducted under ambient conditions. The solar specimens were placed on the roof of a six-story building in Laramie, Wyoming. The tidal specimens were hung from the fender system of the SR 206 bridge in Crescent Beach, Florida.

Table 1. Summary of exposure conditions used to weather the specimens

Exposure Condition	Temp. (^oF)	Approximate Exposure Times (months)	Number of specimens	Group
Submerged	86	0.25, 0.5, 1, 3, 6, 12, 18	210	1&2
	104	0.25, 0.5, 1, 3, 6, 12, 18	210	1&2
	122	0.25, 0.5, 1, 3, 6, 12, 18	210	1&2
	140	0.25, 0.5, 1, 3, 6, 12, 18	300	1&2
100% Relative Humidity	68 and 140	0.5, 1, 2, 3, 6, 12	105	1
75% Relative Humidity	68	0.5, 1, 2, 3, 6, 12	105	1
Wet-dry cycling 2 days submerged/5 days dry	68	2, 4, 6, 11.5	90	1
Chloride solution (submerged)	122	12	15	2
Alkali solution (submerged)	122	12	15	2
Sustained Load + Submerged	122	6	15	2
Ultraviolet Radiation+ 2 weeks submerged/2 weeks dry	Solution – 122 Dry – 68	12	15	2
Fatigue-Repeated load	68	n/a	45	1
Tidal- Outdoor real time	Variable	12, 18	45	2
Solar-Outdoor real time	Variable	18	30	1
Pressurized hygrothermal (pressure vessel)	140	0.1, 0.25, 0.5	45	1
Control (dry ambient)	68	28 days	60	1&2

Definition and fabrication of test specimen

A major consideration during the development of the test specimen was to replicate the stress condition in concrete beams subjected to flexure or shear loadings. The test procedure had to be sufficiently convenient so that statistically significant number of specimens could be constructed and tested in a reasonable time frame. Furthermore, the test result interpretation should be robust enough to ensure acceptance by state departments of transportation and CFRP suppliers. The following sections summarize the process used to select a test specimen and evaluate the test methodology.

Selection of test specimen

The standard test method for flexural testing of concrete beams AASHTO T97-03 (ASTM C78-02), which is used to obtain the modulus of rupture (MOR) for concrete, was selected as the starting point for specimen definition. The saw cut simulated a crack and assured that the CFRP was exposed to the environment at the location of maximum moment. Three-point loading resulted in a higher moment than four-point loading for the same maximum shear. This loading reduced the possibility of a flexure-shear failure in the concrete. The configuration shown in Figure 1 was selected for the durability tests. A single layer of wet-layup or pre-cured composite was centered on the saw-cut. Shear and bearing at the specimen end was a concern so Group 1 specimens were constructed with a length of 15 in. and Group 2 specimens were constructed with a length of 14 in. to have a 1 in. and 1 – ½ in. extension past the center line of the supports respectively. A span length of 12 in. was used by both groups when conducting testing. For the wet-layup systems the fabric was cut to a width of 1 in. For the pre-cured laminate system Group 1 specimens had a 1-in. width and the Group 2 specimens had a 0.75-in. width to evaluate whether the stiffer laminate would generate excessive flexure-shear failures in the concrete.

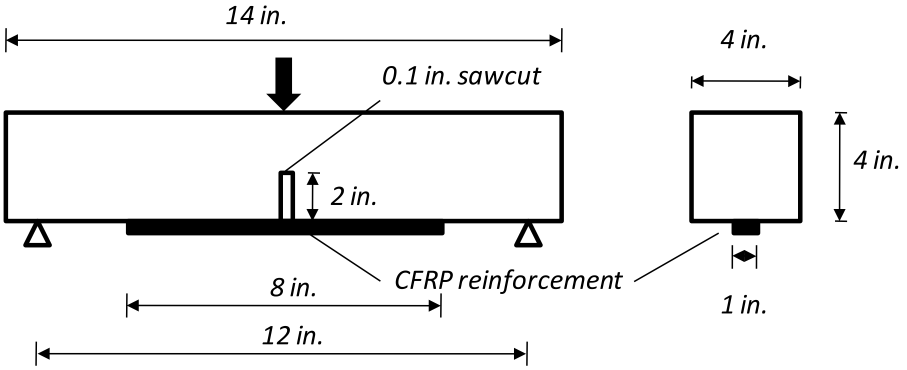


Figure 1. **Final beam specimen configuration**

Fabrication of test specimens

The focus of the study was on the performance of the bonded CFRP; however, the concrete substrate potentially affects results. Therefore, a number of different concrete mixtures were included in the test program.

Group 1 Specimens

Rocky Mountain Prestress, in Denver, CO cast the first batch of approximately 500 beams with a concrete 28-day compressive strength of 9,700-psi. The high strength was representative of precast prestressed bridge beams and was selected to limit flexure-shear failure in the specimen. The concrete mixture had a water:cement ratio of 0.32, and cement:fine aggregate:coarse aggregate ratio of 1:1.65:1.96 by weight.

An additional 315 specimens were cast in two separate batches of 105 and 210 specimens, respectively. The two batches of concrete were cast in wooden forms with same design mix except that pea gravel was used in the first batch and 3/8-in. maximum in the second batch. These mixtures were representative of cast-in-place concrete beams. Type I/II low alkali cement was used and the cement: sand: coarse aggregate ratio was 1:2.09:2.41 by weight. The specimens were cured in the fog room at nearly 100% relative humidity and temperature of 68°F. The 28-day compressive strength was 6,700 psi for the first batch and 6,900 psi for the second batch (Deng 2008).

Group 2 Specimens

Six batches of 75 beams constituted the 450 Group 2 beams. They were cast at the Florida Department of Transportation State Materials Office (FDOT) in Gainesville, FL. The concrete was designed to have a 28-day compressive strength of 10,000-psi. The mixture had a water:cement ratio of 0.35 and a cement:fine aggregate:coarse aggregate ratio of 1:1.5:1.7 by weight. The measured 28 day compressive strength varied between 9,250 to 10,500 psi and the MOR varied between 990 psi to 1090 psi (Gartner 2007).

CFRP SYSTEMS

The test procedures were designed to differentiate the durability performance of CFRP systems. To determine if the procedures could differentiate performance, four - unidirectional wet-layup CFRP systems (A, B, D, and E) and one unidirectional carbon laminate system (C) were selected to construct the specimens. Systems A, B, and C were commercially available systems in which the fiber and epoxy are provided together. These systems were proprietary so the chemical composition of the resins and primers was not known. System D and E epoxies were formulated using of commercially available components for which the chemical composition was known.

Composite A was a unidirectional carbon fiber fabric and a two-component epoxy resin. The system also included a sealant to provide a protective coating. To assess the effectiveness of the coating, Group 1 specimens did not apply the coating and Group 2 specimens used the coating.

Composite B consisted of unidirectional carbon fiber fabric, epoxy primer, epoxy putty, epoxy saturant, fiber weave, and protective top coat. The primer was a low viscosity, 100% solids, polyamine cured epoxy. The putty was a 100% solids non-sag paste used to level small surface defects and provided a smooth surface to apply the composite system. The saturant was a 100% solids, low viscosity epoxy material used to encapsulate the fiber fabric. The top coat protected against UV radiation and mild abrasion.

Composite C consisted of a pre-cured unidirectional carbon fiber polymer laminate and epoxy putty. The putty was a 100% solids, structural epoxy paste adhesive that conformed to AASHTO M-235 and ASTM C-881 specifications. Group 1 used a 1 in. wide strip and Group 2 used a ¾ in. wide strip to assess the effects on concrete flexure-shear failure of the concrete specimen.

Composites D and E consisted of a Composite B CFRP fabric and a custom formulated, two component, epoxy with known properties. Composites D and E consisted of the two components of this generic system, but different mixing ratios. The thermal and mechanical properties of several mixture proportions were tested to determine the mixture ratios for the generic system. The glass transition temperature (T_g) of these two epoxy mixtures was measured using differential scanning calorimetry (DSC) and the effect of cross-linking on the glass transition temperature was analyzed. The effect of water immersion over short term periods was evaluated using tension tests on epoxy coupons. Composite D epoxy used a ratio that allowed for equal number of reaction sites for both saturant components and was assumed to simulate commercial systems. Composite E used an alternate ratio of the two parts of the epoxy resulting in a different number of reaction sites.

4. LABORATORY TEST PROGRAM AND RESULTS

Experimental work performed in this project included flexure and direct tension tests summarized in this report. This work was performed to evaluate and refine the test procedures and recommendations. While individual CFRP systems were evaluated. The test program demonstrated the variability of the CFRP systems and the ability of the procedures to identify these variations.

FAILURE MODES

ACI 440.2R *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* (ACI 440.2R 2002) Section 9.2.1 identifies five possible failure modes for flexural strengthening with CFRP. Three modes deal with steel yield and primary or secondary concrete compression failure. The other two conditions address substrate failure (cover delamination) and debonding. The test procedure developed in this research addresses only the last two items and ϕ_d applies only to the bond actions, e.g., Eq. 9-2 in ACI 440.2R-02 or similar bond related behavior. If the bond is sufficient, even with the reduced capacity, to force other modes of failure, e.g., compression failure of the concrete, then the design is not bond critical. In this case the ϕ_d is applied only to bond sensitive conditions.

Bonded CFRP failure modes are reported in the literature; however there was wide variation in the reporting nomenclature. In consequence, the definitions and descriptions in Table 2 were developed and used in this research. Substrate failure is the desirable failure mode in practice. The test procedure was designed to develop substrate failure in the control specimens and to ensure the capacity obtained from testing directly correlates to the loss of CFRP bond strength. A system having substrate failure following exposure is assumed to have no durability strength reduction. Mixed mode, adhesive and composite delamination failures were evidence of durability deterioration. Any flexure-shear failure was considered an invalid test result and was excluded from test results.

Table 2. Definition and description of beam test failure modes

Failure mode	Visual Condition
Substrate	Cohesive failure with rupture surface through concrete paste and aggregate. Concrete remains adhered to CFRP composite.
Mixed-mode adhesive/substrate	Partial substrate and adhesive failure.
Adhesive	Adhesive failure with rupture surface between CFRP and concrete surface. CFRP failure surface clean or covered with thin layer of concrete.
Composite delamination	CFRP composite splits between laminations. Lamination(s) remain adhered to concrete.
Flexure-shear	Diagonal crack initiated at the end of the CFRP on one end of the specimen. CFRP remains intact and fully attached to the concrete specimen.

SUMMARY OF TEST RESULTS

A series of tests were conducted on composite specimens with CFRP Systems A, B, C, D and E to evaluate one or more of following exposure conditions:

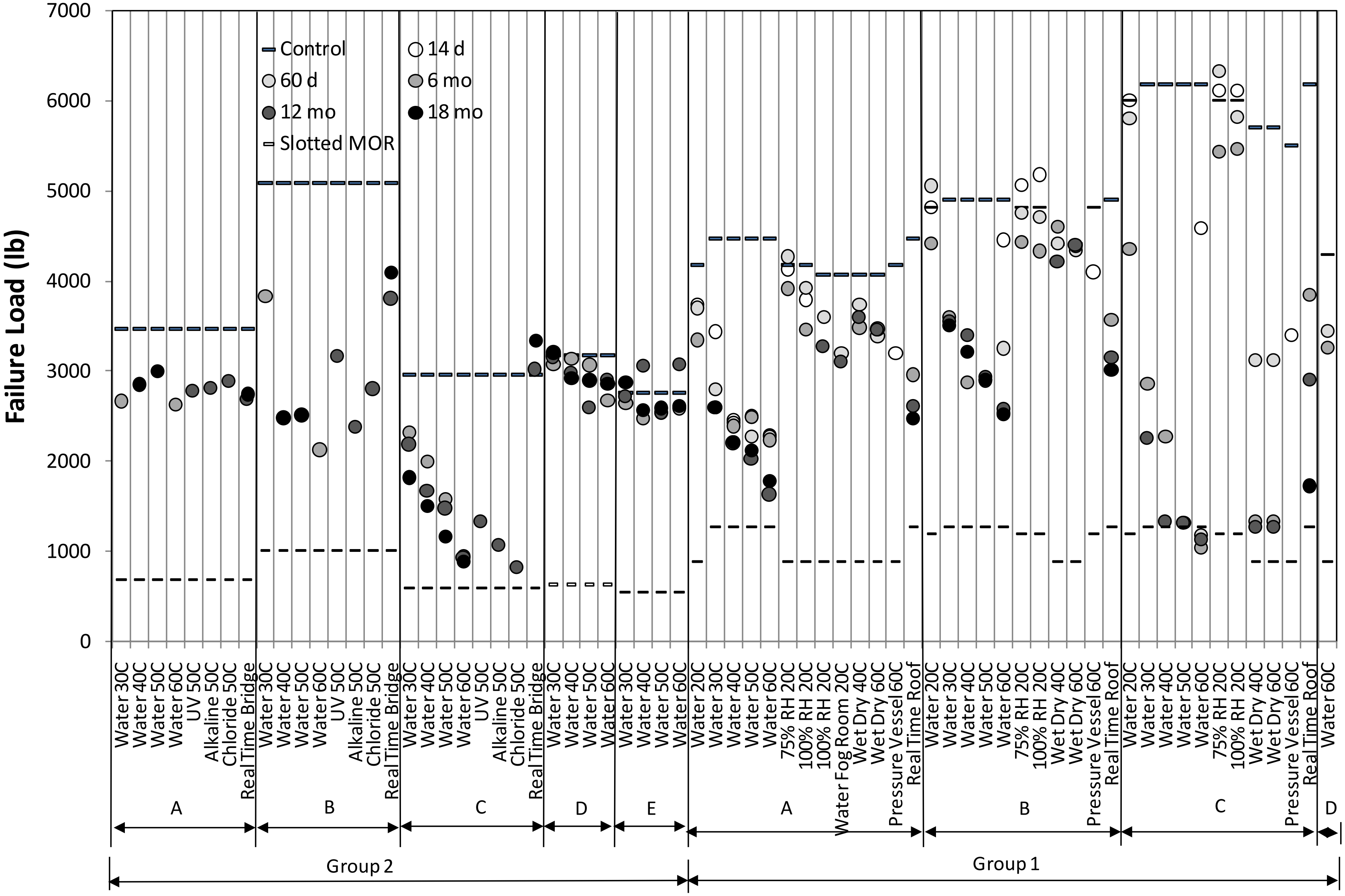
- Elevated temperature water immersion;
- Different levels of Relative Humidity (RH);
- Intermittent Wet/Dry exposure;
- Cyclic and sustained loading;
- Ultraviolet radiation;
- Alkaline or chloride;
- Pressurized hygrothermal;
- Real time tidal; and
- Real time solar.

General

A summary of all tests results is given in Figure 2.

Figure 2 and summary graphs for Systems D and E give the control strength and the final strength in terms of the load that caused flexural failure. This allows comparison of strength of alternative adhesive systems. Individual system test reports provided data in the format of strength ratio, that is, the strength of the exposed specimen divided by the strength of the control specimen, to better display strength losses. The control strength of CFRP System A varied between 4000 and 4500 lb. for Group 1 and was approximately 3500 lb. for Group 2. Control strength of System B was about 5000 lb. for both groups. Differences in the amount of epoxy applied to the specimen, concrete strength, and aggregate composition explained the differences between Group 1 and 2 CFRP Systems A and B. The difference in initial strength observed between Group 1 and Group 2 specimens CFRP System C was attributed to differences in the width of the CFRP laminate. Initial concrete specimen strength and CFRP width affect the final strength loss because a higher concrete strength or wider CFRP strip has a higher control value. A wider strip results in a higher initial flexural strength and increases the opportunity for a flexure-shear failure in the test specimen. The ¾ in. and 1 in. laminate strips were chosen to assess the occurrence of a concrete flexure-shear failure. The occurrence of concrete flexure-shear failures was low, so a 1 in. width was recommended in the test procedures. The test procedure included a tolerance on the CFRP width.

The flexural beam strength of the plain concrete prisms with the saw cut and without CFRP was approximately 20% of the control strength. In the flexural specimens, when the bonded CFRP failed, the load transferred to the concrete and the concrete failed in a brittle fashion. Consequently, once the strength of the CFRP composite specimen drops below the residual strength of the concrete, the CFRP was assumed to have reached zero strength. This was consistent with direct tension tests, where the direct tension test results indicated no remaining strength.



30°C=86°F; 40°C=104°F; 50°C=122°F; 60°C=140°F

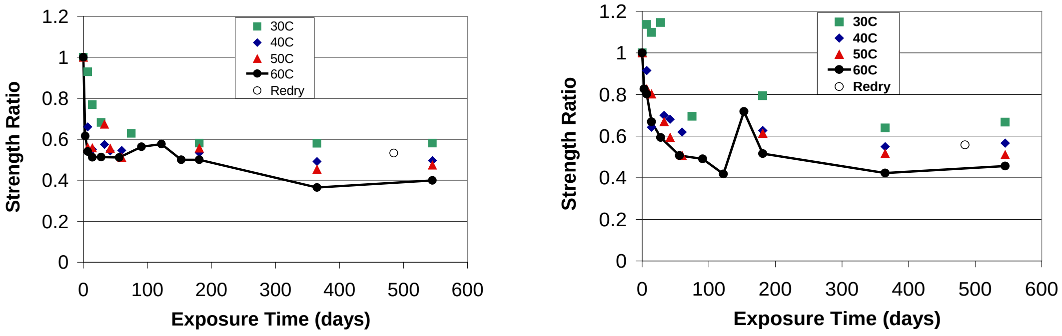
Figure 2. Summary of test results for all CFRP systems

WATER IMMERSION

Test results are given for Systems A, B, C, D and E specimens immersed in water for up to 18 months at 86°F, 104°F, 122°F and 140°F. System C specimens were tested at 6 and 12 months; none were tested at 18 months because of the near complete strength loss after 12 months. Systems D and E were tested at 6, 12, and 18 months. Group 1 did confirmation tests of System D at 9 months and Group 2 performed confirmation tests on Systems A and B. The inter-laboratory validation process expanded the research to include effects of different cements, aggregates, mixture designs and laboratory techniques.

System A

Flexure test results of System A in water immersion at 86°F, 104°F, 122°F and 140°F are shown in Figure 3. The strength ratio is defined as the flexural strength of an exposed specimen to that of the 28 day old control specimen.



a) flexural test results

b) direct tension test results

30°C=86°F; 40°C=104°F; 50°C=122°F; 60°C=140°F

Figure 3. Strength ratios for System A tests

Test results for 6 and 12 months indicate a loss of strength due to water immersion. The majority of the strength loss occurs within 14 days and further deterioration stabilizes for temperatures of 104°F, 122°F and 140°F out to 540 days. Higher strength ratios were observed in the Group 2 tests. These higher results were attributed to higher epoxy coverage and the optional UV coating used in Group 2 specimens.

Lefebvre et al. (1991); Toutanji (1999); and Abanilla et al. (2005) reported similar results and suggest this loss can be partially recovered after drying. To evaluate the effect of drying, five System A specimens were removed from the 140°F water bath tanks after 16 months, placed in a dry environment for 2 months then tested. The open circle symbols in Figure 3 represent the drying test results.

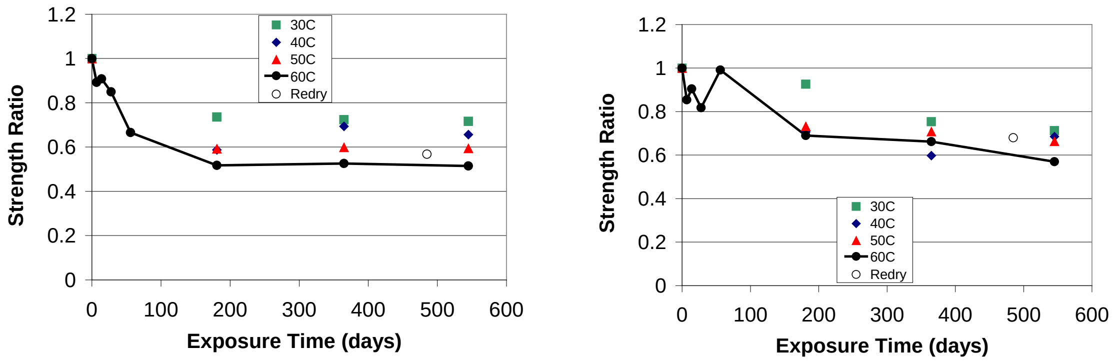
The following observations are based on the System A test results.

- The flexural strength decreases rapidly in the first 14 days and slowly afterwards.
- The strength of CFRP specimens immersed in water at different temperatures stabilized after approximately two months. The flexural strength of specimens submerged in 86, 104, and 122°F water baths for 18 months had no further loss than the 12-month test results.
- The failure modes changed from substrate failure in the control specimen to mixed mode failure after 14 days, to adhesive failure; after 60 days.
- The re-dried specimens showed a 13% flexural strength recovery compared to specimens after 18 months of continuous immersion at 140°F.
- There was a different lower bond strength loss for each exposure temperature.
- The direct tension results showed a strength increase in the first 30-60 days, and then had a strength loss similar to the flexure test results.
- Test results at 140°F for 60 days were representative of long-term test results at lower temperatures and were slightly lower than the long-term 86°F results.

System B

Test results of System B after 18 months of different elevated temperature water immersions are shown in Figure 4. No additional strength loss was noted at 6 months, 12 months and 18 months for 86°F, 122°F and 140°F. The strength ratio of 0.5 to 0.7 at 18 months was consistent in both the Group 1 and Group 2 data.

Five System B specimens were removed from the 140°F water after 16 months, placed in a dry environment for 2 months, and then tested. The results are given as the open circle in Figure 4.



a) flexural test results b) direct tension test results

30°C=86°F; 40°C=104°F; 50°C=122°F; 60°C=140°F

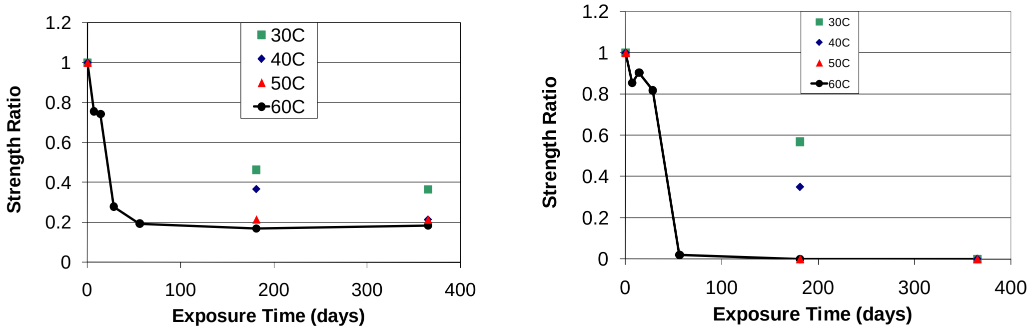
Figure 4. Strength ratios for System B tests

The following observations were based on the System B tests.

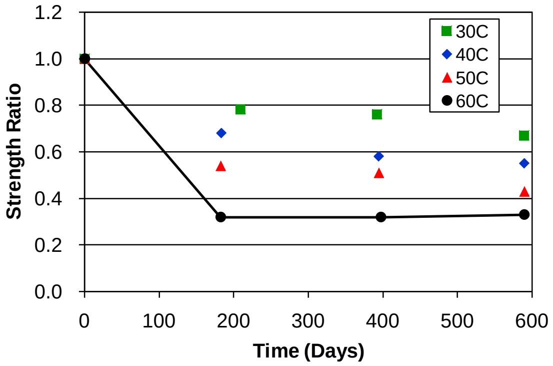
- The flexural strength decreased as the exposure temperature increases and each temperature has its own lower bound.
- No appreciable change in flexural strength occurred after six months of exposure for all temperatures.
- The flexural strength increased by 5% after drying.
- The direct tension results show higher strength ratios in the first 30-60 days, and then deteriorated toward the flexure test results.
- The strength ratio for 60 days at 140°F was lower than long-term test results at lower temperatures.

System C

System C flexural test results for water immersion are shown in Figure 5. System C lost all strength after 12 months and a visible CFRP material delamination and laminate expansion occurred. Testing at 18 months was terminated.



a) flexural test results (Group 1) b) direct tension test (Group 1)



c) flexural test results (Group 2)

30°C=86°F; 40°C=104°F; 50°C=122°F; 60°C=140°F

Figure 5. Strength ratios for System C tests

System C specimens exhibited substantial strength loss at 6 and 12 months for both flexural and direct tension tests exposed to all temperatures. Specimens exposed to 122°F and 140°F provided no additional strength to the plain concrete and therefore were recorded as having 100% strength loss. The Group 2 strength ratios were slightly higher than Group 1 at 86°F, 104°F and 122°F.

All specimens displayed nearly complete strength loss and composite delamination. One test series was conducted for 60 days at 140°F with all edges of the CFRP laminate sealed with epoxy to evaluate whether wicking of water along the carbon fibers contributed to the strength loss. The results were the same as the unsealed specimens.

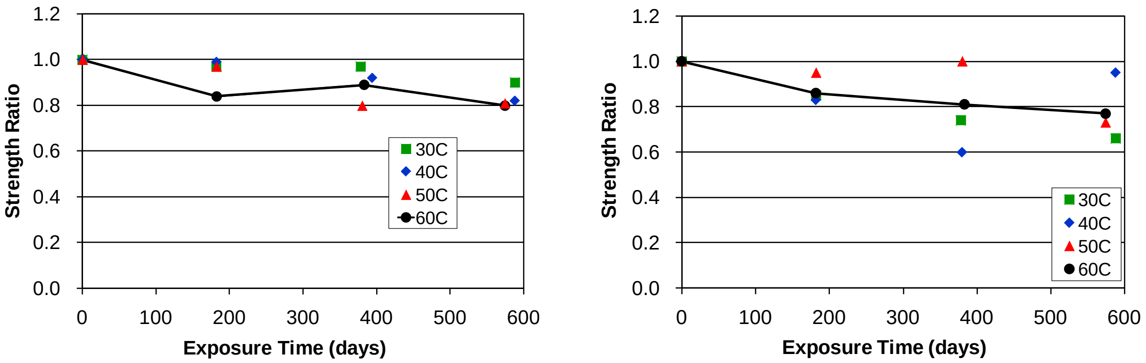
The results of the System C tests were:

- Immersion in elevated temperature water resulted in complete strength loss.

- The flexural strength loss rate increased with an increase in water temperature.
- Eighty to one hundred percent strength loss occurred after submersion in 140°F water for 28 days.
- Sealed specimens had strength loss comparable to unsealed specimens indicating that wicking along the laminate was not a source of premature failure.
- Test results at 140°F for 60 days were representative of long-term test results at lower temperatures.

System D

Test results for System D beam indicated flexural strength ratios above 0.80 for all temperatures when submerged for 6, 12 and 18 months, Figure 6. The Group 1 comparison specimens submerged in 140°F water have a strength ratio of 0.76 at 9 months. The failure mode of System D specimens was consistently adhesive.



a) flexural test results b) direct tension test

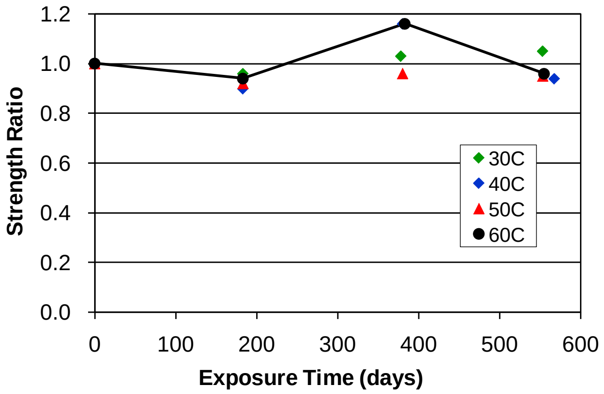
30°C=86°F; 40°C=104°F; 50°C=122°F; 60°C=140°F

Figure 6. Strength ratios for System D tests

System E

Test results for System E exhibited strength ratios above 0.80 after submersion at elevated temperature for up to 600 days, Figure 7. The strength ratio was greater than 1 after 12 months at 104°F and 140°F. Epoxy coupon testing indicated that the increase in strength of epoxy resin at elevated temperature was due to reactivation of amine, the curing agent. After 18 months of exposure, the strength ratios were 1.05, 0.94, 0.95 and 0.96 at 86°F, 104°F, 122°F and 140°F, respectively.

The failure mode in System E specimens was consistently adhesive, with a few mixed mode failures.



30°C=86°F; 40°C=104°F; 50°C=122°F; 60°C=140°F

Figure 7. Strength ratios for System E tests

OTHER TESTS

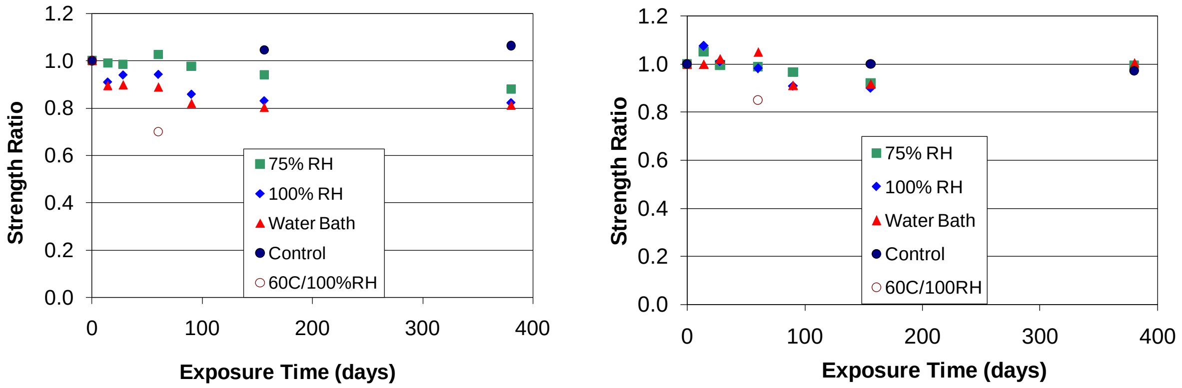
In addition to submersion tests, alternative conditions were investigated for Composite Systems A, B and C. These exposures were:

- Relative humidity (RH) exposure;
- Wet/dry exposure;
- Sustained load;
- Ultraviolet radiation;
- Alkaline exposure;
- Chloride exposure;
- Fatigue loading;
- Pressurized hygrothermal;
- Solar exposure; and
- Tidal exposure.

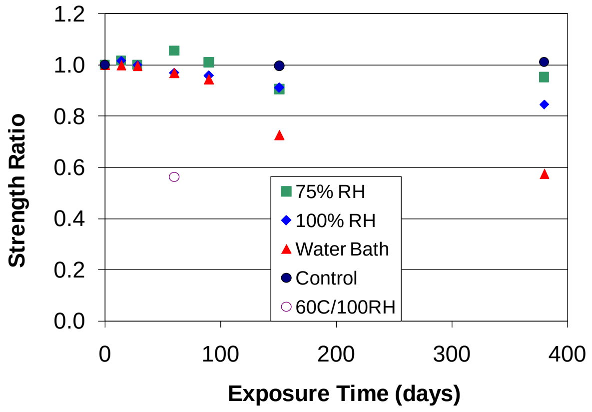
Different levels of RH exposure

Tests were conducted at 75 and 100% RH, at room temperature water bath, and at 100% RH at 140°F for Systems A, B and C, Figure 8. The maximum strength loss occurred in the 100%

RH specimens at 140°F. For room temperature exposure conditions, the maximum strength loss was in the submerged specimens. The strength loss generally increased with time.



(a) System A **(b) System B**



(c) System C

30°C=86°F; 40°C=104°F; 50°C=122°F; 60°C=140°F

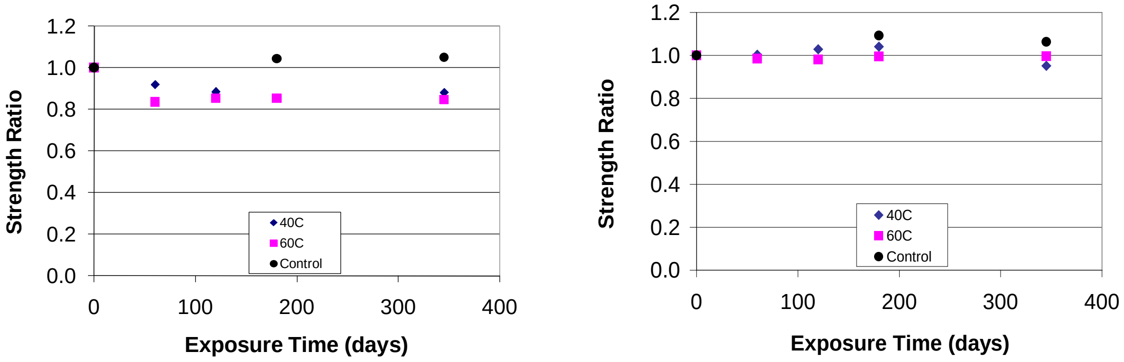
Figure 8. Strength ratios for different RH levels

Wet-Dry specimens

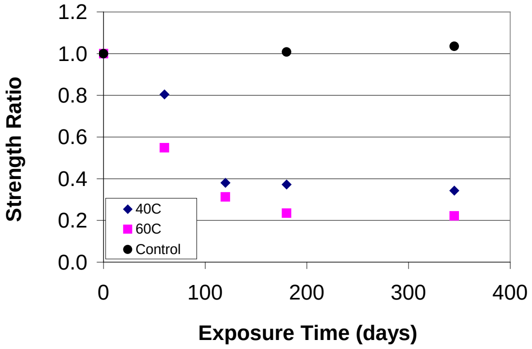
System A, B and C tests were conducted for 11.5 months at intermittent wet/dry cycles, 30°C=86°F; 40°C=104°F; 50°C=122°F; 60°C=140°F

Figure 9. Each wet/dry cycle consisted of two days submersion and 5 days in 68°Fair. The control specimens gained 5% strength over the exposure period, Figure 10. Systems A and C exhibited strength reduction with increasing temperature and exposure time. Very little

strength reduction was observed for System B. For Systems A and B, the failure modes were mixed mode. System C failure modes began as mixed mode failure and transitioned to adhesive or delamination failure modes. System C experienced nearly complete strength loss under wet/dry exposure. In general, intermittent wet/dry exposure was more moderate than full immersion in elevated water conditions for CFRP systems.



(a) System A **(b) System B**



(c) System C

30°C=86°F; 40°C=104°F; 50°C=122°F; 60°C=140°F

Figure 9. Strength ratios for wet/dry intermittent exposure

Sustained load

Systems A, B, and C were subjected to a continuous sustained flexural load of 50% of the control strength and submerged in 122°F water. Within two weeks of initial submersion at least one specimen in each frame had failed. All specimens had failed within 60 days. The failure mode was the same as the 122°F water immersion test results for each system.

Ultraviolet Radiation, Alkali Exposure and Chloride Exposure

Systems A, B, and C were exposed to chloride solution (TC) at 122°F, alkali solution (TA) at 122°F, and UV light cycled (UV) with water immersion in 122°F water over a 12-month period. All specimens included UV coatings. After 12 months, Systems A, B, and C specimens were removed from the tanks and tested.

The strength ratio for a 12-month test of System A in thermal chloride exposure (TC) at 122°F, thermal alkali exposure (TA) at 122°F, and UV light exposure cycled with water immersion at 122°F temperature (UV) is shown in Figure 10. The flexural strength ratio ranged from 0.84 to 0.81 after exposure to TC, TA, or UV. The flexural strength ratios were slightly higher than the strength ratio after water exposure at 140°F over a 6 month period, which was 0.76. The failure mode in System A specimens was consistently adhesive, except for a few specimens in thermal chloride exposure that had mixed mode failure.

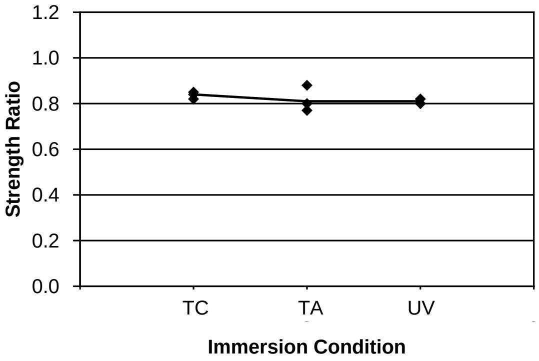


Figure 10. Strength ratios for System A after 12 months exposure to chlorides, alkali and UV at 122°F

System B showed a lower strength after 12 months of exposure to TA, TC or UV than Specimen A, Figure 11. Flexural strength decreased 40%, 49% and 32% with TC, TA, and UV exposure, respectively. System B control specimens had substrate failure modes, the exposed specimens had mixed mode failures, the same as were observed after 6 months of water exposure.

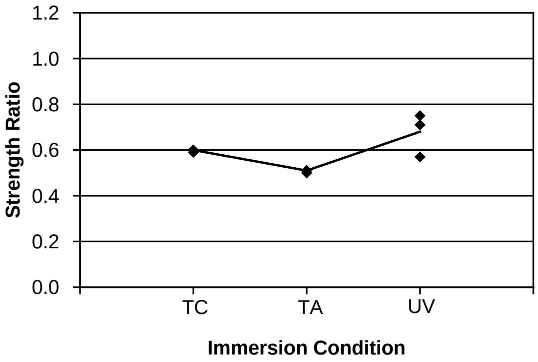


Figure 11. Strength ratios for System B after 12 months exposure to chlorides, alkali and UV at 122°F

System C test results had strength ratios of 0.29 for TC, 0.37 for TA, and 0.46 for UV exposures, Figure 12.

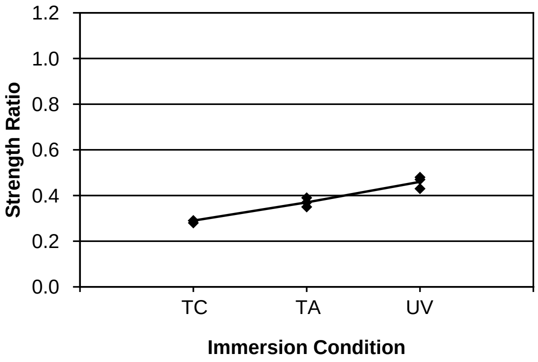
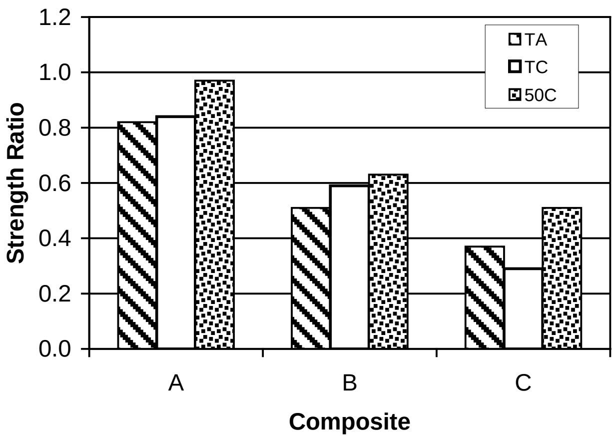


Figure 12. Strength ratios for System C after 12 months exposure to chlorides, alkali and UV at 122°F

Test results of 12-month exposure to the chemical solution were compared to specimens submerged in water at 122°Ffor 18 months are shown in Figure 13. The results indicated that the chemical solutions were more severe than water only. Composites A and B appeared to be affected more by the alkaline environment than that of the chloride solution. Conversely, composite C was affected more by the chloride solution. There did not appear to be sufficient difference in performance to warrant routine use of the chemical solution testing.



Note: System A tests results in water were for 12 months
50°C=122°F

Figure 13. Comparison of effects of chemical solutions to water

Fatigue

Three sets of specimens were tested to evaluate the effects of fatigue and exposure:

- Control specimens: no fatigue loading, no exposure;
- Unconditioned specimens: no water immersion followed by fatigue loading; and,
- Water conditioned specimens: exposure followed by fatigue loading.

System A, B and C specimens were conditioned by placing them in water baths for sufficient time to obtain a 10 percent strength reduction. Unconditioned specimens were loaded to 50% of the control strength for 2,000,000 cycles then tested for residual flexural strength. System B and C conditioned specimens were loaded to 45% of the control strength for 2,000,000 cycles. The conditioned CFRP System A specimens were loaded to 380,000 cycles at which time the displacement limits of the test machine were exceeded. Test results of CFRP Composite A, B and C Systems are shown in Figure 14 and were in agreement with other investigators referenced in Chapter 2.

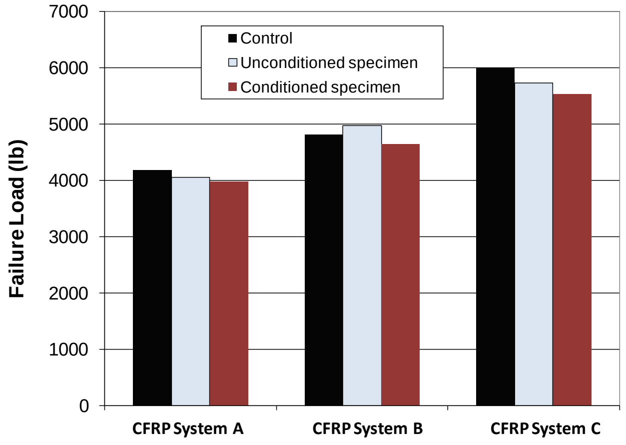


Figure 14. Failure loads for fatigue loading

Fatigue test results for System A, B and C were:

- Unconditioned CFRP Systems A, B and C showed no flexural strength loss after 2,000,000 cycles.
- After exposure to different temperature and periods of water baths to obtain a 10% reduction of ultimate strength, CFRP Systems B and C showed no further flexural strength loss after 2,000,000 cycles.
- Conditioned CFRP System A Specimens were subjected to 380,000 cycles because the deflections exceeded the limit of the servo-controlled test machine. The specimens were then tested to failure and no further flexural strength loss was observed.

Pressurized hygrothermal (pressure vessel) accelerated tests

The pressure vessel test provides a 100% RH environment at three atmospheres to accelerate the migration of water into the specimen. The flexural test results of CFRP Composite A, B and C Systems after 7, 10, and 14 days of pressure vessel exposure are shown in Figure 15.

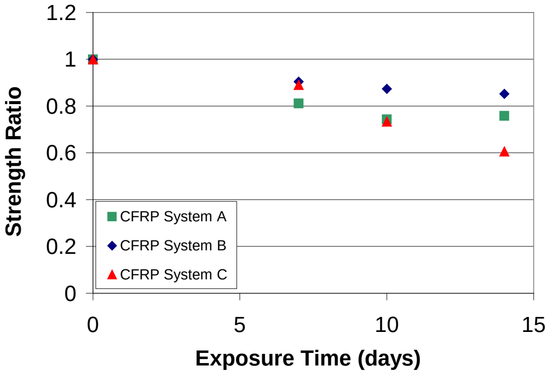


Figure 15. Strength ratio for pressurized hygrothermal exposure results

The test results from CFRP System A, B and C subjected to pressure vessel exposure indicated the following:

- CFRP Composite System A experienced a flexural strength loss of 20% and specimens exhibited a mixed mode failure after 7 days, a 26% flexural strength loss and mixed mode failure after 10 days, and a 24% flexural strength loss and mixed mode failure after 14 days of exposure.
- For CFRP Composite System B, the flexural strength loss was 10% and specimens had mixed mode failure after 7 days. A 13% flexural strength loss and mixed mode failure occurred after 10 days, and a 15% flexural strength loss and mixed mode failure after 14 days of exposure.
- For CFRP Composite System C, the flexural strength loss was 11% and specimens had mixed mode failure after 7 days. A 27% flexural strength loss and mixed mode failure occurred after 10 days, and a 39% flexural strength loss and mixed mode failure occurred after 14 days.

The test results of CFRP System A, B and C specimens indicated that the hygrothermal exposure at a pressure of 30 psi after 14 days shows promise of being able to differentiate the performance of CFRP systems. The 14-day pressure vessel tests correlate well with all Group 2 exposure tests except CFRP System C. The 14-day test suggests further development is warranted.

Solar exposure

Solar exposure is a real time environment that combines UV, moisture variation and ambient freeze-thaw cycles present at 7200 ft. The flexural test results of CFRP Composite A, B and C Systems after 18 months are shown in Figure 16.

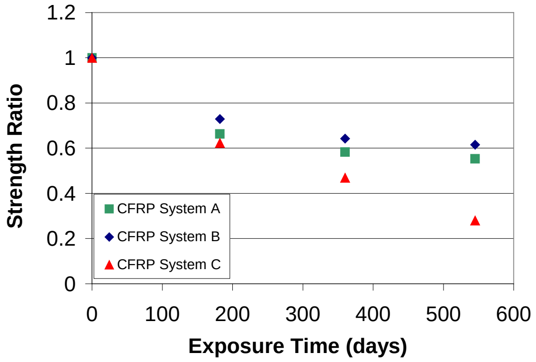


Figure 16. Strength ratios for solar exposure

The test results from CFRP System A, B and C solar exposure indicated the following:

- System A flexural strength decreases sharply in the first 200 days. The specimens failed by a mixed mode failure after 6 months and adhesive failure after 12 months.
- System B flexural strength decreased sharply in the 200 days. The flexural bond strength degraded up to 28% and specimens failed by a mixed mode failure after 6 months. At 12 months and beyond, the flexural strength tended to stabilize.
- System C flexural test results showed linear strength reduction with time. The specimens failed by mixed mode failure after 6 months. Adhesive failure mode occurred after 12 months, and CFRP laminate slip was observed after 18 months.

System A, B and C solar exposure resulted in strength loss. The System A losses compare to the 140°F, 60-day losses and were aggravated by the intentional omission of UV coatings and further influenced by thermal cyclic loading due to differences in the coefficient of thermal expansion (CTE) of the laminate, adhesive, and concrete. The diurnal temperature changes and the CTE differences result in a residual stress between CFRP and the concrete that may affect the bond strength.

Tidal exposure

Tidal specimens were exposed to a real-time wet-dry environment in Florida. Systems A, B, and C were tested after 12 and 18-month exposure. A buildup of barnacles was observed, which were removed before testing. Test results after 12 and 18 months of tidal exposure are shown in Figure 17.

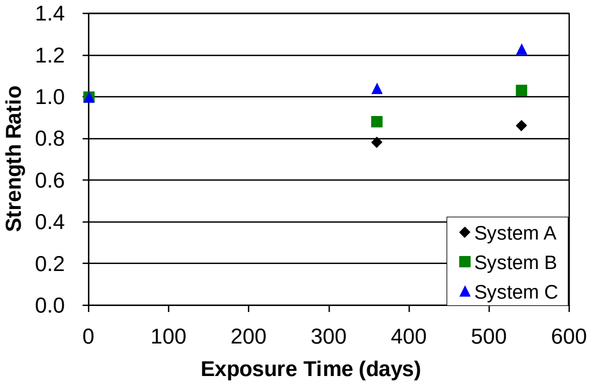


Figure 17. Strength ratios for tidal exposure

The strength ratio after 12 months of exposure of System A was 0.78. The initial drop in strength at 12 months was followed by a slight increase in strength to 0.86 at 18 months. This increase might be due to the buildup of barnacles and their associated marine adhesive, which protected specimens from deterioration and acted as additional adhesive or sealant (El-Hawary 2000). The failure mode for System A was consistently adhesive.

The reduction of the flexural strength in System B was 12% after 12 months. This was much less than the 58% strength reduction for continuous water exposure over a 6 month period at 140°F. Although the FRP composite reinforcement was oriented upward, the specimens were protected from direct sunlight for most of the daylight hours by the fender system. This prevented direct UV exposure and large temperature swings from solar heating. Since System B was affected by temperature, it was postulated that System B was not affected in the Tidal environment by the sea water because of the protection provided by the fender.

The initial drop in the failure strength of System B after 12 months was followed by an increase in strength to 1.04 after 18 months. The loss in strength for System B after 6 months of water exposure at elevated temperature was associated with a change to an adhesive failure mode.

The relatively small loss in strength and lack of change in failure mode for tidal exposure indicated that the specimens had not experienced severe strength loss.

System C showed little effect from the tidal exposure to sea water and seemed to behave more consistently over time than Systems A and B. After 12 months, the loss in strength of one specimen was 12% and the residual strength of the other two specimens was higher than that of the control specimen. After 18 months, the strength ratio increased further to 1.23, which may be due to the buildup of barnacles. System C specimens degraded severely after immersion in water at elevated temperatures. Thus, it was possible that the relatively cool sea water (less than room temperature) did not cause degradation of System C. The fact that failure mode of the room and elevated temperature submerged specimens was delamination but the failure mode of the tidal specimens was adhesive supports this assertion.

The 18-month strength ratio of concrete beams without CFRP was an average of 1.01. The plain concrete specimen with barnacles exhibited a higher flexural strength than plain concrete suggesting that all strength losses were in the CFRP system.

Epoxy coverage

A study was performed to evaluate the relationship between durability and epoxy coverage for 80%, 100% and 200% of the manufacturers' recommended coverage rates for System A. The manufacturers' recommended epoxy coverage assumes using 100% of the epoxy on a large area. Laboratory specimens use small amounts of epoxy and total coverage was influenced by the amount of epoxy mixed, left in the roller, left in the mixing cups and spread to the side of the CFRP. For this test, coverage was determined by two methods: 1) weighing all instruments and epoxy prior to application and again after applying epoxy, and 2) weighing the beam and CFRP without epoxy and weighing after applying epoxy. Both methods yielded similar results.

The test results showed that strength ratio remains at 1.0 for unexposed specimens, indicating that coverage does not affect control strength. The strength ratio for 80% coverage at 140°F for 60 days was approximately 0.25. The strength ratio for 100% coverage averages 0.65 and for 200% coverage averages 82%. Strength ratio variation with respect to coverage suggested epoxy coverage was critical to durability. The testing procedure in Attachment B provides recommendations for epoxy preparation to be consistent with the manufacturer's recommendations.

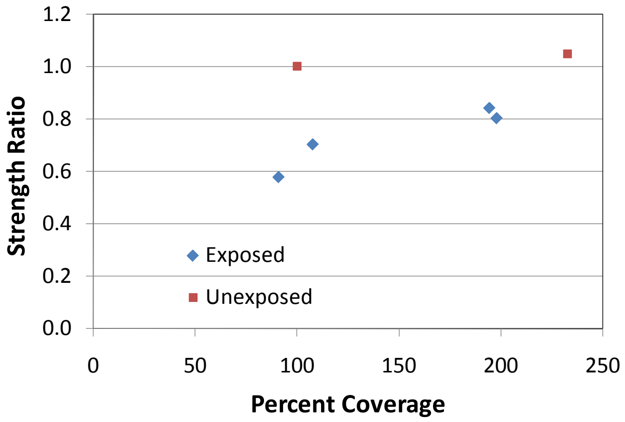


Figure 18. Strength ratio for different epoxy coverage

Concrete strength

Control specimens exhibited substrate failure. Therefore, the strength of the control was influenced by the strength of the concrete, which in turn, influenced the strength ratio. Comparison of test results using different concrete mixtures indicated that epoxy coverage and width of the CFRP were far more critical to establishing the control strength than the base concrete strength.

GENERAL TEST OBSERVATIONS

Test results indicated that the recommended test procedures and specimens were capable of differentiating CFRP durability performance. Furthermore, Figure 3 and Figure 4 indicated that the flexural test specimen was more consistent in predicting the strength ratio during the first 60 days. The strength ratios of Systems A, B and C indicated a substantial loss of strength. Comparison of the strength ratios for Systems D and E with Systems A, B, and C suggested that more durable epoxy formulations are available.

The test program further confirmed the findings in the literature that individual epoxy systems have highly varied durability characteristics. The variability is seen in these tests and is observed in the following sections.

Comments on System A

The strength reduction for System A in the Group 1 submerged tests and solar exposure tests were considerably greater than the comparator tests of Group 2 and the pressure vessel tests. After evaluating the data, there appeared to be two possible explanations. The improved performance measured for Group 2 specimens may be due, in part, to the UV coating that was added to those specimens as part of the comparator studies. A consequence of this difference was the recommendation that UV coating be used in all applications.

The second factor was the quantity of epoxy coverage. Multiple checks of the quantity of epoxy used in Group 1 specimens indicated that the first set of test specimens was prepared at the manufacturer's minimum recommended coverage. Subsequent sets of specimens had increased the epoxy quantity. The manufacturer's literature provides recommended coverage, thus use of more or less epoxy was permissible. When the first set of specimens was adjusted to account for later higher coverage, the strength ratios generally agree with Group 2. These results suggested epoxy coverage rate has an impact on durable performance. Field epoxy coverage rates must be comparable to the coverage rates use in the tests to assure comparable results.

Comments on System B

The System B strength ratio was nearly constant at 6, 12 and 18 months for each of the 86°F, 122°F and 140°F tests. The final strength ratio of 0.5 to 0.7 was consistent for both the Group 1 and Group 2 data.

Comments on System C

System C specimens showed severe deterioration when submerged in 104°F, 122°F and 140°F water. System C specimens placed in the tidal zone in Florida displayed an increase in strength. Marine growth by itself does not seem to be the sole cause of the strength gain because the failure mode resulted from delamination of the pre-cured laminate. Other factors that may have contributed to the difference in strength between the laboratory-stored and tidal specimens and the field exposure were the wet/dry cycling and exposure temperature. The Group 1 wet/dry exposure results were conducted at 104°F and 140°F and had strength reduction similar to the Group 2 submerged specimens. The control specimen had strength gains comparable to the

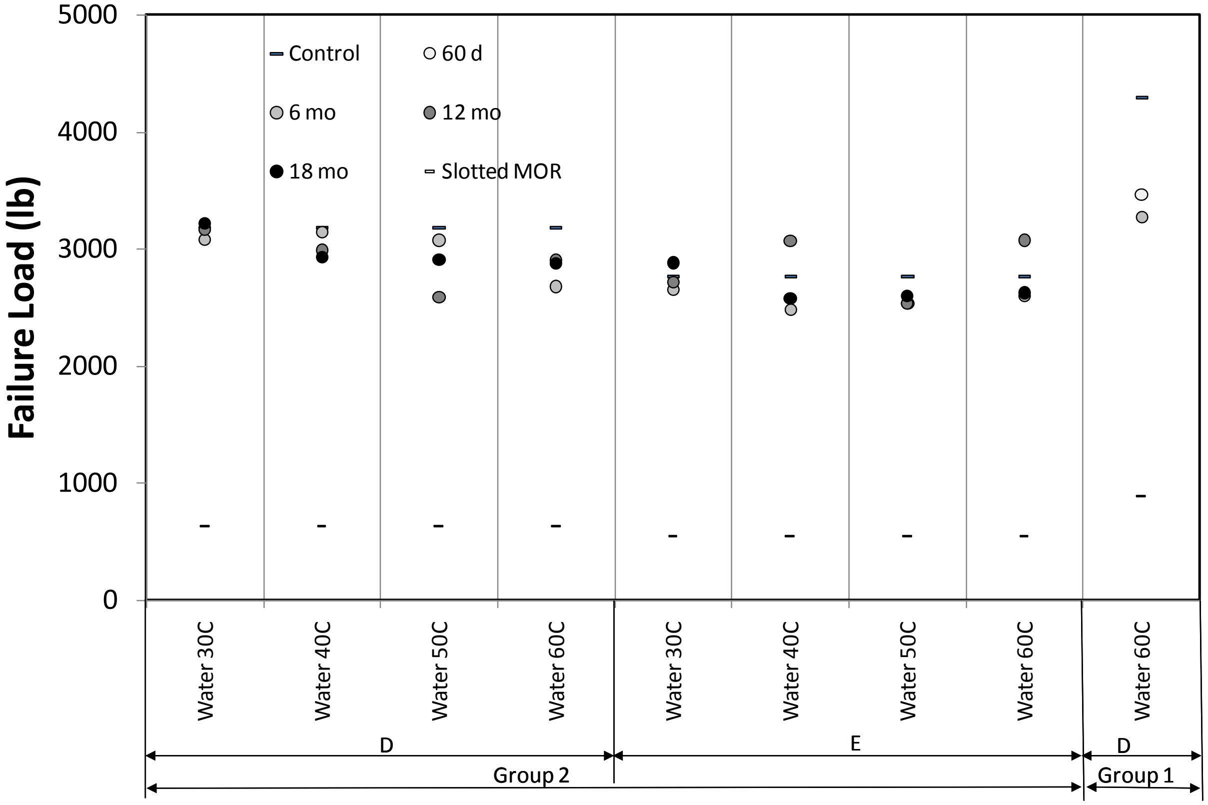
Group 2 tidal specimens. This leads to the possible explanation that the pre-cured laminate was particularly sensitive to water submersion at elevated temperature.

Although the test methodology identified a potential defect in the material; the durability strength reduction factor for this system may be overly conservative. Relative humidity exposure may be more appropriate, but does not yet ensure consistently conservative results.

Comments on Systems D and E

Group 2 System D 18-month exposure specimens had flexural strength failure loads between 0.8 and 0.85 of the control for submersion in water at 122°F and 140°F.

Figure 19. Group 1 specimens had a flexural strength of 0.75 at 140°F. The strength reduction factors for System E were greater than 90%.



30°C=86°F; 40°C=104°F; 50°C=122°F; 60°C=140°F

Figure 19. Summary of Epoxy Systems D and E

5. RELATIONSHIP BETWEEN TESTS AND DURABILITY

The definition of a durability strength reduction factor and supporting test procedures partially address evaluating of CFRP durability. They provided lower bound durability strength but not a prediction of remaining service life. The Arrhenius equation was proposed as a tool to provide the correlation between accelerated exposure tests and strength loss at any time during the service life of in-field structures. The equation failed to accomplish this objective for two reasons; the time needed for deterioration and the non-uniform durability behavior. The submerged specimen strength loss at room temperature occurred in less than 8 weeks. Because water can migrate to the bond surface through the concrete adjacent to the CFRP, a field application in a Wet environment (water accumulates on the bond surface) could also reach the lower strength ratio in about 8 weeks. Thus, in a worst case condition, the 8 week period could occur any time in the life of the structure and prediction of an alternative service life was meaningless. Second, the Arrhenius equation assumes continuous degradation behavior and no change in degradation mechanism throughout the exposure period. The multiple pathways for moisture migration, through the concrete, the epoxy or the CFRP, may occur at different times during exposure, resulting in a variation in the mechanism by which moisture diffuses into the specimen. The assumptions underlying the equation proved to be inconsistent for this application. Thus, there was no meaningful correlation between the accelerated tests and the time to deterioration in a “real” structure.

These tests indicated that exposure condition, not time, was the critical variable. The lower bound of strength reduction factor, based on the appropriate exposure condition, is recommended for use in design. This value assures that the strength of the CFRP repair is valid for the service life of a structure. Test results for exposure at 140°F for 60 days were comparable to long-term exposure at 86°F and 104°F.

VALIDITY OF RECOMMENDED TEST PROCEDURE OUTPUT

The recommended test procedure provided a durability strength reduction factor for any CFRP system. Tests on all CFRP systems evaluated in this research had strength reduction factors for submerged exposure for 60 days and 140°F that were lower than the strength reduction factor for comparable specimens exposed to Solar or Tidal conditions for 18 months or for specimens submerged at room temperature for up to 12 months. The elevated temperature compensated for the longer exposure time in both cases; however, the direct correlation of elevated temperature is, as yet, undefined.

Exposure to 100% relative humidity at 140°F resulted in durability strength reduction factors higher than those for submerged exposure at room temperature and is recommended as representative of a structure in Air. As a demonstration of the procedures, the durability reduction factors for Systems A, B and C for two exposures is given in Table 3. With nearly a 50% difference in durability strength reduction factor between the two environments, the selection of an exposure environment has both technical and economic ramifications.

Table 3. Comparison of durability strength reduction factors for a 60-day/140°F exposure

CFRP System	Durability Strength Reduction Factor for Wet Environment	Durability Strength Reduction Factor for Air Environment
A	0.50	0.70
B	0.65	0.85
C	0.0	0.55

System C failed when the CFRP laminate degraded completely in the heated-Wet (submerged) environment. The tests were confirmed on different batches of CFRP laminate, different environments and different laboratories. Long-term use of this system in a Wet environment with elevated temperature is not recommended.

SELECTION OF FIELD ENVIRONMENT AND COVERAGE RATES

The beginning of this Chapter points out that there was no correlation between accelerated aging and structure life at this time. Consequently, it is recommended that a field environment be defined to address durability behavior of CFRP systems. The Wet environment is applicable for any structure where water can accumulate on the bond surface. Test specimens indicated durability strength reduction occurs in less than two weeks. Because water migrates through the concrete faster than through the CFRP this classification extends to any structure in direct contact with the ground, such as foundations, cut-and-cover structures, and retaining walls. For safety, the Wet exposure condition is the default and applies to soffits of beams and slabs with low clearance over water splash zones and soffits of bridge decks when the deck is frequently wetted.

The Air environment applies to applications where water does not accumulate on the bond surface. Specimens in the tidal exposure exhibited no strength loss after 12 months. This suggests that the marine encrustations, drying time compared to wetting time, and lower water temperature, successfully compensated for the wetting effects. Six month exposure tests at less than 100% RH exhibited less strength loss than the 100% relative humidity exposure. These tests further confirmed that the 100% RH at 140°F represented a lower bound loss. The exception to this was the solar specimens, which exhibited large strength loss after an 18-month exposure. The strength loss in the solar specimens was attributed to the lack of a UV protection coating; therefore, they were not fully representative of a proper field application. The performance of the solar exposure specimens reinforced the recommendation that all applications include a UV coating.

EPOXY COVERAGE RATE AND DURABILITY

Correlation of laboratory epoxy application and field epoxy coverage rates is a critical issue. Durable performance was sensitive to the epoxy coverage, especially the first coat that was applied to the concrete. Changes in coverage rates had no appreciable effect on the control specimen flexural strength but had an effect on the exposed specimens. Coverage less than the manufacturer’s recommendations resulted in accelerated deterioration of the CFRP system compared to systems with the specified coverage. The specimen preparation procedures in Attachment B specifically address application rates that would be used in the lab. Epoxy applied on the test specimen in excess of that used in the field will result in a higher than actual, or unconservative, durability strength reduction factor.

Correlation of lab epoxy coverage and field coverage is complicated by the installation procedure. Lab specimens are made with the CFRP facing up. Therefore, gravity assists in retaining the wet epoxy on the surface. Field applications are typically on the soffit of the structure so the total amount of epoxy that can be absorbed by the concrete may be less. Engineers will want to consider this when specifying the epoxy coverage as recommended in Attachment B.

6. CONCLUSIONS AND RECOMMENDATIONS

Field durability degradation of CFRP bonded to concrete beams is defined by selection of an installation environment and comparison of the durability strength reduction factor, established by test, for the CFRP contribution. The test procedures recommended in this report provide the data necessary to compute the durability strength reduction factor. The elevated temperature used in the test procedures results in test specimen deterioration that is slightly greater than the strength reduction observed at temperatures close to nominal operating conditions. All accelerated and real-time tests reached final strength reduction factors in a time-span on the order of weeks. This rate of the strength deterioration made service life predictions of CFRP repairs unnecessary because the applications reached their reduced strength well within any reasonable service life of the structure. Selection of an application environment is a more important indicator or performance than attempting to predict a time for deterioration.

EVALUATION AND USE OF DURABILITY STRENGTH REDUCTION FACTORS

1. Test procedures and computation of durability strength reduction factor, ϕ_d

The test procedure consists of five standard specimens exposed to either a Wet or Air environment plus five control specimens. The exposed specimens are conditioned for 60 days at 140°F by either immersion in water for a Wet environment or in 100% relative humidity at 140°F for an Air environment. They are then removed from their exposure chamber, placed in a room temperature bath for one day, removed from the room temperature bath, and then allowed to dry for at least 2 hours before testing. Specimens are tested in flexure on a 12-in. span in three-point bending. The flexural failure loads are reported and are used to compute the strength reduction factor. Details of the recommended test procedures and epoxy preparation procedures are given in Attachments A and B and also address recommended coverage rates.

The recommended standard test specimen for the establishment of a durability strength reduction factor is a 4-in. x 4-in. x 14-in. concrete beam. This specimen provided more consistent test results than a direct tension test. The tension side of the specimen has a 2-in. deep saw cut perpendicular to the beam at mid-span to simulate a crack in the structure. The specimen is strengthened with a 1-in. wide x 8-in. long CFRP fabric strip or laminate centered on the saw cut in accordance with NCHRP Report 514. The test specification is described in detail in Attachment A.

The durability strength reduction factor, ϕ_d, is the ratio of the flexural strength of exposed test specimens to the flexural strength of control specimens cured at ambient room conditions. Specimens conditioned by submersion in water for 60 days at 140°F provide the reduction factor for Wet environments. Specimens conditioned for 60 days in a 100% humidity environment at 140°F provide the reduction factor for Air environments.

The reduction factors are applicable to the CFRP system tested and to the environment corresponding to the exposure: Wet or Air (submerged or 100% relative humidity). In addition, the reduction factors have three caveats. The factors are applicable if:

- the epoxy coverage rate in the field is equal to or greater than that used in the test,
- the CFRP is protected from ultraviolet exposure , and
- the concrete strength used in the test specimens corresponds to the field concrete strength.

Specimens exposed to sustained loads greater than 50% of the CFRP capacity and immersed in water failed within two weeks. Therefore, use of bonded CFRP for sustained loading in Wet environments is not recommended. Each CFRP system tested in this program had a different durability response. Therefore, until a scientifically based model of adhesive deterioration is defined, experimental validation is the only acceptable method to determine the strength reduction factor.

2. Selection of a field application environment

The selection of a design environment for field applications recognizes that bonded CFRP systems are sensitive to water and that deterioration can occur after a short exposure time. Water migration to the bond surface from either the CFRP or the concrete side of the structure results in deterioration. Two design environments are suggested: Wet and Air. The default design environment is a Wet environment. A Wet environment is characterized by an installation that has extensive exposure to water and where water can accumulate on the bond surface (the interface between the epoxy and the concrete). Examples would be bridge beams and decks that are regularly wetted for extended periods, extensive exposure to precipitation and 100% RH, beams with low clearance over water, or beams in splash zones. The alternative Air environment is for structures that have intermittent exposure to water or precipitation that has time to dry between exposures so the water does not accumulate at the bond surface. If an Air environment is selected, the Wet environment test is recommended to allow engineer to compare the relative strength performance associated with both environmental exposures.

3. Application of the durability strength reduction factor

The durability strength reduction factor is applied to all strength calculations involving the strength of bonded CFRP systems where the strength of the CFRP and epoxy is integral to the performance of the member. The factor is a multiplier and is used in addition to the resistance factors defined in the AASHTO Bridge Design Specification (AASHTO 2008).

QUALITY OF ADHESIVE BONDING MATERIALS

At the initiation of this research, the research team assumed that the deterioration of epoxy bonding materials would be slower than was found in the experimental program. The strength losses reported in journal articles cited in Chapter 2, and the time to the stabilized loss were consistent with this report. In short, the epoxies used today were adequate for control and nominally dry applications. They were at risk for deterioration in continuously damp or wet environments. The test procedures in this report allow an assessment of any proposed CFRP system and allow system suppliers to evaluate and improve products for field application. Custom epoxies developed for and tested in this program had higher strength reduction ratios than commercially available adhesives. This response suggested that improvements in the durability of bonded CFRP systems are possible and cost effective.

RECOMMENDED FUTURE WORK

The recommendations in this report provide a methodology to evaluate durability of CFRP bonded repair and strengthening of concrete beams. The following research is suggested to substantially expand the understanding and performance of durability of bonded CFRP systems.

- A mechanical or chemical model that accurately defines the relationship of epoxy bonding to concrete and definition of the specifiable material properties for this behavior is needed to provide a functional predictive tool.

- The pressure vessel test procedure showed promise of more rapid test results and should be explored further. Test results suggest that strength reduction factors can be evaluated in approximately 2-4 weeks instead of 60 days.
- The intermittent wet-dry environment exposure procedures need long-term testing to establish their effectiveness in modeling Air environments. The full effect of wetting and drying exposure was not fully defined nor was the potential strength recovery. The ratio and time of exposure of the wet/dry cycle times appeared to be crucial to correlation with field applications.
- The behavior of pre-cured laminates to wet environments and elevated temperature needs further refinement. The proposed test specification identified problems but did not provide insight to potential solutions.

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ATTACHMENT A – TEST METHOD FOR DETERMINATION OF DURABILITY STRENGTH REDUCTION FACTOR FOR CFRP BONDED SYSTEMS

PREFACE

This proposed test method is the recommendation of the NCHRP Project 12-73 researchers. The method has not been approved by NCHRP or any AASHTO community nor formally accepted for the AASHTO Specifications.

Scope

a. This test method covers the determination of the durability strength reduction of carbon fiber reinforced polymer (CFRP) composites bonded to concrete using a simply supported beam specimen subjected to a three-point loading.
b. The values stated in inch-pound units are to be regarded as the standard.
c. This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

Referenced Documents

AASHTO Standards:

T24-05 Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
T231-05 Practice for Capping Cylindrical Concrete Specimens
T67-05 Practices for Force Verification of Testing Machines

ASTM Standards:

C 192 Practice for Making and Curing Concrete Test Specimens in the Laboratory
C 1077 Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Laboratory Evaluation
D 4541 Standard Test Method for Pull-off Strength of Coatings Using Portable Adhesion Testers

Significance and Use

a. This test method shall be used to determine the durability strength reduction factor for CFRP bonded to the tensile face of plain concrete beam specimens. The concrete beams shall be prepared and cured in accordance with Test Methods C 192 or Practice C 42. The CFRP shall be prepared and cured in accordance with NCHRP Report 514 and the manufacturer’s specifications. The strength will vary where there are differences in specimen size, preparation, moisture condition, curing, or where the beam has been molded or sawed to size.

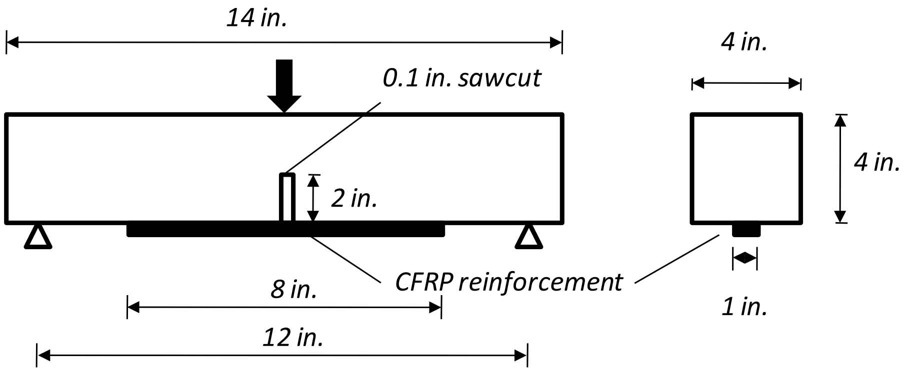
b. The results of this test method may be used to determine the durability strength reduction factor, for validating compliance with specifications, or as a basis for selection of a CFRP system.

Specimens

The beam specimen shall be a 4 in. x 4 in. x 14 in. long plain concrete beam with a 12 in. span length loaded at mid-span, Figure 20 below.

Note: A single reinforcing bar may be placed in the specimen to improve the specimen shear performance. Reinforcement is not required typically for concrete strength above 7000 psi, but may be needed for lower strength concrete. No reinforcement was included in the tests conducted in development of this specification. Any reinforcement must be cut at mid-span.

A 3 in. x 3 in. end patch of CFRP may be applied to one end of the specimen for evaluating direct tension adherence. Direct tension tests are not part of is standard.



NOTE: Specimen may be 15 in. long with 1-1/2 in. inset from each end to the centerline of the support.

Figure 20. Durability strength reduction test specimen

a. The test specimen concrete strength shall be either:
   - i. approximately the same as the proposed field application or,
   - ii. a range of strength from 4,500 psi to 10,500 psi in 2,000 psi increments.

b. Fabricate the test specimens in accordance with ASTM C 192

c. A minimum of 10 specimens shall be prepared for each concrete strength.

Note: Five specimens are used for the control strength and five for the deteriorated strength. If a decay curve is desired, five additional specimens are required for each intermediate point. Intermediate points are recommended at 7, 14 and 28 days.

d. Prepare three standard 4 in. x 8 in. or 6 in. x 12 in concrete cylinders at the same time as the beam specimens.

e. Cure the specimen for a minimum of 28 days prior to application of CFRP.

Specimen Preparation

a. The specimen shall be rotated 90 degrees so the hand finished surface shall be the beam side face.

   The specimen shall be saw cut at mid-span to a depth of 2 in. The width of the saw cut shall be approximately 0.1 in. and may be either a composite blade or a diamond blade. The saw cut side becomes the tension face of the specimen. One end of the specimen and the tension face are sandblasted to an ICRI profile minimum of 3.

b. Define the epoxy coverage rate in oz./sq. ft.

   Note: Epoxy coverage rate may be determined by the manufacturer's literature or preferably by test. The epoxy coverage used in the test must be specified as the minimum coverage for field applications.

c. A 1 in. ± 1/16 in. wide by 8 in. long wide strip of carbon fiber fabric laminate shall be applied to the tension surface of the specimen following *Specification for Mixing Epoxy for Laboratory Specimens*, the manufacturer's recommendations, and NCHRP Report 514.

   Note: Control specimens fail in the concrete substrate. An over width CFRP strip will raise the control strength and result in a lower durability strength reduction factor for the exposed specimens.

d. Center the carbon fiber on the saw cut.

e. Should the manufacturer's specification conflict with NCHRP Report 514, then NCHRP Report 514 shall be used.

f. An optional direct tension strength test patch 3.5 in. square shall be applied to the sand blasted end of the specimen following the manufacturer's recommendations and NCHRP Report 514.

   Note: If direct tension tests are not specified, this step may be omitted.

g. Cure the CFRP specimen at 68°F ± 4°F for 14 days.

Figure 21. Completed specimen with end patch

Environmental Conditioning

Specimens shall be conditioned for either control, wet or air environment.

a. Control specimens: Cure at 68°F in air.

b. Wet Environment Conditioning: Specimens shall be submerged in water in insulated chambers heated to 140°F ± 5°F for 60 days.

c. Air Environment Conditioning

Place specimens on non-absorbent shelves in the wet conditioning chamber so no part of the specimen shall be in direct contact with water to expose the specimen to 100% relative humidity. Cure specimens at 140°F for 60 days.

Preparation for Testing

a. Following the specified curing period, conditioned specimens shall be removed from the curing chambers and placed in a 68°F water bath for 24 hours.

b. Conditioned specimens shall be removed from the water bath and stored in air. Test within 2 to 4 hours after removal from 68°F water bath.

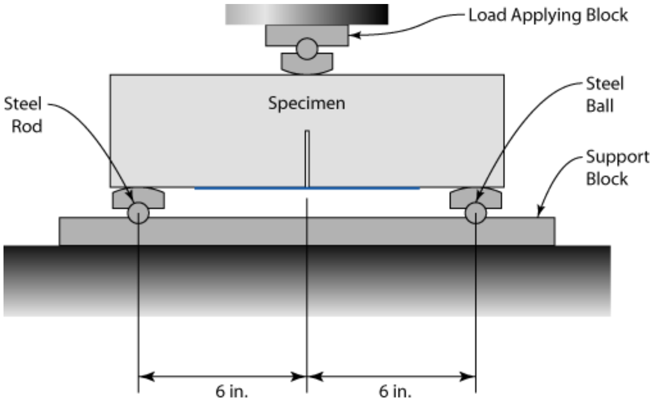
Flexural Test Apparatus

a. The testing machine shall conform to the requirements of the sections on Basis of Verification, Corrections, and Time Interval between Verifications of Practices E 4. Hand operated testing machines having pumps that do not provide a continuous loading in one stroke shall not be permitted. Motorized pumps or hand operated positive displacement pumps having sufficient volume in one continuous stroke to complete a test without requiring replenishment shall be permitted and shall be capable of applying loads at a uniform rate without shock or interruption.

b. Loading Apparatus-The three-point loading method shall be used. Flexure tests of concrete shall employ bearing blocks that ensure that forces applied to the beam will be perpendicular to the face of the specimen and applied without eccentricity. A diagram of an apparatus that accomplishes this purpose is shown in Figure 22.

c. All apparatus for making flexure tests of concrete shall be capable of maintaining the specified span length and distances between load-applying blocks and support blocks constant within ± 0.05 in.

d. If an apparatus similar to that illustrated in Figure 22 is used: the load-applying and support blocks shall not be more than 2½ in. high, measured from the center or the axis of pivot, and should extend entirely across or beyond the full width of the specimen. Each case-hardened bearing surface in contact with the specimen shall not depart from a plane by more than 0.002 in. and shall be a portion of a cylinder, the axis of which is coincidental with either the axis of the rod or center of the ball, whichever the block is pivoted upon. The angle subtended by the curved surface of each block should be at least 45 degrees (0.79 rad). The load-applying and support blocks shall be maintained in a vertical position and in contact with the rod or ball by means of spring-loaded screws that hold them in contact with the pivot rod or ball. The uppermost bearing plate and center point ball in Figure 22 may be omitted when a spherically seated bearing block is used, provided one rod and one ball are used as pivots for the upper load-applying blocks.



NOTE:-This apparatus may be used inverted. If the testing machine applies force through a spherically seated head, the center pivot may be omitted, provided one load-applying block pivots on a rod and the other on a ball.

Figure 22. Diagrammatic view of a suitable apparatus for flexure test of concrete by three-point loading method

Testing

a. Test reference cylinders concurrent with control specimens.

b. The test specimen shall conform to all requirements of Practice C 192 applicable to beam and prism specimens and shall have a test span within 2 % of being three times its depth as tested. The sides of the specimen shall be at right angles with the top and bottom. All surfaces shall be smooth and free of scars, indentations, holes, or inscribed identification marks.

c. The technician performing the flexural strength test shall be certified as an ACI Technician-Grade II, or by an equivalent written and performance test program.

NOTE:-The testing laboratory performing this test method may be evaluated in accordance with Practice C 1077.

d. Bring the load-applying blocks in contact with the surface of the specimen at the half point and apply a load of between 3 and 6 % of the estimated ultimate load. Using 0.004 in. and 0.015 in. leaf-type feeler gages, determine whether any gap between the specimen and the load-applying or support blocks is greater or less than each of the gages over a length of 1 in. or more. Grind, cap, or use neoprene shims on the specimen contact surface to eliminate any gap in excess of 0.004 in. in width. Neoprene shims shall be of uniform 1/4 in. thickness, 1 to 2 in. wide, and shall extend across the full width of the specimen. Gaps in excess of 0.015 in. shall be eliminated only by capping or grinding. Grinding of lateral surfaces should be minimized inasmuch as grinding may change the physical characteristics of the specimens. Capping shall be in accordance with the applicable sections of Practice C 617.

e. Apply the load at a rate that the specimen fails between 3 and 5 minutes after initiation of load.

f. A load rate of between 100 and 170 lb/sec or a displacement rate of approximately 0.033 in/min results in failure in the specified time.

Note: A flexure-shear failure of the specimen beyond the limits of the CFRP constitutes an invalid test and the strength from the invalid test shall be excluded from the test results.

Determination of Durability Strength Reduction Factor

a. The durability strength reduction factor is the ratio of the average flexural strength of the exposed beam specimens divided by the average flexural strength of the control beam specimens.

b. The durability strength reduction factor is reported to two significant figures.

ATTACHMENT B – PROCEDURE FOR MIXING EPOXY FOR LABORATORY SPECIMENS

PREFACE

This proposed test method is the recommendation of the NCHRP Project 12-73 researchers. The method has not been approved by NCHRP or any AASHTO community nor formally accepted for the AASHTO Specifications.

Scope

a. This epoxy mixing method applies to bonding carbon fiber reinforced polymer (CFRP) composites to plain concrete specimens by hand application in the laboratory. This method can be used as a guideline for mixing epoxy for application to carbon fiber fabric.

b. The values stated in in-lb units are to be regarded as the standard.

c. This standard does not purport to address all of the safety concerns, if any, associated with its use. It shall be the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

Referenced Documents

ASTM Standard C192 Practice for Making and Curing Concrete Test Specimens in the Laboratory

NCHRP Report 514 Bonded Repair and Retrofit of Concrete Structures using FRP Composites Recommended Construction Specifications and Process Control Manual

Manufacturer's Application Guidelines

Significance and Use

a. This standard describes the epoxy mixing process for bonding a carbon fiber reinforced polymer (CFRP) composite matrix to a concrete laboratory specimen. Specifically, this standard addresses mixing less than full batch quantities of epoxy resins. The concrete beams specimens shall be prepared and cured in accordance with *Standard Test Method for Determination of Durability Strength Reduction Factor for CFRP Bonded Systems* found in Attachment A of this report.

Notes: 1. Coverage rate is critical to durability performance. Exceeding the manufacturer's recommended coverage results in higher bond strength than exists in field applications.
2. This standard mixing procedure was used in the NCHRP 12-73 Project.

Determine Mix Quantities

a. Using the manufacturer's literature determine the mixture ratio by weight for each component.
b. Determine the coverage requirements for the test specimen
c. Estimate the quantity of epoxy retained in the roller and in the mixing cups for quality assurance

NOTE: Coverage requirements may include consideration that multiple specimens are prepared in batch quantities

Materials for Mixing

a. Clean pair of laboratory gloves to handle carbon fiber fabric.
b. Sheet of new plastic liner to be used for applying epoxy system to carbon fiber fabric separately from prepared concrete surface.
c. A clean small paint roller for applying epoxy.
d. A clean set of mixing tools; screwdrivers and spoons.
e. Six new clear plastic 16 oz plastic cups.
f. Mass scale accurate to one - one thousandth of an ounce.
g. Prepared fabric coupons to be applied to the concrete beams placed on a new clean sheet of fully restrained plastic.

Premixing Part A (smaller component by weight)

a. Place new, clean empty plastic cup onto the mass scale and tare balance.
b. Open **Part A** container.
c. Stir **Part A** thoroughly for three (3) minutes at low speed until uniformly blended using a clean mixing tool.
d. Carefully pour at least 1 oz. of **Part A** into the cup on the mass scale with desired amount to an accuracy of one hundredth of an oz.

   *Note: The minimum quantity of **Part A** is **1 ounce** to assure sufficient quantities for complete mixing**.***

e. Close the container, being careful not to contaminate the contents.
f. Set the plastic cup aside

Premixing Part B

- Use the same mixing procedure from premixing Part A prepare the **Part B** component

Mixing Parts A and B Together

a. Mix cup with **Part A** into cup with **Part B** (**A into B**) being careful to transfer all of the **Part A** components into the **Part B** cup by waiting one (1) minute until the cup drips empty.
b. Thoroughly mix combined materials according to the manufacturer's instructions for **three (3) minutes** at low speed until uniformly blended using a clean mixing tool.

Other Mixtures

a. If the CFRP system uses other primers, putties or sealers, repeat the premixing and mixing steps for each component.

Preparing Concrete Surface and CFRP

a. Use the following steps for each two part sealer, primer, putty, epoxy or sealer in the sequence recommended by the manufacturer.
b. Separately away from the fabric coupons, slowly pour the mixed material from the cup to the spoon to distribute over the prepared concrete surfaces, apply enough material to saturate the concrete surface to the manufacturer's desired coverage by fully saturating the substrate. Use the small paint roller to spread the mixed primer in after it has been placed using the spoon.

Preparing CFRP Fabric

a. Using laboratory gloves, place the CFRP fabric on a new clean sheet of fully restrained plastic.
b. Slowly pour the mixed material from the cup using a clean spoon to distribute over the fabric coupons.
c. Saturate one side of the coupons by rolling them with the small paint roller.
d. Once one side of the coupons has been saturated and rolled several times, use the small paint roller and the spoon to flip the fabric coupons.
e. Repeat the process for the second side.

Applying Prepared CFRP to Prepared Concrete Surface

a. Remove the prepared fabric coupons from the plastic sheet and place onto the prepared concrete surface.
b. Apply additional epoxy to fabric and roll over the fabric coupons on the concrete with the small paint roller several times with light pressure.
c. Save remaining mixed cups for quality assurance evaluation after curing.
d. Clean all tools and put away all materials.
e. After 24 hours, inspect quality assure sample to verify that epoxy set up.
f. Cure at 68°F for 14 days in air environment.

Notes: The quantities specified in this standard assume the use of a small paint roller. Larger rollers may require larger initial material quantities to compensate for the adhesive absorbed by the roller.