DEVELOPMENT OF A FLEXURAL BOND STRENGTH TEST TO DETERMINE ENVIRONMENTAL DEGRADATION OF CARBON FIBER-REINFORCED POLYMER (CFRP) COMPOSITES BONDED TO CONCRETE

By

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Abstract of Thesis Presented to the Graduate School
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DEVELOPMENT OF A FLEXURAL BOND STRENGTH TEST TO DETERMINE ENVIRONMENTAL DEGRADATION OF CARBON FIBER-REINFORCED POLYMER (CFRP) COMPOSTIES BONDED TO CONCRETE

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The use of carbon fiber reinforced polymer (CFRP) composites for repair and strengthening of concrete has been increasing in recent years. Much research has been performed to evaluate CFRP mechanical properties as well as its structural effectiveness as reinforcement. More recently, research has focused on the durability of CFRP on concrete. Unfortunately, there are no standard test methods by which CFRP repaired concrete can be evaluated for durability. The goal of the research reported in this thesis was to develop a standard test method that can be used to evaluate CFRP durability. Several existing test methods were evaluated for suitability. One important criterion was that the specimen be small and easily handled by laboratory personnel. Another was that it can be tested in a typical universal test machine. The most significant criterion for the test configuration was that it forced and adhesive failure mode, not cohesive. This ensures that the loss in specimen strength is due to the CFRP adhesive and not the concrete tensile strength. After evaluating existing methods, a series of pilot studies examining specimen and test variables were conducted. Based on these test results, a

4-in x 4-in x 14-in concrete beam with a 1-in x 8-in CFRP composite strip reinforcement, tested in 3-pt bending was selected. For the adhesives used in this study, the minimum concrete strength needed to force an adhesive behavior was found to be 7000-psi. A half-depth, mid-span saw cut was incorporated to isolate the reinforcement.

Design, construction, and operation of the environmental exposure systems are also described herein. Exposure tanks were created to provide full immersion of the specimens in water at elevated temperatures of 30°C, 40°C, 50°C, and 60°C. The effects of chloride, alkaline, sustained load, and UV radiation were also combined with 50°C water. Exposure systems were created with insulated coolers, PVC piping, magnetic driven pumps, and household water heaters. 450 beams were constructed and exposed to the above listed environments.

Preliminary results of exposure showed a significant capacity loss after short periods of exposure. Sustained load frames supplying a load 50% of experimental capacities failed after 2 weeks of environmental exposure. These results indicate the effect of moisture and elevated temperature reduced the strength of the CFRP/concrete bond by 50% in 2 weeks. Similar results were found by a congruent study performed at the University of Wyoming.

Testing will be done on epoxy and composite samples to determine the individual components effect in the beam specimen degradation. Flexural tests will continue to be performed on beams exposed for different periods to confirm the strength reduction trend with exposure time and temperature.

CHAPTER 1
INTRODUCTION

Carbon fiber-reinforced polymer (CFRP) composites are being used in civil infrastructure in applications ranging from reinforcing bars, column wrapping for improved seismic resistance, and externally bonded reinforcement for strengthening of walls, beams, and slabs. The use of CFRP for building infrastructure is a relatively new concept, and the durability of these materials has not been extensively researched. The capacity of CFRP materials under sustained load and changing environmental conditions is a particular concern. Concrete bridge beams have in practice been repaired and strengthened with externally bonded polymer CFRP composite sheets or prefabricated CFRP laminates. The short-term behavior of these applications has been studied, and construction specifications for bonded repair were developed under NCHRP Project 10-59A. Nevertheless, research into their long-term performance is incomplete, and durability issues remain unanswered.

There are a several CFRP systems available for surface-bonded treatment of concrete. The more common methods include wet lay-up and pre-cured laminates. In the wet lay-up system, dry sheets of unidirectional or multidirectional fabric are saturated at the job site and rolled onto the surface using the saturant as the adhesive. Sometimes a primer is needed to aid in bonding to the surface. The system is formed in the field, including mixing of the resin and catalyst. Pre-cured systems include laminates and grids that are manufactured in a controlled factory setting. These pre-cured systems are then bonded to the surface of the concrete with an adhesive putty to provide stress transfer.

The adhesive putty consists of resin and catalyst which are mixed in the field. Another category of CFRP composite used in building infrastructure is spray-up. This technology is similar to that used in boat manufacturing. The final product is a chopped mat of randomly oriented, discontinuous fibers encapsulated by a resin that is usually a polyester or vinylester. This material is adhered to the substrate surface by the matrix resin during the spraying process, eliminating the need for an additional coupling or bonding agent. Due to their limited use in beam repair, spray-up systems will be considered similar to wet lay-up systems for this study.

CFRP composites have been successfully used for years in automotive, marine, industrial and aerospace applications. In these applications, however, the CFRP composite is manufactured in a controlled environment and not in the environment to which the component will be exposed. This same controlled manufacturing setting is applied to pre-cured laminate systems. The wet lay-up or spray-up systems include mixing and impregnating the resin matrix on-site. On-site resin curing conditions are not as well controlled as the factory counterparts, perhaps leading to very different performance characteristics.

For civil engineering structures, field conditions can present significant challenges to ensuring that proper temperature and humidity conditions are maintained during installation and curing periods. Mixing and wetting of the fabric is performed on site for wet lay-up applications as shown in Figure 1-1, and is therefore not easily controlled. Moreover, the temperature and humidity during mixing, saturation, and curing are generally controlled by the ambient weather conditions.


A

B

Figure 1-1. CFRP application A) pre-cured laminate application B) wet lay-up application

In adhesively bonded CFRP systems, one face of the material is adhered to the concrete while the other is exposed to the environment. Consequently, the exposure conditions (related to moisture) for the CFRP composite are controlled simultaneously by the local environment and the underlying concrete. Highly or even moderately porous concrete will readily transmit available moisture to the bond line. In addition, cracks and porosity in the underlying concrete allow moisture access through diffusion and capillary action. Moisture can gain access to the resin and fibers from the exposed face as well. Accumulated moisture behind the bond line can create water cells that may initiate or accelerate corrosion of the steel reinforcement.

Environmental durability issues of CFRP composites as investigated by previous research are outlined in the next chapter. The current environmental durability design procedure for CFRP composites is outlined and the role that this research plays in perfecting the durability design is given.

CHAPTER 2
BACKGROUND

Previous Research in CFRP Durability

Some research has been performed on CFRP durability, but the bulk of the studies have been performed on constituents of the CFRP system, mainly neat resin samples and composite testing. Little research has been performed on CFRP bonded to concrete and most have involved a peel, bond, or shear tests. Durability of CFRP bonded concrete beams tested in flexure has not been studied extensively. The main research performed and findings on CFRP materials exposed to environmental conditioning are given below.

Moisture

Exposure to moisture can have degrading effects on CFRP. The moisture can lower the glass transition temperature (Tg) and also cause relaxation in the polymer matrix. Stress-induced cracking and a reduction in fiber-matrix adhesion also occurs due to moisture exposure. The overall effect of moisture exposure on CFRP is reduced strength and mechanical properties, eventually leading to a matrix/fiber bond failure as shown by the previous research outlined below.

Au and Buyukozturk (2006) performed peel and shear tests on pre-cured CFRP laminate bonded to concrete with epoxy. Specimens were exposed to 100% relative humidity (RH) at 23º and 50º C for 0-56 days. Dry specimens failed cohesively within concrete. Wet specimens failed adhesively at the epoxy/concrete bond line. A 50-60% loss in fracture toughness was observed after environmental exposure.

Tu and Kruger (1996) and Aiello et al. (2002) performed bond strength tests on epoxy bonded concrete. The bond test was performed according to ASTM C882. A loss in bond strength of 20-50% was found after 135 days immersion in 23°C water (Tu and Kruger 1996). After a cycle of 48 hours immersion in 23°C water followed by 48 hours of drying, Aiello, Frigione, and Acierno (2002) found 17-35% reduction in bond strength.

Hulatt et al. (2002) exposed prepreg CFRP coupons to wet-dry cycles which consisted of complete immersion for 5 hours and drying in 50% relative humidity for 2 days, up to a total immersion time of 2000 hours. The samples were then tested in tension on an Instron model 1185 according to ASTM D3039M. The coupons subjected to moisture exposure were found to have a 3.8% reduction in failure stress when compared to unexposed coupons. This reduction has been attributed to water infiltration weakening the fiber/matrix bond and therefore causing stress relaxation within the specimen.

Karbhari et al. (1997) constructed 9-in. x 6-in. x 1-in. test beams reinforced with 2-ply 12-in. x 1-in. strips of wet lay-up unidirectional CFRP. The beams were then immersed for 60 hours at 20°C. A peel test was performed, where the peel force was read directly from the load cell. It was found that interfacial fracture energy decreased with exposure to water as plasticization of the matrix occurs and bond stresses on the resin/fiber surface increased due to matrix swelling.

Banks et al. (2004) immersed prepreg CFRP coupons for 330 days at 65°C. The specimens underwent dielectric measurements to determine moisture absorption and shear testing to determine deleterious effects of exposure. It was found that the failure mode of the coupons changed from fiber tear to adhesive failure upon exposure. The water was also found to be ‘bound’ to the adhesive rather than located as free water in voids.

Ferrier and Hamelin (2002) constructed wet lay-up CFRP samples and exposed them to immersion in water at 20°C and 45°C for up to 2500 hours. The specimens were then tested using Barcol hardness, Differential Scanning Calorimetry (DSC), and water absorption analysis. It was found that increased water exposure decreased Tg, surface hardness, and mechanical properties of the CFRP. An increase in temperature also increased the water absorption of the sample, decreasing mechanical properties.

Moisture/Salt

The exposure of CFRP to salt and other chemical solutions will have similar effects as that with water exposure. The moisture will penetrate the composite and cause the matrix material to swell and relax. The addition of salt and other solutions accelerates the degradation of the polymer matrix further.

Sen et al. (1999) exposed CFRP wet lay-up bonded to concrete to cyclic environmental exposures involving seawater. The specimens underwent17 months followed by 6 months of continuous outdoor exposure or 23 months continuous outdoor exposure. The specimens then underwent torsion and tension testing through an apparatus bonded to the surface of the CFRP. A 0-55% loss in bond strength was observed after salt water exposure and a 0-45% loss in bond strength for outdoor exposure.

El-Hawary et al. (2000) exposed epoxy bonded concrete to tidal saltwater exposure. Exposure times were 6, 12, and 18 months. Split tension and slant shear tests were performed on exposed specimens. It was found that the failure mode changes from cohesive to adhesive with aging time. No change in tensile strength was observed upon exposure, and a 25% decrease in bond strength was observed after 18 months of exposure. Specimens appeared to become protected by build-up of shells.

Toutanji and Gomez (1997) exposed CFRP and GCFRP wet lay-up bonded concrete beams to simulated saltwater. One cycle involved 4 hours immersion and 2 hours at 35º C and 90% RH. Specimens were exposed for 75 days and then tested in 4-pt flexure. A 5-30% loss in flexural strength was observed with exposure.

Karbhari et al. (1997) constructed 9-in. x 6-in. x 1-in. test beams reinforced with 2-ply 12-in. x 1-in. strips of wet lay-up unidirectional CFRP. The beams were then immersed in synthetic sea water according to ASTM D1141 for 60 hours at 20°C. The peel force of the composite was read directly from a load cell during a peel test. Dynamic Mechanical Analysis (DMA) results show exposure to sea water reduced interfacial fracture energy when compared to unexposed specimens. This result occurs due to plasticization of the matrix and stresses developing between the fiber and matrix due to matrix swelling.

Hulatt et al. (2002) tested prepreg CFRP coupons for reduction in tensile stress on an Instron model 1185 according to ASTM D3039M. The exposed specimens were subjected to wet-dry cycles which consisted of complete immersion for 5 hours in sodium chloride solution and drying in 50% relative humidity for 2 days, up to a total immersion time of 2000 hours. The coupons subjected to salt solution exposure were found to have a 3.1% increase in failure stress when compared to unexposed coupons.

Banks et al. (2004) subjected prepreg unidirectional CFRP to 330 days of immersion in simulated ocean water (ASTM D1141-90) at 65°C. Dielectric measurements for moisture absorption showed the adhesive absorbed 1% water. Shear tests determined the mode of failure changed from fiber tear to adhesive failure upon exposure to simulated ocean water.

Moisture/Alkali

Alkali solutions can be created by concrete pore water and have high pH values of 12-13. Exposure to these solutions degrades the polymer matrix in excess to that of water exposure. The alkali attacks the polymer chains and assists in the degradation. This attack is especially severe for under-cured specimens.

Katsuki and Uomoto (1995) exposed CFRP rods (6-mm diameter, 40-mm length) to NaOH solution at 40°C for 7-120 days. The rods were then tensile tested to determine effects of exposure. It was determined that there was not penetration of alkali or reduction in failure stress upon exposure.

Nanni et al. (1998) performed pullout testing on carbon vinyl-ester rods in concrete. The exposure conditions were immersion in $Ca(OH)_2$ with a pH of 12-13 at 26, 60, and 80°C. It was found that the pullout load reduced for increasing temperature and exposure time.

Chin et al. (1998) constructed dogbone specimens of isophthalic polyester and vinyl ester resins. The dogbones were immersed in 0.32 mol/L KOH, 0.17 mol/L NaOH, 0.07 mol/L Ca(OH)2 solution with distilled water (pH 13.5) at room temperature, 60°C, and 90°C up to 1300 hours. Tensile tests were performed on dogbone specimens after exposure and were found to have 60% of original strength when exposed to solution at room temperature and have deteriorating strength as temperature and exposure are increased. Isophthalic polyester specimens lost all strength after 10 weeks of exposure at 90°C.

UV Radiation

Ultraviolet radiation causes degradation in polymeric materials due to chain scission. Long term exposure of CFRP to UV radiation will cause surface defects and cracks, which could facilitate the entrance of water and other surface impurities into the composite. This facilitation could eventually lead to loss of mechanical properties in the composite system.

Hulatt et al. (2002) exposed CFRP prepreg coupons to 2000 hours of UV radiation according to ASTM G53. After exposure, coupons were tested in tension and compared to unexposed specimens. It was found that the stress at failure increased after exposure. This result was attributed to possible cross-linking during post-cure due to UV exposure.

Startsev et al. (1999) performed long-term experiments with carbon/epoxy specimens exposed to hot, humid environmental conditions for 2 years. The specimens underwent interlayer tensile and fatigue testing after exposure. The outer surface underwent degradation, causing an outer layer decrease in shear and fatigue, while the inner portion of the sample remained unaffected.

Liau and Tsent (1998). performed tensile tests on exposed coupons of prepreg CFRP. The results indicated surface degradation. The surface degradation caused crack initiation, eventually reducing the strength due to stress concentration. As exposure time increased, it was found that the tensile strength retention of the specimens decreased.

Haeberle et al. created carbon fiber vinylester resin matrix coupons 1.5-mm thick and 2.54-cm square. The specimens were exposed to a 100 watt arc bulb for 45 days of exposure, 1.5 hours of exposure per side per day. After exposure, specimens were tested on an Instron testing machine. It was found that exposure caused surface cracking, but no decrease in tensile strength.

Fatigue

Fatigue loading is common in service bridges. This loading can cause stress relaxation in the polymer composite, leading to reduced strength and stress to failure.

Heffernan, Wight, and Eriki (2002) performed fatigue testing on one-way steel and CFRP reinforced slabs. The fatigue test was a four point test where the specimens were fatigue loaded to failure. It was found that the CFRP reinforcing increased load to failure over un-reinforced specimens. In all cases, the steel yielded, causing a transfer of the load to the CFRP, resulting in bond line failure.

Brena, Wood, and Kreger (2002) created test beams reinforced with either unidirectional CFRP or pultruded CFRP plates. The specimens were subjected to cyclic loading of 10000 or 1000000 cycles with a strain equal to 33-50% yield load. The specimens were then tested to failure using a four-point bend test. It was found that the CFRP did not fail at the strain levels typical to service loads, but if the load was increased above the service load, failure did occur. The larger the stress was in the CFRP, the lower the number of cycles to failure. Both the pultruded bars and unidirectional CFRP failed by debonding.

Conclusions of Previous CFRP Environmental Durability Research

The combination of moisture, elevated temperature, and other aggravating effects such as alkaline, salt, UV, and sustained load have proven to have deleterious effects on the performance of CFRP bonded concrete. Moisture exposure from relative humidity or immersion at room temperature was found to have a decrease of mechanical properties up to 60%. Addition of alkali and salt to the moisture exposure resulted in reduction of the mechanical properties of the CFRP and a change in failure mode. Exposure to UV did not have an effect on the mechanical properties when investigated independently, but did cause micro-cracking which aids in moisture facilitation to the impregnating resin matrix when moisture exposure is congruently investigated.

Durability Design

Currently, an environmental reduction factor is used in design of CFRP systems according to ACI Report 440.3R. This factor is applied to manufacturer specified composite material properties to account for long-term exposure to environmental conditions. The design ultimate tensile strength and rupture strain are determined by applying the environmental reduction factors given by Table 8.1 in ACI 440.3R (Table 2-1) to the design values given by the composite manufacturer. The environmental reduction factors currently in use are "conservative estimates based on the relative durability of each fiber type" (ACI 440R). There is little research supporting these values.

Table 2-1. Environmental-reduction factors given by ACI 440.3R for various CFRP systems and exposure conditions

Exposure conditions	Fiber and resin type	Environmental-reduction factor C_E
Interior exposure	Carbon/epoxy	0.95
	Glass/epoxy	0.75
	Aramid/epoxy	0.85
Exterior exposure (bridges, piers, and unenclosed parking garages)	Carbon/epoxy	0.85
	Glass/epoxy	0.65
	Aramid/epoxy	0.75
Aggressive environment (chemical plants and waste water treatment plants)	Carbon/epoxy	0.85
	Glass/epoxy	0.50
	Aramid/epoxy	0.70

NCHRP Research

Limited research has been performed on CFRP bonded to concrete, but mostly in the form of peel and hardness tests. Little research was found in the literature related to flexural testing of concrete beams with bonded CFRP composite reinforcement. What research has been performed does not relate to long term durability of this type of specimen.

Durability of CFRP composite bonded to concrete tested in flexure will be investigated by the National Cooperative Highway Research Program (NCHRP) project 12-73 "Design Guidelines for Durability of Bonded CFRP Repair/Strengthening of Concrete Beams". The objectives of the NCHRP research are to develop 1) design guidelines and 2) material selection criteria that consider the effects of mechanical and environmental loads on the durability of bonded carbon fiber-reinforced polymer (CFRP) repair and strengthening of concrete beams. The methods used to fulfill the objectives are threefold. First, the current knowledge available on the durability of CFRP composites used in bridge applications will be evaluated to identify the environments that appear to have the most extreme effect on the CFRP mechanical properties. Next, a series of mechanical tests will be created and performed to determine effect of the selected environments on the adhesive bond properties of the CFRP composite. Finally, a single "environmental reduction factor" will be developed based on the measured reduction in capacity of the CFRP composites exposed to the critical environments.

Research Contribution

The research reported in this thesis is in support of the NCHRP project 12-73. Standard test procedures and specimen configuration were developed to be used in the NCHRP project. Several factors such as concrete specimen geometry, concrete strength, and CFRP geometry were investigated to determine a suitable configuration for the project. The results from flexural testing were used to determine the desired configuration. Once the specimen configuration and test procedures were determined, specimens were constructed for the NCHRP study. An environmental exposure system was developed and constructed for aging the specimens. Specimens exposed to environmental conditioning were tested to provide preliminary durability results.

CHAPTER 3
RESEARCH APPROACH

A design factor is required to be applied to the mechanical properties of the CFRP composites used during the design process. As of yet, the factor used for durability design is not founded by research. Results from durability research will need to be correlated into a factor that can be used for design of CFRP systems. Short-term durability results will need to be extrapolated for long-term structural design.

Accelerated Aging Model

Specimens will be exposed to hygrothermal conditions at four temperatures and three time points. The results from the hygrothermal exposure tests will then be used with an accelerated aging model to predict long term results. These long term results can be used to predict the behavior of CFRP composite bonded to concrete, and therefore be used for structural design.

The Arrhenius model was chosen to predict long term behavior using accelerated test data. Traditionally, the method of extrapolation for aging is done through the Arrhenius relationship given in Equation 3-1.

$$K = Ae^{\left(-Q/R\cdot T\right)} \qquad \text{Equation 3-1}$$

Coefficients A and Q are pre-exponential and activation energies, respectively. If they are assumed constants then the above can be rewritten for two different test conditions as:

$$\ln\left(t/t_{ref} \right) = \frac{Q}{R}\left[\left(1/T \right) - \left(1/T_{ref} \right) \right] \qquad \text{Equation 3-2}$$

The activation energy can be determined as the slope and intercept of the ln (1/t) (time) vs. (1/T) (Temperature) plot. Figure 3-1 shows such plots for a typical sample material. Once the activation energy is known, Equation 3-2 can be used to predict the service time for a given property value at a service temperature, given the time and temperature for that same property value under the accelerated aging conditions. This procedure is considered the "standard" aging relationship and is applied to metals, ceramics and polymers equally. (National Academy Press 1996; LuValle et al. 1998; Nickles and Wiest 2000; Caruso and Dasgupta 1998; White and Turnbull 1994)

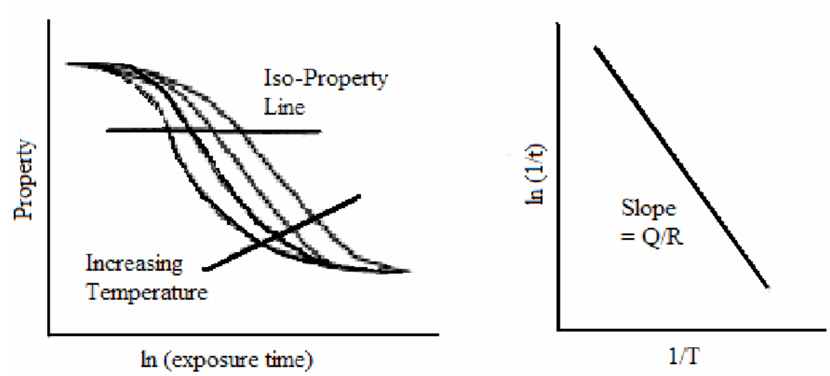


Figure 3-1. Arrhenius correlation plots (National Academy Press 1996)

An understanding of the theoretical basis behind this extrapolation procedure provides a basis for extending the accelerated test conditions. For the situations considered in this work, property changes in the resin occur due to plasticization effects from moisture absorption. Thus, increasing the temperature at constant relative humidity causes acceleration in aging due to two effects: an increase in the diffusion coefficient and an increase in the absolute concentration of moisture in the aging environment. Both of these factors cause an increase in the rate of moisture absorption by the resin, and thus an increase in the aging rate. The increases in diffusion coefficient and the moisture concentration at constant relative humidity are described by the Arrhenius relation. Thus, use of the procedure described above results from a superposition of the two effects, and the "apparent" activation energy measured in aging experiments is a combination of the activation energies for the two processes.

The assumptions made for use of this model are:

- Moisture is the critical parameter governing degradation
- Alkali, salt, and other aggravating factors accelerate deterioration, but the governing transport mechanism is the basic mechanism of moisture diffusion
- The Arrehenius law, based on moisture migration, can be used to model the moisture degradation. The Arrehenius law results in exponential decay behavior.
- The Arrehenius law can be correlated across different temperatures

Specimens will be immersed in water at four different temperatures and a minimum of three time points. The capacity loss relative to control specimens at each time and temperature point will be used to create decay curves similar to that of Figure 3-1. A horizontal line at any desired capacity can be used to generate a (1/T) vs ln(1/t) plot. From these data, equivalent exposure times for elevated temperatures can be determined. For example, exposure at 20°C for 24 months could be equivalent to exposure at 40°C for 6 months.

The data from the Arrehenius durability correlation tests will be used to develop a design coefficient, C_e. Over time the degradation due to environmental effects will increase. To account for the effect of time, two forms of evaluation will considered. First, for a given reduction in strength (e.g. $C_e = 0.85$), the time for the reduction to occur will be computed using the methods outlined above. For example, a repair system may have a C_e of 0.85 for a 48-year life-span. Inversely, for a given time (say t = 50-years), the strength reduction due to environmental factors will be computed. In this case, a repair system designed for a 50 life span may have a C_e of 0.84.

Research Plan

This thesis covers the development of the standard test procedures and the design, construction, and operation of the exposure system. The milestones performed were the development of a testing procedure, creation and testing of pilot specimens, construction of the 375 specimens to be tested at UF, and design and construction of the exposure system.

The objective of the pilot study was to determine an ideal specimen and test configuration as part of the larger study. The specimens needed to be of the beam type so as to be tested in flexure. This type of specimen was chosen based on ASTM standard C78-02. The study required a large number of specimens to be exposed to different environmental conditioning, as shown in Table 3-1. The table shows the seven environmental conditions considered, as well as the temperatures and times investigated. For each environmental condition, multiple composites were to be investigated, each unique combination including 3 replicates. This produced a specimen requirement of around 400 in number. The specimen configuration needed to be small enough for this large number to be produced, yet large enough to accurately represent the behavior of the concrete.

The goal of the environmental conditioning study was to produce a correlation between the flexural strength of the CFRP bond to the concrete for the different environmental conditions and time periods. To compare the results of the flexural testing, it was imperative that the failure modes for all tests be the same. The failure mode needed to be adhesive to ensure the failure load was indicative of the bond failure strength. It was therefore necessary to determine the configuration of each composite that would produce an adhesive failure mode. The failure mode was governed by the surface preparation, concrete strength, CFRP bond strength, and CFRP width. Each of these factors was investigated to determine the desired specimen configuration that would cause adhesive failure.

Table 3-1. Environmental Conditioning Test Matrix

Condition	Solution	Temp. (°C)	Exposure Time (mos)	# Specimens
Control	Atmospheric	Room Temp	6	18
			12	18
			24	18
			60	12
			120	12
Thermal & Chloride	Chloride Water	50	12	12
Thermal & Alkali	Alkali Water	50	12	12
Sustained Load	Water	50	6	12
			12	15
			24	12
UV/Wet/Dry	Water/UV drying	50	12	12
Real Time	Outdoors	N/A	24	9
			60	12
			120	9
Arrhenius	Water	30	6	12
			12	12
			24	18
			60	6
		40	6	9
			12	9
			24	15
			60	3
		50	6	9
			12	9
			24	15
			60	3
		60	6	12
			12	12
			24	18
			60	6

CHAPTER 4
BEAM TEST: DEVELOPMENT

This chapter covers the experimental work conducted to optimize the specimen and testing configuration for determining the bond strength of CFRP composite reinforcement bonded to concrete. The investigation was designed to consider the variables shown in Table 4-1. Three beam sizes and two concrete strengths were investigated. In addition, four different composite systems, both commercially available and homemade, were tested. Supplemental reinforcement both internal and external was tested as well. Although each variable was not evaluated independently, 104 specimens were constructed and tested before finalizing the test protocol. The following sections describe the fabrication and testing techniques used.

Table 4-1. Factors investigated for determination of specimen configuration

Beam Type	Concrete Strength	CFRP System	CFRP Size	Added Reinforcement	Load Config.
6 X 6 X 30 (in)	5 ksi	Composite C	Length	None	3-pt
6 X 6 X 22 (in)	7 ksi	Composite T	Width	External steel plate	4-pt
4 X 4 X 14 (in)		Composite A		Internal steel bar	
		Composite S		Internal glass bar	

Concrete Beam Fabrication

Concrete construction

The concrete beams were cast at the Florida Department of Transportation (FDOT) State Materials Office (SMO) located in Gainesville, FL using concrete mixed at their facility. The 104 specimens were constructed using nine different batches of concrete. The beams were created by pouring concrete into steel or wooden forms in the desired dimensions. The concrete was Class V and a mix typically used by the SMO in bridge applications. The cement used was Type I/II and the ratio of cement:sand:coarse aggregate was 1.0:2.07:2.30 by weight. The materials used for the concrete construction are showed in Figure 4-1.

A B C

Figure 4-1. Materials used for concrete construction A) Type I cement B) Sand C) Coarse aggregate

Each mix had a 28-day compressive strength ranging from 4500-psi to 7500-psi. The beams were poured into the forms and covered with plastic for 24 hours to set up. The forms were then removed from the beams, and they were transported to a moisture chamber to cure. The beams were cured for a minimum of two weeks and removed to dry before application of the CFRP composite.

A half-depth saw-cut through the cross-section was made in all but two of the specimens. The saw-cut was made at mid-span and intended to facilitate moisture to the concrete/CFRP bond line during the exposure period. A concrete saw was used to make the saw-cut, as shown in Figure 4-2. The width of the saw-cut was 0.1-in and the depth was half the depth of the concrete beam (3-in for 6-in deep beams, 2-in for 4-in deep beams).

Figure 4-2. Concrete saw creating half-depth saw-cut

Surface preparation

Before application of the composite, the surface of the specimen was prepared by sand-blasting. According to the NCHRP Report 514:

"Surface preparation shall promote continuous intimate contact between CFRP and concrete by providing a clean, smooth, and flat or convex surface. Cleaning shall remove any dust, laitance, grease, oil, curing compounds, wax, impregnations, stains, paint coatings, surface lubricants, foreign particles, weathered layers, or any other bond inhibiting material. The cleaned surface shall be protected against redeposit of any bond inhibiting materials".

To promote continuous contact between the CFRP and concrete, the surface was roughened with a sand blaster (Figure 4-3). After sand blasting, the surface was cleaned and free of sand and dust as specified by the NCHRP Report.

Figure 4-3. Surface sandblasting a specimen

The amount of surface roughness was found to relate directly to the performance of the CFRP system. The greater the surface roughness, the greater the surface area contact between the CFRP and concrete, creating a better bond, and allowing the CFRP to be engaged as stress is transferred across the concrete/CFRP bond line. Good sandblasted surfaces were characterized by a rough surface caused by exposed aggregate. According to the composite manufacturer, the sandblasted surface should have an ICRI profile minimum of 3, as shown in Figure 4-4.

Figure 4-4.Sandblasted surface with aggregate exposed compared to ICRI profiling chip

Composite Application

Composite was applied in strips on the tension face of the concrete beams. One laminate and three fiber weaves were used with six epoxies for fabric saturation and adhesive bonding to the concrete surface. The composite was applied in several steps, which are given in detail below.

The laminate used was Composite C graphite pre-cured laminate while the fiber weaves used were Composite T, Composite A, and Composite S (Figure 4-5). The fiber weaves were high strength unidirectional carbon fiber fabrics. The physical and mechanical properties of the fabrics and laminate are given in Table 4-2.

A

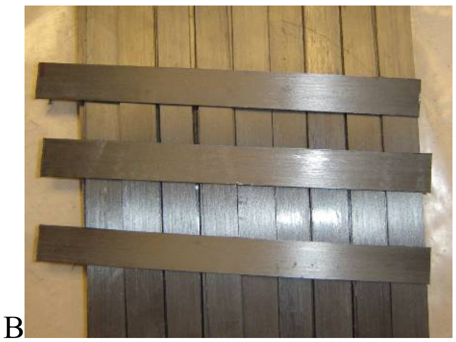
B


Figure 4-5. Graphite reinforcement used for the composite A) fabric weave B) pre-cured laminate

Table 4-2. Physical and mechanical properties of graphite fabrics and laminate

Material	Weight per square yard (oz)	Tensile strength (psi)	Tensile Modulus (psi)	Elongati on (%)	Density (lbs/in^3)
Composite C	-	$4.06*10^5$	$23.9*10^6$	1.69	-
Composite T	19	$5.5*10^5$	$33.4*10^6$	1.7	.063
Composite A	18	$5.5*10^5$	$34*10^6$	1.5	.065
Composite S	6.7	$5*10^5$	$33.4*10^6$	1.5	.065

The laminate was bonded to the concrete using Putty C epoxy resin. The fabrics were saturated and bonded to the concrete using six epoxy resins. The saturant and adhesive used to bond the fabric to the concrete were not always the same epoxy resin.

The epoxy resins used were Putty C, Saturant A, Saturant S, Saturant T, Tack Coat T, and Saturant T with Cab-O-Sil®, with mechanical properties for each given in Table 4-3.

Table 4-3. Material properties of epoxy resins

Epoxy Resin	Tensile Strength (ksi)	Tensile Modulus (ksi)	Flexural Strength (ksi)	Flexural Modulus (ksi)	Elongation (%)
Putty C	3.60	650	6.8	1700	1.0
Saturant A	8.00	250	11.5	500	3.0
Saturant S	4.35	551	-	551	1.5
Saturant T	10.50	461	17.9	452	5.0
Tack Coat T	N/A	N/A	N/A	N/A	N/A
Saturant S w/Cab-O-Sil®	10.50	461	17.9	452	5.0

The composite application was a multi-step process. The laminate was provided in a 2-in wide, 10-ft long coil. It was then cut to length using tin-snips and cut to width using a razor. The cutting process was done so as to ensure no cracking along the length of the laminate. Once the laminate was the desired dimensions, it was adhered to the concrete. The epoxy resin paste was prepared by mixing the appropriate ratio of parts A and B (1:.34 by weight) for three minutes. The paste was then applied with a consistent thickness to both the laminate and the concrete surface using a spatula. The laminate was then placed on the concrete surface with the pasted surfaces touching. Pressure was applied to the laminate to ensure bonding. The excess resin squeezed from between the laminate and concrete was removed with a spatula.

The fabric application began with cutting the fabric in strips to length using fabric scissors. The fabric was supplied in rolls approximately 2-ft wide and 20-ft long and was cut to width between fiber rovings, so as to not fray the edges. The surface of the concrete was cleaned with acetone. The manufacturer specified ratio of parts A and B of the saturant resin epoxy were hand mixed for three minutes. A layer of epoxy was applied with a 4-in long nap roller to the location where the composite was to be constructed, ensuring that all voids were coated as shown in Figure 4- 6.

Figure 4- 6. Application of saturant to concrete surface for fabric composite

The firs saturant coat was allowed to tack approximately 1 hour. After the surface was tacky, an adhesive epoxy resin was applied on top of it using a 4-in wide nap roller or spatula, depending on the material. The adhesive was prepared by mixing manufacturer specified ratios of parts A and B for 3 minutes. In some instances, the adhesive material was the same as that of the saturant. Figure 4-7 shows the application of an adhesive using a spatula.

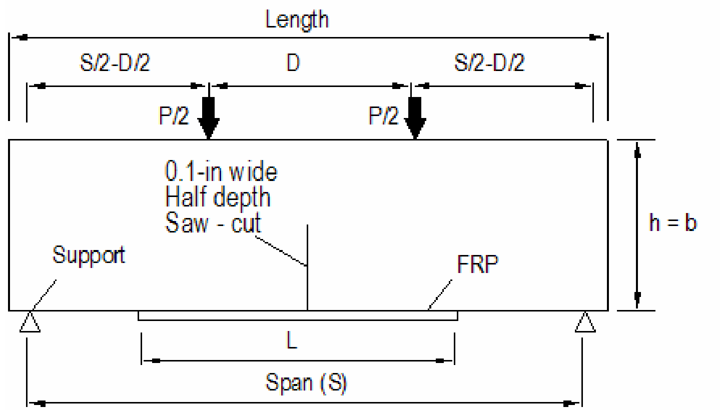
Figure 4-7. Application of adhesive using a spatula

The fiber fabric strips were saturated with the saturant epoxy resin, causing a saturant:fabric weight ratio of 1:1. The saturant was rolled through the rovings of the fabric using a nap roller. The fabric was then placed on the concrete surface on top of the adhesive, as shown in Figure 4-8. The composite was then rolled with the nap roller to ensure adhesion.

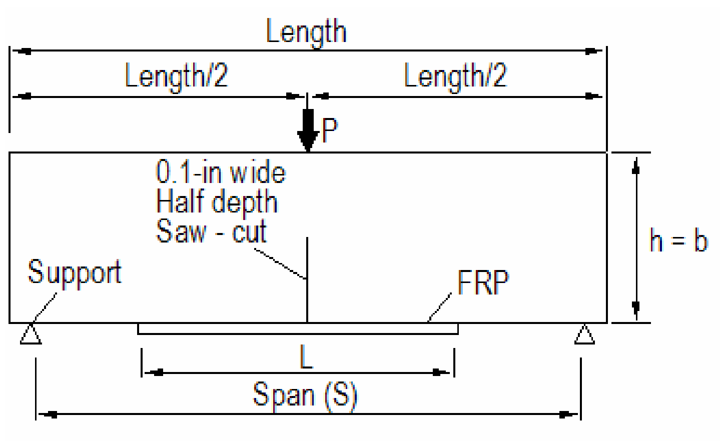
Figure 4-8. Fabric composite placed on adhesive

Flexural Testing Procedures

As a starting point, the standard test method for flexural testing of concrete beams (ASTM C78-02) was looked to. This test method, shown in Figure 4-9A, has two load points that create a region of constant maximum moment and zero shear. Three-point loading was investigated because it will create a higher moment at mid-span with the same applied load. To achieve the maximum moment capacity of the CFRP, a higher load would have to be applied with the 4-pt loading configuration. This higher load could potentially lead to a shear failure at the ends of the beam. For this reason, a 3-point loading as shown in Figure 4-9B, was also investigated.



A



B

Figure 4-9. Schematic of flexural testing loading conditions. A) Four-point loading B) Three-point loading

The specimens were loaded using an Instron 3384 testing machine as shown in Figure 4-10 with the CFRP composite on the bottom face (not visible in photos). The bottom and top of the beam when placed in the testing apparatus corresponded to surfaces that were formed. This ensured flat and parallel testing surfaces.

The software used to control the cross-head was Partner, a program configured to work with the testing machine. The load was applied at a constant rate of 0.01 in/min so as to cause specimen failure 1-2 minutes after half-capacity was reached. Load and cross-head position were recorded during testing by the Partner program. These data were then exported to a spreadsheet.


A

B

Figure 4-10. Small beam flexural testing with Instron machine A) 3-pt loading B) 4-pt loading

Variables in Test Protocol

3-pt vs. 4-pt Testing Procedures

Twenty-eight specimens were used to compare flexural loading conditions. Load was applied using one or two application points, separated by a distance, D. D was varied to compare beam behavior. Two composites were investigated, along with the effect of internal reinforcement. The specimens investigated, including the composite type and geometry and load application spacing are shown in Table 4-4.

The failure mode and strength of specimens tested in the 3-pt configuration were compared to those of the 4-point loading. Similar results were desired between the two tests to ensure that the 3-point loading was indicative of the results obtained using the standard test method. All aspects except the location of the load application remained constant in all tests. The effect of load application spacing, D, was also investigated.

Table 4-4. Specimens investigated for flexural loading condition

Specimen	D (in)	w (in)	Fiber	Adhesive	Reinforcement
TG-1	0	1	A	Saturant A	Glass bar
TG-2					
TG-3					
TG-4	2				
TG-5					
TR-1	0	1	A	Saturant A	Steel bar
TR-2					
TR-3					
TR-4	2				
TR-5					
TS-5	0	1	A	Saturant A	None
TS-6					
T4-5	2				
T4-6					
T4-7	4				
T4-8					
TS-9	0	2	A	Saturant A	None
TS-10					
TS-11					
TS-12					
T4-1	2		T	Cab-O-Sil	
T4-2					
T4-3	4				
T4-4					

Beam Size

In total, 24 specimens were constructed and tested to compare concrete geometric properties. The specimens included eight 30-in long specimens (6-in square cross-section), eight 22-in long specimens (6-in square cross-section), and eight 14-in long specimens (4-in square cross section). The specimen set-up is shown in Figure 4-11 and the dimensions investigated are given in Table 4-5. The 6-in cross-section specimens were originally investigated because this is the size that ASTM standards recommend. The 4-in cross-section specimens were further investigated due to their ease of use and the large number of specimens needed for the research program. Each specimen was constructed with varying CFRP dimensions. The composite system used was Composite T. The composite system consisted of Saturant T, Tack Coat T, and graphite unidirectional fiber weave. Once the specimens were constructed and cured, they were loaded in a 3-point flexure test to failure. The failure load and mode were examined and used to determine the ideal specimen size.

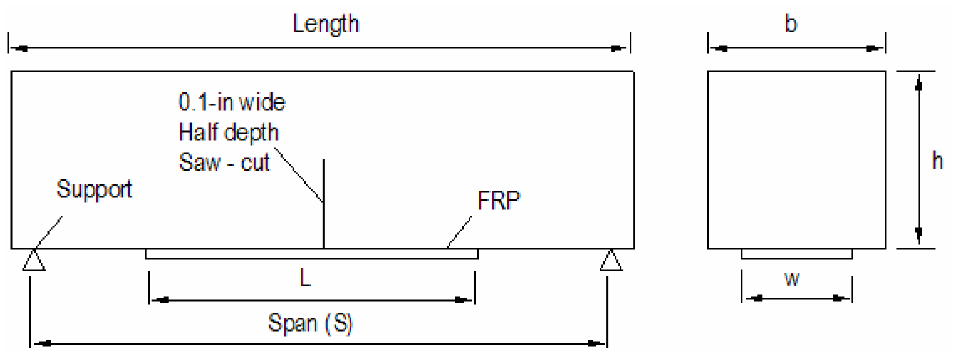


Figure 4-11. Beam and CFRP dimensions for beam size investigation

Table 4-5. Beam and CFRP dimensions for beam size investigation

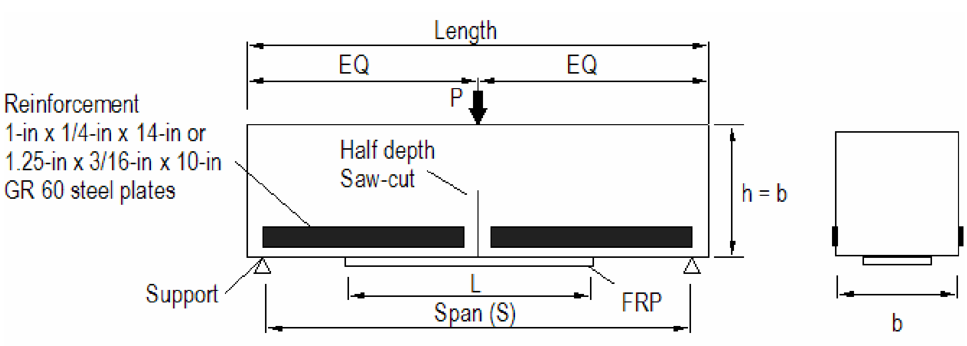
Specimen	b=h (in)	Span (in)	w (in)	L (in)
T30-1, T30-2	6	28	4	12
T30-3, T30-4	6	28	4	16
T30-5, T30-6	6	28	2	8
T30-7, T30-8	6	28	2	6
T22-1, T22-2	6	20	4	8
T22-3, T22-4	6	20	4	12
T22-5, T22-6	6	20	2	6
T22-7, T22-8	6	20	2	4
T14-1, T14-2	4	12	3	6
T14-3, T14-4	4	12	3	8
T14-5, T14-6	4	12	1	4
T14-7, T14-8	4	12	1	2

Comparing specimens of different cross-section dimensions, it was found that the failure mode was consistent. This is significant because the investigation calls for the use of numerous environmental conditions. A large volume of specimens will be required to accomplish this elaborate investigation. It is therefore necessary to use the smallest specimens possible while still maintaining reasonable results. Because the 4-in square cross-section experienced the same failure mode as the 6-in specimens, it is concluded that using the smaller specimen will accurately reflect the failure mode. The 4-in cross-section specimen is used for all investigations discussed hereafter.

Additional Flexural Reinforcement

Additional flexural reinforcement was added to 12 specimens to strengthen against shear cracking at the ends of the beam and at mid-span along the saw-cut. There were three reinforcement types used: number 3 glass bars, number 3 Grade 60 rebar, and ¼-in thick steel plates. The bars were internal reinforcement, and the plates were external reinforcement.

The plates were added to the beams after concrete cure. These plates were Grade 60 steel and had dimensions of 1-in x ¼-in x 14-in for specimen T30-3 and 1¼-in x 3/16-in x 10-in for specimen T22-4. They were adhered to the concrete face located on each side of the specimen on either side of the saw-cut. Putty C epoxy was used to adhere the plates. The epoxy was applied to both the concrete and the plates with a spatula to a uniform thickness. The plate was then pressed to the concrete, epoxy faces touching. The plates were held in place overnight with steel clamps. The placement of the steel plates is shown in Figure 4-12.



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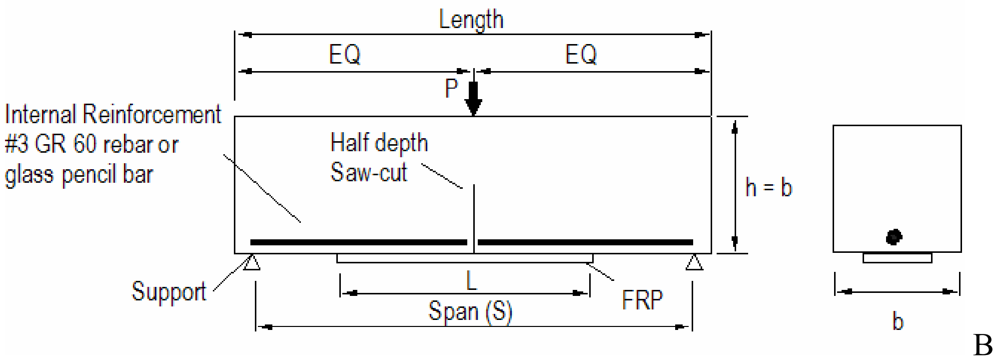


Figure 4-12. Schematic showing placement of additional reinforcement A) external reinforcing plates B) internal reinforcing bars

The internal reinforcing bars were added during concrete pouring. The bars were placed in the specimen molds so as to sit 1.5-in from the tension face of the beam and were centered on the width of the beam as shown in Figure 4-12. They were continuous through the length of the beam, but were cut at mid-span when the 0.1-in saw-cut was made.

Concrete Strength

Little data are available in literature that addresses the effect of concrete strength on the failure mode of CFRP composite bonded concrete. Preliminary testing indicated that an adhesive failure could be forced if the concrete strength was sufficiently high. Initial tests performed with a concrete strength of 5000-psi yielded inconsistent failure modes. Consequently, beams were constructed with 7000-psi concrete, which proved to be successful in promoting a consistent adhesive failure mode.

Two fiber types and six epoxy types were investigated with the two strength concretes. The specimens analyzed for this study, including the CFRP types and dimensions are shown in Table 4-6.

Table 4-6. Specimens used to analyze effect of concrete strength

Specimen	f'c (ksi)	composite	adhesive	w (in)	L (in)
T14-13-2	7.00	Composite T	Putty C	1	12
T14-14-2	7.00	Composite T	Putty C	1	12
T14-15-2	7.00	Composite T	Putty C	1	12
T14-16-2	7.00	Composite T	Putty C	1	12
T14-17	7.00	Composite T	Cab-O-Sil	1	12
T14-18	7.00	Composite T	Cab-O-Sil	1	12
T14-19	7.00	Composite T	Cab-O-Sil	1	12
T14-20	7.00	Composite T	Cab-O-Sil	1	12
T14-21	7.00	Composite T	Saturant T	1	12
T14-22	7.00	Composite T	Saturant T	1	8
T14-23	7.00	Composite T	Saturant T	1	12
T14-24	7.00	Composite T	Saturant T	1	8
T14-25	7.00	Composite T	Cab-O-Sil	1	8
T14-26	7.00	Composite T	Cab-O-Sil	1	8
T14-27	7.00	Composite T	Cab-O-Sil	1	8
T14-28	7.00	Composite T	Cab-O-Sil	1	8
TS-1	7.00	Composite A	Saturant A	1	8
TS-2	7.00	Composite A	Saturant A	1	8
TS-3	7.00	Composite A	Saturant A	1	8
TS-4	7.00	Composite A	Saturant A	1	8
TS-5	5.32	Composite A	Saturant A	1	8
TS-6	5.32	Composite A	Saturant A	1	8
TS-13	5.32	Composite A	Saturant S	1	8
TS-14	5.32	Composite A	Saturant S	1	8
TS-15	4.74	Composite A	Saturant S	1	8
TS-16	4.74	Composite A	Saturant S	1	8
TS-17	5.32	Composite A	Putty C	1	8
TS-18	5.32	Composite A	Putty C	1	8
TS-19	4.74	Composite A	Putty C	1	8
TS-20	4.74	Composite A	Putty C	1	8

It was necessary to ensure that the adhesive failure would occur for all fiber and epoxy types. Flexural testing was performed, and the failure mode of each specimen noted. The two concrete strengths were compared, and it was determined that having a strength of 7000-psi or greater would cause adhesive failure, while strengths less than this value will result in the other types of failure discussed previously.

CHAPTER 5
BEAM TEST: RESULTS AND DISCUSSION

This chapter presents the results and analysis of the tests conducted to optimize the test methodology. Results such as failure load, mode, and CFRP composite shear stress were compared to determine the effect of each variable. The final prototype configuration and test procedures were then selected based on the most favorable results.

Failure Modes

There are several possible failure modes for CFRP composite strengthened concrete beams tested in flexure. These failure modes are noted in the literature with sometimes conflicting names. The failure modes noted in the beam testing for the pilot study are detailed in Table 5-1, along with the names that will be used for the remainder of this report. Adhesive failure was the target mode during the development of the beam test protocol because the capacity obtained from testing directly correlates to the CFRP to concrete bond strength. In practice, interfacial failure is the desired failure mode.

Flexural loading was applied to the beam specimens at a constant displacement rate until failure. The beam had an initial stiffness before cracking occurred, as shown by the change in slope on the load vs. position plot in Figure 5-1. The point at which the slope changes represents cracking of the concrete beam. The third region is where cracking further reduces the stiffness of the beam, until the beam is fully cracked and cannot carry additional load. The failure of the specimen occurred along the bond line (adhesive or interfacial) or as a flexure-shear crack. These failure modes are outlined below.

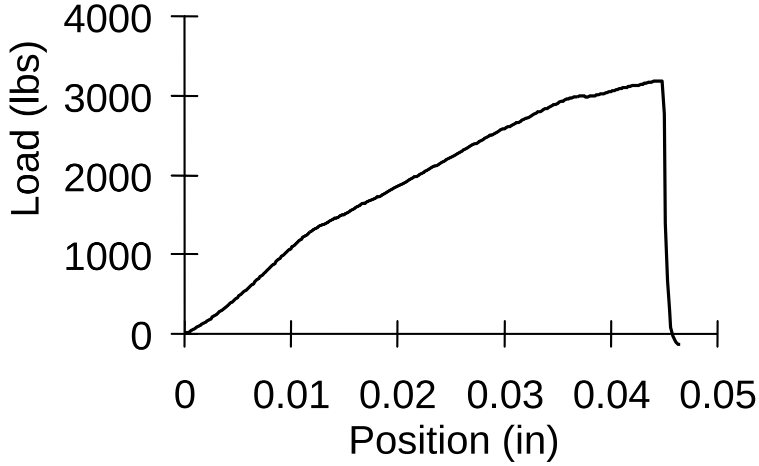


Figure 5-1. Load vs. position plot for a typical beam test

Table 5-1. Definition and description of Beam Test failure modes

Failure mode	Visual Characterization	Causes	Figure
Adhesive	Adhesive failure with rupture surface between CFRP and concrete surface. CFRP failure surface clean or covered with thin layer of concrete	Low adhesive strength or improper surface preparation.	15
Interfacial	Cohesive failure with rupture surface through concrete paste and aggregate. Concrete remains adhered to CFRP composite	Desired failure mode in practice.	16
Mixed-mode adhesive/interfacial	See interfacial failure	See interfacial failure	17
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	Beam strength with CFRP is sufficiently high to cause a Flexure-shear failure at the end of the CFRP.	18
Composite delamination	CFRP composite splits between laminations. Lamination(s) remain adhered to concrete	Adhesive strength is greater than the bond between composite laminations.	19

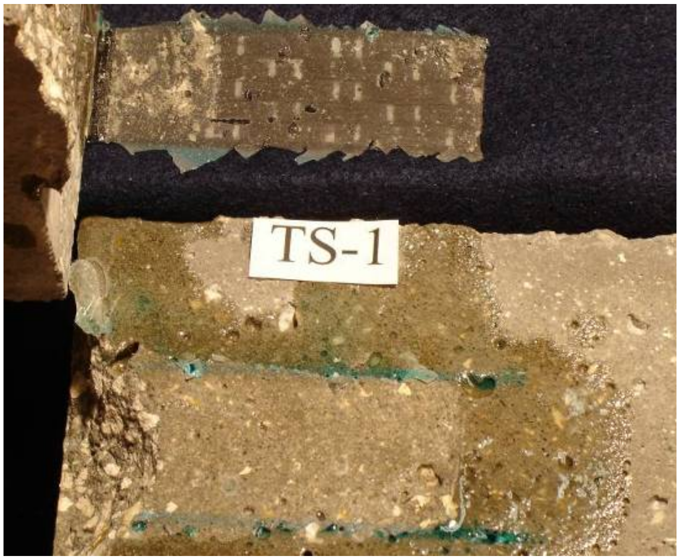


Figure 5-2. Adhesive failure mode

Figure 5-3. Interfacial failure mode

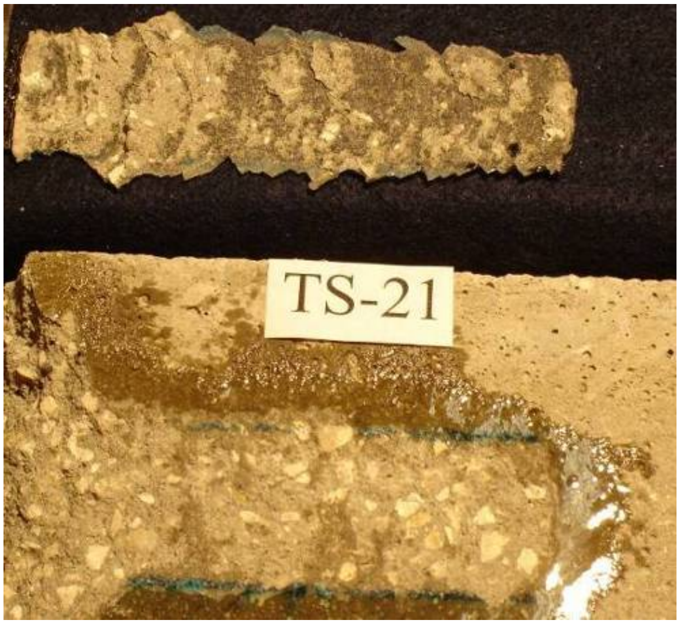


Figure 5-4. Adhesive/Interfacial failure mode

Figure 5-5. Flexure-shear failure mode

Figure 5-6. Composite delamination failure mode

Analysis

The peak measured load from each test was used to calculate both the peak tension in the CFRP composite and the shear stress at the bond line between the composite and concrete. Figure 5-7 shows a free-body diagram of the test beam including the internal stresses that develop during loading.

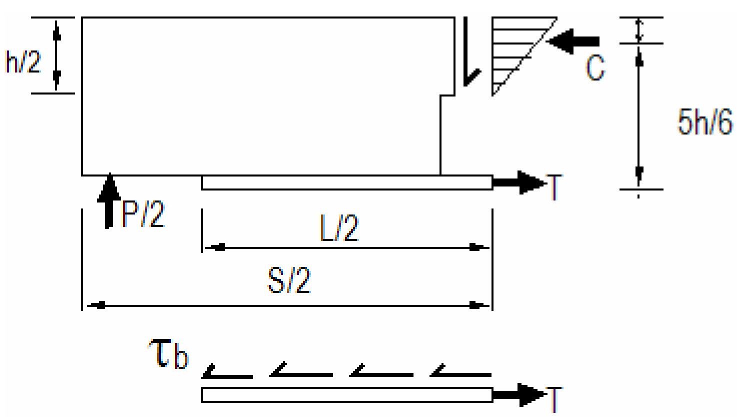


Figure 5-7. Cross-section of beam showing internal moments used to calculate shear stress in composite

Equating the moment from the internal actions to the applied moment gives:

$$\frac{P \cdot S}{4} = \frac{5}{6} \cdot h \cdot T \qquad \text{Equation 5-1}$$

Solving for T gives the force in the CFRP composite at the peak load:

$$T = \frac{3 \cdot P \cdot S}{10 \cdot h} \qquad \text{Equation 5-2}$$

It is a well known fact that the bond line shear stress varies drastically along the length of the composite. For simplification, the analysis presented in this report has assumed an average bond line shear stress (τ_b) along the length of the composite, which is calculated by dividing T by the contact area on one side of the saw-cut and using the peak measured load from the beam test for P:

$$\tau_b = \frac{T}{w \cdot L/2} \qquad \text{Equation 5-3}$$

$$\tau_b = \frac{3 \cdot P \cdot S}{5 \cdot h \cdot w \cdot L} \qquad \text{Equation 5-4}$$

Although the concrete compression region does not realistically extend the entire region above the saw-cut, it has been generalized in this analysis for easy comparison among specimens. During testing, a crack in the concrete was visible above the saw-cut,, thus increasing the internal moment arm from that shown in Figure 21. The simplified analysis procedure will be used for comparison of specimens with similar concrete and composite stiffness, so the assumed moment arm is appropriate.

Effect of Beam Size

Table 5-2 presents the results of beam tests in which the beam size and reinforcement length were varied. All beams were tested in 3-point bending. The failure mode was typically bi-modal in which a portion of the de-bonded length was interfacial and the remainder was adhesive (Figure 5-8). As the overall length of composite was reduced, however, the interfacial portion remained fairly constant while the adhesive portion shortened. The extreme example of this behavior is shown in Figure 5-9 where the adhesive failure was eliminated due to the short length of the composite used.

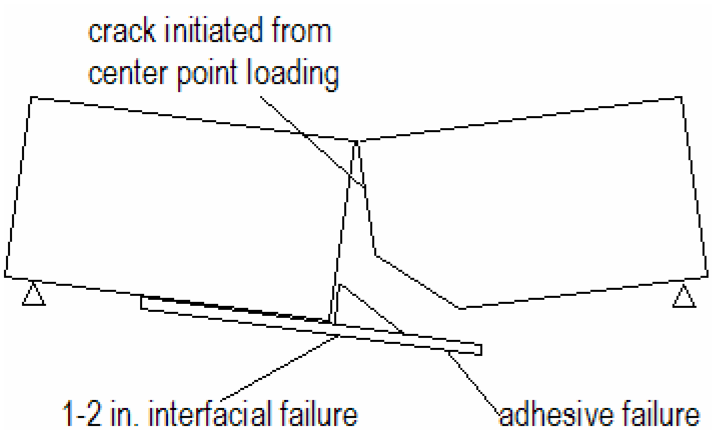


Figure 5-8. Flexural failure progression

A 

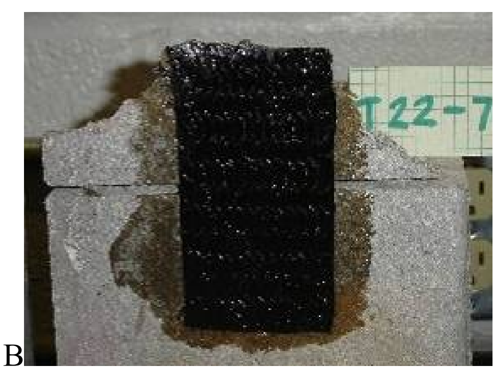
B 

Figure 5-9. Interfacial failure caused by short CFRP A) concrete failure surface B) CFRP failure surface

Table 5-2. Failure modes of concrete geometry specimens

Specimen	b=h (in)	w (in)	L (in)	L/S	Failure mode	P (kip)	τ_b (psi)
T30-1	6	4	12	0.43	Adhesive	3.85	225
T30-2	6	4	12	0.43	Adhesive	5.31	310
T30-3	6	4	16	0.57	Adhesive	4.51	197
T30-4	6	4	16	0.57	Adhesive	5.63	246
T30-5	6	2	8	0.29	Adhesive	1.96	343
T30-6	6	2	8	0.29	Adhesive	2.79	488
T30-7	6	2	6	0.21	adhesive/interfacial	1.98	462
T30-8	6	2	6	0.21	adhesive/interfacial	2.4	560
T22-1	6	4	8	0.40	Adhesive	6.29	393
T22-2	6	4	8	0.40	Adhesive	6.77	423
T22-3	6	4	12	0.60	Adhesive	6.12	255
T22-4	6	4	12	0.60	Adhesive	5.06	211
T22-5	6	2	6	0.30	adhesive/interfacial	3.89	648
T22-6	6	2	6	0.30	interfacial	3.82	637
T22-7	6	2	4	0.20	interfacial (substrate)	2.75	688
T22-8	6	2	4	0.20	interfacial (substrate)	2.80	700
T14-1	4	3	6	0.50	Adhesive	5.37	537
T14-2	4	3	6	0.50	Adhesive	5.19	519
T14-3	4	3	8	0.67	Adhesive	3.02	227
T14-4	4	3	8	0.67	Adhesive	2.73	205
T14-5	4	1	4	0.33	adhesive/interfacial	2.04	918
T14-6	4	1	4	0.33	adhesive/interfacial	2.14	963
T14-7	4	1	2	0.17	interfacial (substrate)	N/A	N/A
T14-8	4	1	2	0.17	interfacial (substrate)	1.55	1395

As the CFRP length to span ratio (L/S) was increased, the bond line shear stress decreased linearly as shown in Figure 5-10. This trend occurred for all span lengths considered. The bond line shear stress for a particular L/S value decreased with increasing span lengths until a critical L/S value was reached. For L/S values greater than 60%, the shear stress remained constant for all span lengths considered. These results were confirmed by an investigation of composite length with the 14-in long specimens.

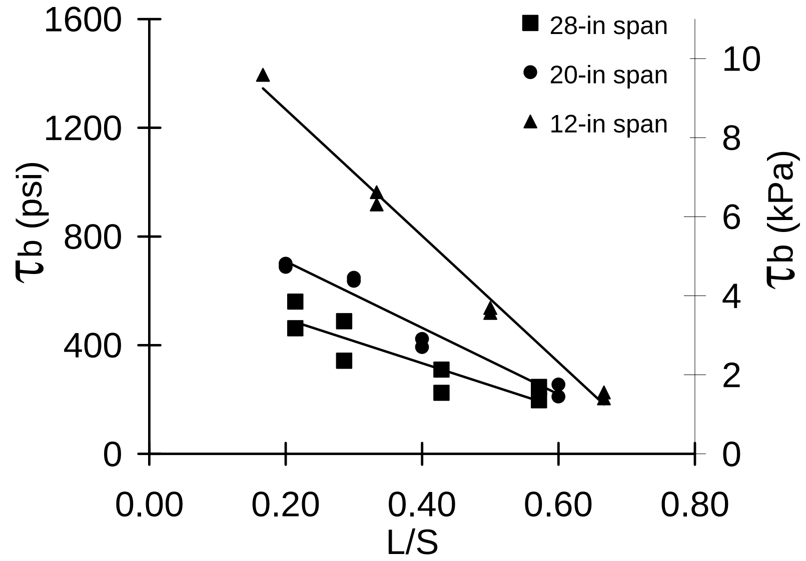


Figure 5-10. Bond line shear stress vs. length to span ratio

The failure load increased as the composite length was increased from 2-in to 8-in, but remained effectively constant for lengths between 8-in and 12-in, as shown in Figure 5-11. A consistent adhesive failure mode was observed as the length of the composite was increased. The increase in capacity was therefore due to the increase in length, not a change in failure mode. A minimum composite length of 8-in resulted in the maximum capacity for a 1-in width for all composites investigated. Additional length did not change the failure mode or give additional capacity, making the 14-in test beam with an 8-in length of CFRP composite the ideal configuration.

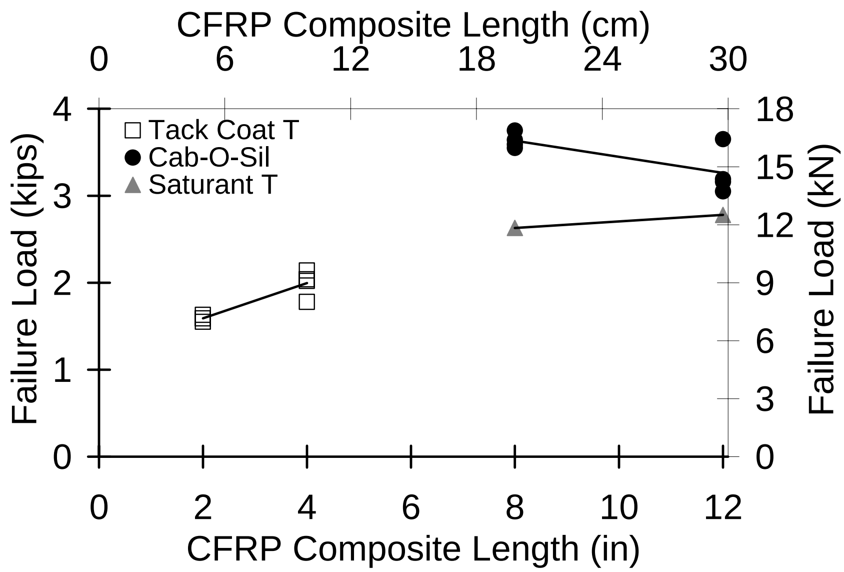


Figure 5-11. Failure load vs. composite length for 3 different composites

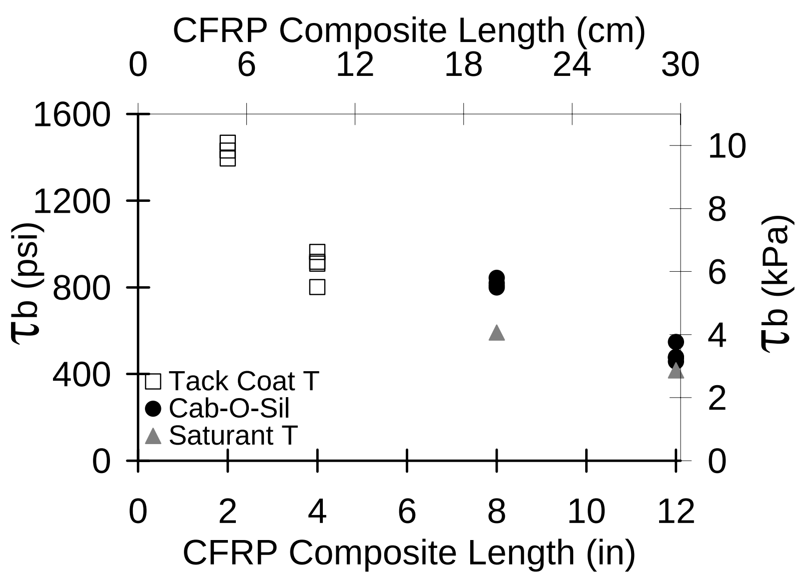


Figure 5-12. Bond line shear stress vs. composite length for 3 different composites

Effect of CFRP Composite Width

The width of the CFRP composite reinforcement influenced the failure capacity and behavior of the beam specimens. To produce the desired results for this study, two widths CFRP wet lay-up composite and three widths of CFRP laminate were analyzed with respect to their failure mode, load, and composite shear stress as given in Table 5-3.

Table 5-3. Flexural testing results for composite width comparison

Specimen	Composite	Adhesive	w	L	Failure mode	P (kip)	Pavg (kip)	T_b (psi)
TS-5	A	Saturant A	1	8	interfacial	2.98	3.21	671
TS-6	A	Saturant A	1	8	interfacial	3.43		772
TS-9	A	Saturant A	2	8	flexure-shear	4.13	4.09	465
TS-10	A	Saturant A	2	8	flexure-shear	4.51		507
TS-11	A	Saturant A	2	8	interfacial	3.88		437
TS-12	A	Saturant A	2	8	flexure-shear	3.82		430
TS-21	S	Saturant A	1	8	interfacial	1.67	1.91	376
TS-22	S	Saturant A	1	8	adhesive/interfacial	1.94		437
TS-23	S	Saturant A	1	8	adhesive/interfacial	2.02		455
TS-24	S	Saturant A	1	8	adhesive/interfacial	1.99		448
TS-25	S	Saturant A	2	8	adhesive/interfacial	3.18	3.21	358
TS-26	S	Saturant A	2	8	adhesive/interfacial	2.99		336
TS-27	S	Saturant A	2	8	adhesive	3.30		371
TS-28	S	Saturant A	2	8	interfacial	3.38		380
TS-33	C	Putty C	2	8	flexure-shear	4.99	4.94	570
TS-34	C	Putty C	2	8	flexure-shear	4.75		543
TS-35	C	Putty C	2	8	flexure-shear	4.70		537
TS-36	C	Putty C	2	8	flexure-shear	5.32		608
TB-1	C	Putty C	1	8	interfacial	3.85	3.75	866
TB-2	C	Putty C	1	8	interfacial	3.64		819
TB-3	C	Putty C	1	8	flexure-shear	3.70	3.76	833
TB-4	C	Putty C	1	8	flexure-shear	3.81		857
TB-5	C	Putty C	¾	8	adhesive	3.48	3.42	1040
TB-6	C	Putty C	¾	8	adhesive	3.37		1010

Increasing widths of CFRP composite were tested to determine the effect on the specimen failure behavior. As the width of the CFRP composite was increased, the capacity of the composite and the specimen increased, as shown in Figure 5-13. This increase in capacity caused a change in failure mode from adhesive to flexure-shear.

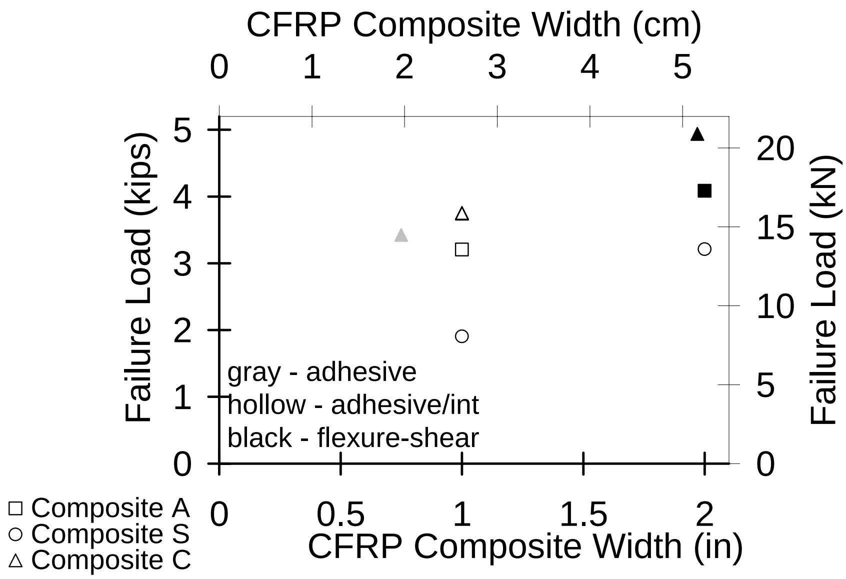


Figure 5-13. Failure load vs. width for different composites

Adhesive failure behavior was observed for small widths of composite as shown in Figure 5- 14a, because the composite bond strength was less than the interfacial failure strength of the concrete. As the width of the CFRP was increased, the bond strength of the composite exceeded the concrete interfacial strength resulting in a transition from adhesive to interfacial failure (Figure 5- 14b and c). As the width of the composite was further increased, the flexural strength of the reinforced portion of the beam became greater than the flexure-shear strength of the concrete. The specimen then failed in flexure-shear and the CFRP remained fully bonded to the tension face of the concrete, as shown in Figure 5- 14d.

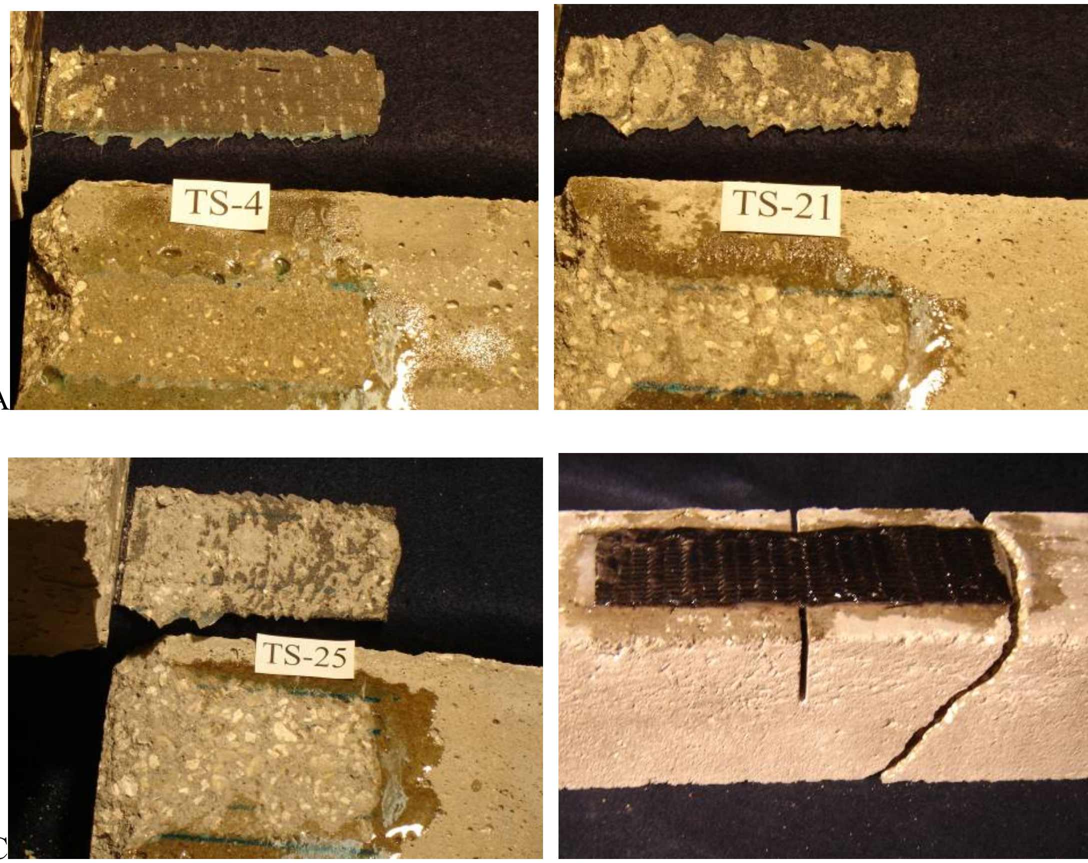


Figure 5- 14. Failure mode progression for increasing CFRP width A) adhesive failure B) adhesive/interfacial failure C) adhesive/interfacial failure D) flexure-shear failure

Results showed that each composite system tested had a maximum width, defined as the adhesive failure transition width, at which adhesive failure occurred. Figure 5-13 shows the failure modes for each composite as a function of capacity and composite width. At 3.5 kips, Composite C had an adhesive failure transition width of 0.75-in. Composite A also had an adhesive failure and a capacity of 3.5 kips, but with a width of 1-in. With a larger 2-in width, Composite S failed adhesively, but did not reach a capacity of 3.5 kips. Therefore, the adhesive transition width for all composites was associated with a failure capacity of 3.5-kips for this mix of concrete. Once the width was increased past this transition point, the concrete capacity controlled and the failure mode changed to interfacial or flexure-shear. The controlling capacity of 3.5-kips is for the particular concrete used in this study, and will change depending on the strength of the concrete.

A change in the failure mode from adhesive to flexure-shear caused a decrease in the bond line shear stress (Figure 5-15). Composite S exhibited adhesive/interfacial failure for both 1-in and 2-in widths. The bond line shear stress remained constant with an increase in width because the failure mode remained the same. For composites A and C, a change in failure mode occurred, causing a decrease in bond line shear stress.

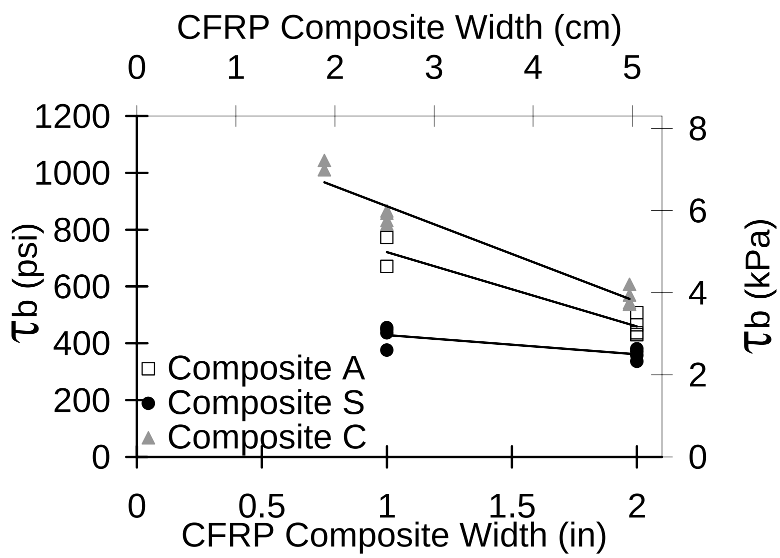


Figure 5-15. Bond line shear stress vs. CFRP composite width for different composites

Effect of Concrete Strength

It is well established that the concrete tensile strength varies with the square root of f'c. In addition, the interfacial failure mode is likely to be greatly influenced by the concrete tensile strength. Consequently to force an adhesive failure (or avoid an interfacial failure), it is necessary to increase the concrete strength of the beam. Flexural testing of thirty specimens with concrete strengths between 4-ksi and 7-ksi produced failure modes ranging from adhesive to interfacial, as shown in Table 5-4. Nearly all specimens with a concrete strength of 7-ksi or greater had adhesive failures, while those with a concrete strength less than 7-ksi had interfacial failures.

Table 5-4. Failure modes for concrete strength comparison

Specimen	f'c (ksi)	composite	adhesive	failure mode	P (kip)	Pavg (kip)	τ_b (psi)
T14-13-2	7.00*	T	Putty C	adhesive/interfacial	3.68	3.91	552
T14-14-2	7.00	T	Putty C	adhesive/interfacial	4.41		662
T14-15-2	7.00	T	Putty C	adhesive/interfacial	3.58		537
T14-16-2	7.00	T	Putty C	adhesive/interfacial	3.97		596
T14-17	7.00	T	Cab-O-Sil	adhesive/interfacial	3.19	3.26	479
T14-18	7.00	T	Cab-O-Sil	adhesive/interfacial	3.16		474
T14-19	7.00	T	Cab-O-Sil	adhesive/interfacial	3.05		458
T14-20	7.00	T	Cab-O-Sil	adhesive/interfacial	3.65		548
T14-21	7.00	T	Saturant T	adhesive	2.78	2.71	417
T14-22	7.00	T	Saturant T	adhesive	2.63		592
T14-25	7.00	T	Cab-O-Sil	interfacial	3.75	3.63	844
T14-26	7.00	T	Cab-O-Sil	adhesive	3.64		819
T14-27	7.00	T	Cab-O-Sil	adhesive	3.59		808
T14-28	7.00	T	Cab-O-Sil	adhesive/interfacial	3.55		799
TS-1	7.00	A	Saturant A	adhesive	2.92	2.88	657
TS-2	7.00	A	Saturant A	adhesive	3.20		720
TS-3	7.00	A	Saturant A	adhesive	3.21		722
TS-4	7.00	A	Saturant A	adhesive	2.64		594
TS-5	5.32	A	Saturant A	interfacial	2.98	3.21	671
TS-6	5.32	A	Saturant A	interfacial	3.43		772
TS-13	5.32	A	Saturant S	interfacial	2.76	2.66	621
TS-14	5.32	A	Saturant S	interfacial	2.53		569
TS-15	4.74	A	Saturant S	interfacial	2.64		594
TS-16	4.74	A	Saturant S	interfacial	2.70		608
TS-17	5.32	A	Putty C	interfacial	2.43	2.70	547
TS-18	5.32	A	Putty C	interfacial	2.96		666
TS-19	4.74	A	Putty C	interfacial	2.54		572
TS-20	4.74	A	Putty C	adhesive/interfacial	2.85		641

* Actual strength not measured, but mix design was for concrete strength equal to or greater than 7.00 ksi

As the concrete strength was increased from 5-ksi to 7-ksi, the failure mode of all specimens changed from interfacial to adhesive or mixed mode. For some specimens, as the failure mode changed, an increase in capacity occurred. The increase in capacity indicated the epoxy bond strength had not been reached with the lower strength concrete. Therefore, the minimum concrete strength to force adhesive failure for these epoxies was 7-ksi or greater. For other specimens, however, the change in failure mode did not statistically alter the capacity. This indicated that the minimum concrete strength to cause adhesive failure is close to 5-ksi. An example of a specimen with constant capacity (Saturant A) and an increase in capacity (Putty C) is shown in Figure 5-16.

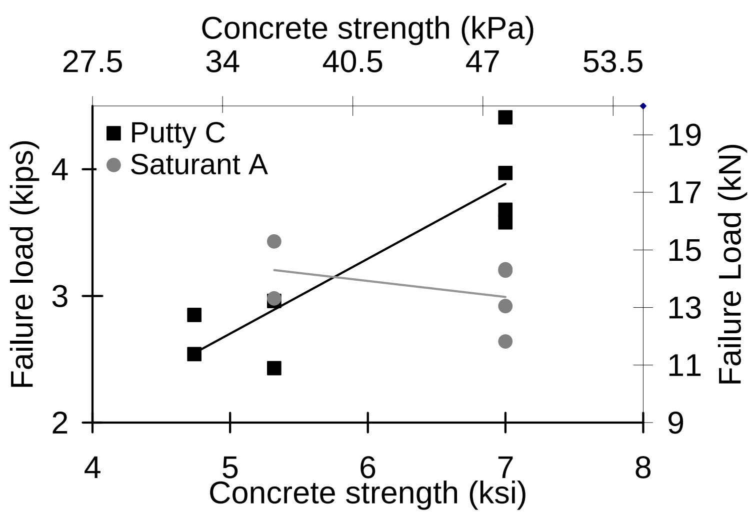


Figure 5-16. Failure load with increasing concrete strength

The durability study requires that the control (unexposed) failure mode be adhesive to ensure that a mode change does not occur after exposure. It has been shown here that the concrete strength must be sufficiently high to meet this criterion. For the limited adhesives tested here, it appears that a concrete compressive strength of 7-ksi will be sufficient. It is critical, however, that the minimum concrete strength be established in this manner for each CFRP composite system to be tested.

Effect of Composite System

Flexural testing results show the composite type had an effect on the capacity of the specimen, while the adhesive type had a minimal effect. Changing the adhesive with a particular composite fiber did not effectively alter the capacity. Changing composite fibers with a particular adhesive did alter the capacity, as can be seen in Figure 5-17.

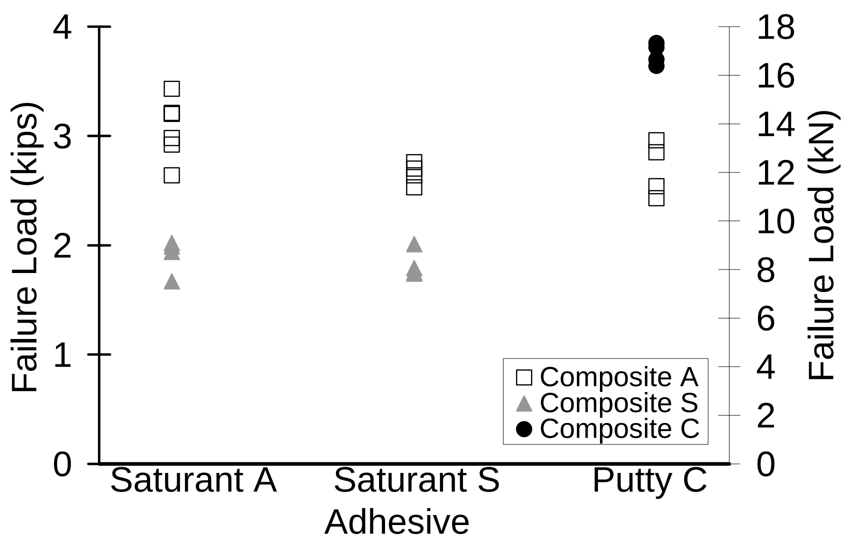
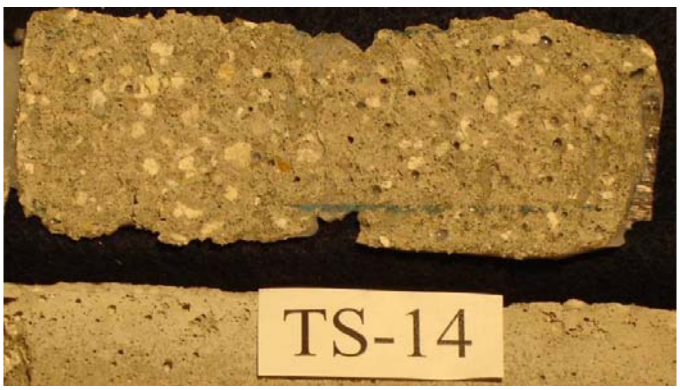


Figure 5-17. Comparison of failure load for composites with different adhesives

Although interfacial failure was observed for most specimens, the failure load varied among different composite systems. Interfacial failure occurred when the interfacial concrete strength was less than the adhesive strength of the composite. The location of the interfacial crack along the concrete bond line was dependant on the shear stress developed across the composite concrete bond line. Table 5-6 shows the relation between failure load and shear stress developed in the CFRP composite. As the shear stress in the composite was increased, the counteracting shear stress in the concrete was increased, developing a deeper interfacial region (Figure 5-18).

If the composite's ability to develop bond line shear stress was weak, the specimen exhibited adhesive behavior as it sheared through the adhesive layer. The failure load was then bounded by the adhesive strength. If the composite strength was greater than the concrete interfacial failure strength, the failure load was dependant on both the concrete interfacial strength and the composite strength. The composite stiffness increased with the use of different composites (Table 5-5), creating more bond line shear stress and increasing the capacity of the specimen.



A

B

Figure 5-18. Interfacial failure modes for two different composite systems with the same adhesive (Saturant S) A) Composite A B) Composite S

Table 5-5. Fiber weight and stiffness for composites C, A, and S

Composite	Fiber wt/sq. yard (oz)	Tensile modulus (ksi)
C	48	23900
A	19	10239
S	6.7	9492

Table 5-6. Failure mode and load for specimens investigated for composite type

Specimen	Composite	Adhesive	Failure mode	P (kip)	Pavg (kip)	tau (ksi)
TS-1	A	Saturant A	adhesive	2.92	3.06	0.66
TS-2	A	Saturant A	adhesive	3.20		0.72
TS-3	A	Saturant A	adhesive	3.21		0.72
TS-4	A	Saturant A	adhesive	2.64		0.59
TS-5	A	Saturant A	interfacial	2.98		0.67
TS-6	A	Saturant A	interfacial	3.43		0.77
TS-13	A	Saturant S	interfacial	2.76	2.66	0.62
TS-14	A	Saturant S	interfacial	2.53		0.57
TS-15	A	Saturant S	interfacial	2.64		0.59
TS-16	A	Saturant S	interfacial	2.70		0.61
TS-17	A	Putty C	interfacial	2.43	2.70	0.55
TS-18	A	Putty C	interfacial	2.96		0.67
TS-19	A	Putty C	interfacial	2.54		0.57
TS-20	A	Putty C	adhesive/interfacial	2.85		0.64
TS-21	S	Saturant A	interfacial	1.67	1.91	0.38
TS-22	S	Saturant A	adhesive/interfacial	1.94		0.44
TS-23	S	Saturant A	adhesive/interfacial	2.02		0.45
TS-24	S	Saturant A	adhesive/interfacial	1.99		0.45
TS-29	S	Saturant S	interfacial	1.74	1.82	0.39
TS-30	S	Saturant S	interfacial	1.79		0.40
TS-31	S	Saturant S	interfacial	2.01		0.45
TS-32	S	Saturant S	interfacial	1.75		0.39
TB-1	C	Putty C	interfacial	3.85	3.75	0.87
TB-2	C	Putty C	interfacial	3.64		0.82
TB-3	C	Putty C	flexure-shear	3.70		0.83
TB-4	C	Putty C	flexure-shear	3.81		0.86

Effect of Testing Configuration

The use of both 3 and 4 point load configurations were investigated. Assuming that the loads are at the third points in the four-point bending, the shear in the 4-point bending must be 50% greater than that in the 3-point bending for the same applied moment. The 4-point bending configuration has a zero shear where the moment is maximum, which is desirable. When testing a strengthened beam, however, it was found that the large forces generated could precipitate a flexure-shear failure at the end of the reinforcement.

Three loading configurations were investigated to determine the effect of the increased shear on the failure mode:

1) Three-point loading
2) Four-point loading with 2-in. between loads
3) Four-point loading with 4-in. between loads

The results of flexural testing, including failure load, CFRP shear stress, and failure mode as given in Table 5-7 were compared for the different load configurations.

Table 5-7. Flexural testing results for testing procedure study

Specimen	Composite	w	D	f'c	P	avg. P	τ_b	avg τ_b	st. dev.	Failure mode
		(in)	(in)	(ksi)	(kip)	(kip)	(psi)	(psi)	(ksi)	
TG-1	Composite A/Saturant A with glass bar	1	0	7.94	4.18	3.57	470	402	0.06	adhesive
TG-2				7.94	3.10		349			adhesive
TG-3				7.94	3.43		386			adhesive
TG-4			2	7.94	3.38	3.82	317	358		adhesive
TG-5				7.94	4.26		399			adhesive/interfacial
TR-1	Composite A/Saturant A with steel bar	1	0	7.94	3.69	3.45	415	389	0.04	adhesive/interfacial
TR-2				7.94	3.57		402			adhesive
TR-3				7.94	3.10		349			adhesive
TR-4			2	7.94	3.53	3.68	331	345		adhesive
TR-5				7.94	3.83		359			adhesive
TS-5	Composite A/Saturant A	1	0	5.32	2.98	3.21	335	361	0.03	interfacial
TS-6				5.32	3.43		386			interfacial
T4-5			2	4.85	3.37	3.33	316	312		interfacial
T4-6				4.85	3.28		307			adhesive/interfacial
T4-7			4	4.74	4.17	3.99	313	300		interfacial
T4-8				4.74	3.81		286			interfacial
TS-9	Composite A/Saturant A (3-pt), Composite T/Cab-O-Sil (4-pt)	2	0	5.32	4.13	4.09	232	230	0.03	flexure-shear
TS-10				5.32	4.51		254			flexure-shear
TS-11				4.85	3.88		218			interfacial
TS-12				4.85	3.82		215			flexure-shear
T4-1			2	7.00	5.30	5.62	248	263		flexure-shear
T4-2				7.00	5.93		278			flexure-shear
T4-3			4	7.00	7.36	6.49	276	243		flexure-shear
T4-4				7.00	5.61		210			flexure-shear

As the distance D was decreased from 4-in to 0-in, the failure mode for like specimens remained the same. Specimens with 1-in CFRP strips exhibited adhesive or interfacial failure while specimens with 2-in CFRP strips had flexure-shear failure.

Although the capacity of the 2-in CFRP specimens increased with an increased distance between load points, the shear stress in the composite remained constant for all loading conditions. There was a decrease in shear stress for the 1-in CFRP strip specimens as the load points were separated, but the standard deviation between like specimens was the same as that between specimens with different loading conditions. The shear stresses were therefore equal within standard deviation with different loading conditions.

By changing the loading condition from 4-pt to 3-pt, there was no change in failure mode or CFRP shear stress for like specimens. An increase in failure capacity was however observed with an increase in distance D between load points. This increase in failure capacity produced greater shear at the end of the specimen, creating a potential for shear failure. The 3-pt loading condition was therefore determined to be the ideal testing configuration for this study.

Effect of Saw-cut

The inclusion of a half-depth saw-cut for moisture transfer to the bond line did not result in a change in failure mode for the specimens tested. The concrete compressive strength was great enough that even when the cross-section was reduced by the inclusion of the saw-cut, the failure mode remained adhesive. The reduction in concrete cross-sectional area at the point of maximum moment did however lead to a reduction in capacity, as shown in Table 5-8. For the NCHRP study, the specimens will be compared by percent capacity retained, so the reduction in capacity due to the inclusion of a saw-cut is not of concern. It is important, however, that the failure mode remain adhesive throughout the study. It was proven that the adhesive failure mode can be achieved with the inclusion of the saw-cut, and it will therefore be used in the durability study to facilitate moisture to the CFRP composite to concrete bond line.

Table 5-8. Flexural testing results for specimens with and without a saw-cut

Specimen	Saw-cut	L (in)	P (kips)	τ_b(ksi)	f_{fu} (ksi)	Failure mode
T14-21	Yes	12	2.78	0.42	63	adhesive
T14-22	Yes	8	2.63	0.59	59	adhesive
T14-23	No	12	3.61	0.68	102	adhesive
T14-24	No	8	3.38	0.95	95	adhesive

Effect of Added Tensile Reinforcement

Flexural testing of specimens including tensile reinforcement in addition to the CFRP composite resulted in similar failure behavior to those specimens reinforced solely with CFRP. The concrete batches used for those specimens with and without additional reinforcement had varying strengths as shown in

Table **5-9**. The failure loads cannot therefore be compared solely on the basis of added tensile reinforcement. The addition of reinforcement causes an increase in capacity, but not outside of the standard deviation. Moreover, the specimens with additional reinforcement had concrete with greater strength than specimens without additional reinforcement. Therefore, the increase in capacity could be attributed to the difference in concrete strength.

The internal bars were cut at the center with the inclusion of a saw-cut in the specimen and the external bars were applied so as to straddle the saw-cut. The additional reinforcement therefore did not affect the centerline behavior. This supports the result that capacity was not increased upon addition of reinforcement.

Table 5-9. Flexural test results for tensile reinforcement investigation

Specimen	f'c	Composite	Reinforcement	P	Failure mode
T30-2	7.41	Composite T	External steel plate	5.31	adhesive
T22-4	7.41	Composite T	External steel plate	5.06	adhesive
T30-1	7.41	Composite T	None	3.85	adhesive
T22-3	7.41	Composite T	None	6.12	adhesive
TG-1	7.94	Composite A	internal glass bar	4.18	adhesive
TG-2	7.94	Composite A	internal glass bar	3.10	adhesive
TG-3	7.94	Composite A	internal glass bar	3.43	adhesive
TR-1	7.94	Composite A	internal steel bar	3.69	adhesive/interfacial
TR-2	7.94	Composite A	internal steel bar	3.57	adhesive
TR-3	7.94	Composite A	internal steel bar	3.10	adhesive
TA-1	7.08	Composite A	None	2.93	adhesive
TA-2	7.08	Composite A	None	3.29	adhesive
TG-4	7.94	Composite A	internal glass bar	3.38	adhesive
TG-5	7.94	Composite A	internal glass bar	4.26	adhesive/interfacial
TR-4	7.94	Composite A	internal steel bar	3.53	adhesive
TR-5	7.94	Composite A	internal steel bar	3.83	adhesive
T4-5	7.00	Composite A	None	3.37	interfacial
T4-6	7.00	Composite A	None	3.28	adhesive/interfacial
TG-6	7.94	Composite C	internal glass bar	3.81	adhesive/interfacial
TR-6	7.94	Composite C	internal steel bar	4.00	adhesive/interfacial
TB-5	7.08	Composite C	None	3.48	adhesive
TB-6	7.08	Composite C	None	3.37	adhesive/interfacial

Specimens TG-4, TG-5, TR-4, TR-5, T4-5, and T4-6 were tested in four-point flexure and the load was therefore applied where the internal bars were continuous. The specimens failed at mid-span where the reinforcement bars were absent and exhibited adhesive/interfacial failure as shown in Figure 5-19. The load capacity also remained the same as specimens without additional reinforcement. The specimen configuration did not allow the additional reinforcement to engage, and they showed no signs of being stressed. The inclusion of additional reinforcement was therefore unnecessary as it did not increase capacity or change the failure behavior of the specimens tested.

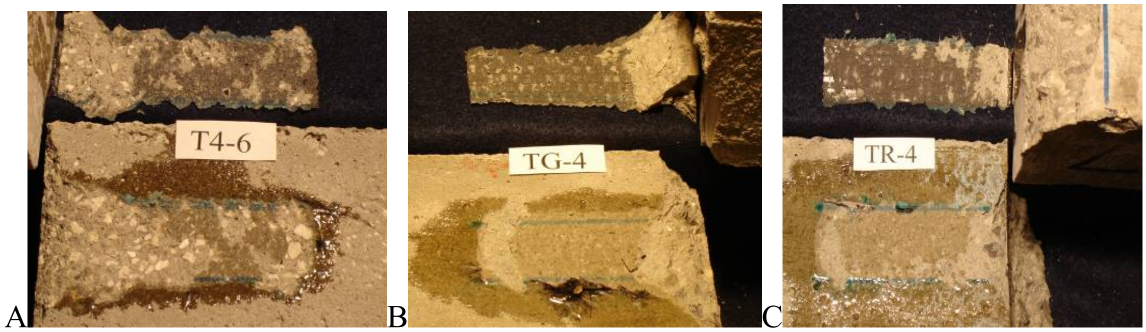


Figure 5-19. Failed specimens with (B and C) and without (A) additional tensile reinforcement.

Pilot Study Conclusions

Small concrete beam specimens were constructed and tested using a variety of beam sizes, loading configurations, CFRP reinforcement system, and concrete strength. The following characteristics were found to be the most suitable for use in the durability testing:

- Loading configuration: Three-point (center point) loading
- Beam size: 4-in. x 4-in. x 14-in. with a half-depth saw cut at midspan
- Concrete strength: Although a 7-ksi concrete strength was found to be suitable in most cases, it was decided that 10-ksi compressive strength would be used
- CFRP reinforcement: composite dimensions 1-in. wide by 8-in. long for wet lay-up and 0.75-in. wide by 8-in. long for pre-cured laminate composites

CHAPTER 6
ENVIRONMENTAL EXPOSURE SYSTEM: DESIGN AND CONSTRUCTION

This chapter describes the design, construction, and development of the environmental exposure system. A standard testing procedure based on the results from the pilot study was also developed. A total of 450 beams were made as detailed in the specimen matrix shown in Table 6-1.

Specimen Nomenclature

The following nomenclature was developed for use in identifying the variables during the experimental work and during analysis and reporting of the results. The naming system includes the exposure period, exposure condition, composite manufacturer, and replicate number. Each specimen name consists of letters and numbers, corresponding to an exposure period, exposure environment, composite manufacturer, and replicate number. Each name consists of six digits, with the order of the naming system as follows:

Exposure condition, Exposure time, Composite Manufacturer-Replicate Number

For resin samples, another letter representing the type of resin (saturant, primer, putty, top coat) is used following the composite manufacturer designation. The naming for the resin samples is as follows:

Exposure condition, Exposure time, Composite Manufacturer, Resin Type-Replicate Number

Table 6-1. Specimen Matrix for University of Florida NCHRP project 12-73

Condition	Solution	Temperature	Time	# Specimens Per Composite						Total	Total per exposure
		°C	months	A	B	C	D	E	MOR		
Control	N/A	N/A	6,12,24,60,120	15	15	15	9	9	15	78	78
Thermal & Chloride	Chloride Water	50	12	3	3	3	0	0	3	12	12
Thermal & Alkali	Alkali Water	50	12	3	3	3	0	0	3	12	12
Sustained Load	Water	50	6	4	4	4	0	0	0	12	39
			12	4	4	4	0	0	3	15	
			24	4	4	4	0	0	0	12	
UV/Wet/Dry	Water/UV drying	50	12	3	3	3	0	0	3	12	12
Real Time	Outdoors	N/A	24	3	3	3	0	0	0	9	30
			60	3	3	3	0	0	3	12	
			120	3	3	3	0	0	0	9	
Arrhenius	Water	30	6	0	0	3	3	3	3	12	48
			12	0	0	3	3	3	3	12	
			24	3	3	3	3	3	3	18	
			60	0	0	3	0	0	3	6	
		40	6	0	0	3	3	3	0	9	36
			12	0	0	3	3	3	0	9	
			24	3	3	3	3	3	0	15	
			60	0	0	3	0	0	0	3	
		50	6	0	0	3	3	3	0	9	36
			12	0	0	3	3	3	0	9	
			24	3	3	3	3	3	0	15	
			60	0	0	3	0	0	0	3	
		60	6	0	0	3	3	3	3	12	48
			12	0	0	3	3	3	3	12	
			24	3	3	3	3	3	3	18	
			60	0	0	3	0	0	3	6	

The letters and numbers used to represent each specimen description are given in Table 6-2 through Table 6-5. Examples for the nomenclature used for a specific specimen are given in Table 6-6.

Table 6-2. Symbols used for Exposure Period

Exposure Time	Symbol Used in Nomenclature
2 weeks	0.5
4 weeks	01
6 months	06
12 months	12
24 months	24
60 months	60
120 months	120

Table 6-3. Symbols used for Exposure Conditions

Exposure Condition	Symbol Used in Nomenclature
Control	CO
Thermal and Chloride	TC
Thermal and Alkaline	TA
Sustained Loading	SU
UV and Wet/Dry	UV
Freeze/Thaw	FT
Real Time Florida	RF
Real Time Wyoming	RW
Hygrothermal Autoclave	HA
Hygrothermal Fatigue	HF
Wet/Dry Thermal	WD
Arrhenius 30C	A3
Arrhenius 40C	A4
Arrhenius 50C	A5
Arrhenius 60C	A6

Table 6-4. Symbol used for Manufacturer/Composite System

Manufacturer/Composite System	Symbol used in Nomenclature
Manufacturer A	A
Manufacturer B	B
Manufacturer C	C
Manufacturer D	D
Manufacturer E	E
Manufacturer F	F

Table 6-5. Symbol used for Resin Type

Specimen Type	Symbol used in Nomenclature
Epoxy Resin (Primer)	R
Epoxy Resin (Putty)	P
Epoxy Resin (Saturant)	S
Epoxy Resin (Top Coat)	T

Table 6-6. Example Specimen Nomenclature for Resin Samples

Exposure time	Exposure Condition	Composite System	Resin Type	Replicate	Nomenclature
12 months	Freeze Thaw	Manufacturer B	Primer	2	FT12BR-2
12 months	Real Time Fl	Manufacturer C	Putty	1	RF12CP-1
60 months	Arrhenius 50C	Manufacturer D	Saturant	3	A560DS-3

Concrete Construction and Testing

The 450 beams to be used for the NCHRP study were constructed in six batches of 75 beams each at the FDOT SMO in Gainesville, Fl. Twenty-eight day testing was performed on concrete cylinders and beams. The details of the concrete construction and testing are given in the subsequent sections.

Construction procedure

The six batches of concrete were designed to have a target concrete 28-day compressive strength of 10000-psi to promote adhesive failure behavior. The mix had a water/cement ratio of 0.35 (lbs/lbs) and a ratio of cement/fine aggregate/coarse aggregate was 1.0:1.5:1.7 by weight. The cement used was Cemex Type I cement. WR Grace Daravair 1000 air entrainer was used to improve the workability due to the low water/cement ratio. WR Grace WRDA 60 and WR Grace ADVA 140 are admixtures that were used to retard the chemical reaction and improve working time and workability. The detailed mix properties and proportions are given in Appendix A.

The materials were mixed in a drum mixer. A 'butter' mix was used to coat the mixer before adding the materials to be used for the mix (Figure 6-1). This was done so the materials for the mix would not adhere to the sides of the mixer.

Figure 6-1. "Butter" mix used to coat the mixer

The coarse aggregate and sand were added first and allowed to mix thoroughly. The coarse aggregate was added to the mixer using a forklift and rocker, as shown in Figure 6-2. The cement and water were then slowly added to ensure consistent dispersion through the mix. The admixtures were then gradually added to the mixer to give it a more workable consistency, as shown in Figure 6-3. The concrete was then mixed for 3-minutes, allowed to rest for 3-minutes, and then mixed for 3-minutes. The slump of the concrete was then measured to ensure the correct consistency was reached. The slump of the concrete batches ranged from 3-in to 3.75-in (Figure 6-4).

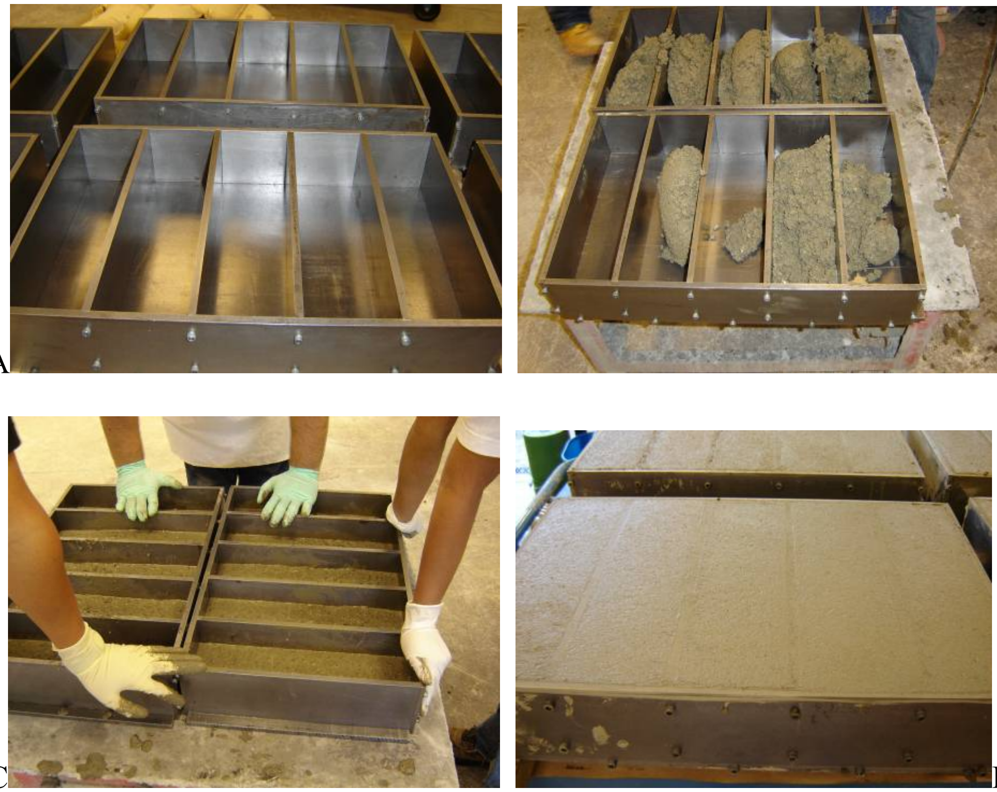
Figure 6-2. Addition of coarse aggregate to mixer

Figure 6-3. Addition of admixtures to the mixer

Figure 6-4. Slump measurement

Fifteen steel forms that held five beams each were used for construction. The forms were machined to give exact 4-in x 4-in x 14-in dimensions and had smooth form edges that were free of defects to give smooth concrete surfaces. The form surfaces were lightly oiled to retard corrosion and aid in de-molding the concrete.

The steel forms were placed 2 at a time on a vibrating table and were half filled with concrete as shown in Figure 6-5a-b. The vibrating table was then turned on for approximately 90-seconds to remove excess air and ensure proper gradation (Figure 6-5c). The forms were then filled completely with concrete and continued to vibrate for 90-seconds. The surfaces of the concrete beams were then finished until smooth and level using a concrete float (Figure 6-5d).

A  B

C D

Figure 6-5. Casting concrete beams. A) steel forms B) first lift of concrete in forms C) consolidation of concrete with vibrating table D) finished concrete in the forms.

Concrete cylinders were also constructed in the same manner. Four-inch diameter by eight-inch tall cylinder forms were filled in two lifts. The forms were filled halfway, and agitated on a vibrating table for 90-seconds. The forms were then filled completely and vibrated again for 90-seconds. The excess concrete was struck from the top of the forms. The top of the cylinder was then smoothed with a trowel.

The finished concrete beams and cylinders were covered with plastic to ensure moisture retention. Twenty-four hours after construction, the beams and cylinders were de-molded as shown in Figure 6-6. Once the beams and cylinders were de-molded, they were transferred to a pallet and placed in the moist cure room at the FDOT SMO. The concrete samples remained in the moist cure room for 28-days until cured.

Figure 6-6. De-molding of concrete beams from steel forms

Saw-cutting and surface preparation

At 14 days cure, the beams were removed from the moist cure room to be saw-cut. The beams were out of the moist cure room for a maximum of two hours, during which time they were periodically sprayed with water to ensure moisture retention. The beams that were to have CFRP applied were cut at mid-span to facilitate moisture transfer to the bond line during exposure. The saw used had a blade thickness of 0.1-in, resulting in a saw-cut width of 0.1-in (Figure 6-7). The cut had an approximate depth of 2-in and was placed between 6.825 and 7.00-in from one end of the beam. After being saw-cut, the beams were replaced in the moist cure room until 28-days cure was reached.

To achieve an adequate bond between the CFRP and the concrete, the concrete surface was roughened with a handheld sandblaster to a minimum ICRI specified profile 3. The sandblasting was performed in single line passes with the brush as shown in Figure 6-8, ensuring that all surfaces to be covered with CFRP had consistent profiles. To ensure consistent dimensions and surfaces on the testing faces, the beam was oriented so that the compressive and tension faces during testing would both be formed surfaces. In other words, the finished (top) surface of the beam during construction would be side facing during testing.

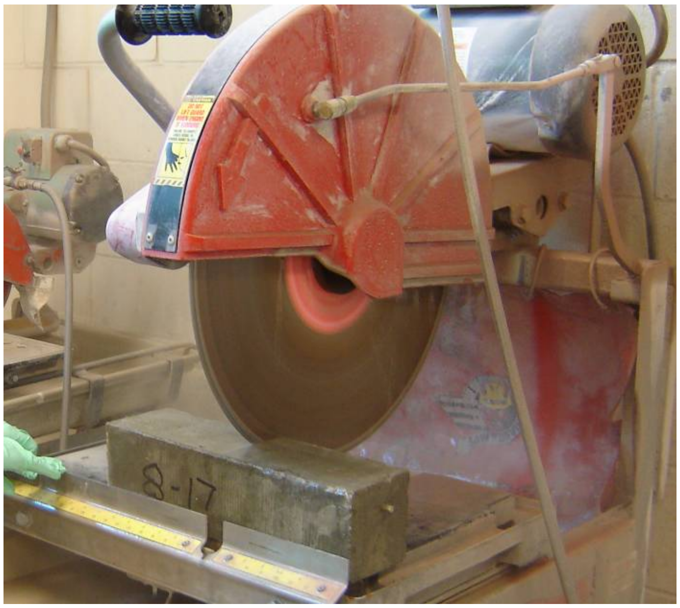


Figure 6-7. Saw-cutting a beam

Figure 6-8. A sandblasted concrete surface

28-day testing procedure and results

Twenty-eight day tests were performed for each concrete mix to determine compressive strength and modulus of rupture (MOR). Four by eight cylinders were used for the compressive test and 4-in x 4-in x 14-in beams were used for the MOR test. The specimens were transferred from the moist cure room at the FDOT to lime water 24 hours before testing. They were then tested immediately after removal from the lime water tank.

Cylinder testing was performed according to ASTM standard C39. Cylinders were placed between two cap plates cushioned with neoprene pads as shown in Figure 6-9. Load was then applied across the plates at a rate of 700 lbs/sec so that the cylinder would break between 1 and 2-min after reaching half capacity. The cylinders were loaded to failure, and the failure load and stress were recorded from the testing software. Three cylinders for each mix were tested with average compressive stresses ranging from 9.25 to 10.5 ksi (Table 6-7).

Figure 6-9. Cylinder compression strength test at 28-days

Table 6-7. 28-day compressive strength results

Mix	Cylinder	Failure load (lbs)	f'c (ksi)	Avg. f'c (ksi)
1	1	117770	9.371	9.86
	2	132330	10.531	
	3	121550	9.673	
2	1	127050	10.111	9.81
	2	130220	10.363	
	3	112640	8.964	
3	1	110300	8.777	9.26
	2	122620	9.758	
	3	116100	9.239	
4	1	123230	9.806	9.43
	2	121480	9.667	
	3	110750	8.813	
5	1	131580	10.471	10.43
	2	132190	10.519	
	3	129410	10.298	
6	1	120390	9.580	9.89
	2	129740	10.324	
	3	122860	9.777	

The modulus of rupture test was performed in accordance to ASTM standard C78-02. Loading was applied at the third points with an Instron testing machine as shown in Figure 6-10. The bottom supports were placed 1-in from the edges of the beam. The load frame was designed for the specimen size and accordance with the ASTM standard.

Figure 6-10. Modulus of rupture flexural strength test at 28-days

The load was applied at a constant displacement rate of 0.01-in/min until failure occurred. The failure load recorded by the testing machine and the measured cross-sectional dimensions were then used to determine the MOR (fr) with Equation 6-1.

$$f_r = \frac{P \cdot S}{b \cdot h^2} \qquad \text{Equation 6-1}$$

P is the failure load, S is the span between bottom supports, b is the cross-sectional width, and h is the cross-sectional depth. The average MOR for the concrete mixes ranged from 1034-psi to 1095-psi (Table 6-8).

Table 6-8. 28-day MOR test results

Mix	Beam	Failure load (lbs)	fr (psi)	Avg. fr (psi)
1	1	5699	1060	1034
	2	5465	1014	
	3	5513	1028	
2	1	5510	1033	1058
	2	5628	1055	
	3	5793	1086	
3	1	6103	1135	1091
	2	5751	1070	
	3	5741	1068	
4	1	5875	1101	1053
	2	5442	1018	
	3	5552	1041	
5	1	6010	1124	1095
	2	5966	1118	
	3	5622	1043	
6	1	5219	979	988
	2	5506	1032	
	3	9894	954	

Composite Properties and Application Procedures

Four unidirectional carbon fiber weaves and one unidirectional carbon laminate system were used to construct the specimens. Before composite application, the concrete surface was cleaned of any debris and grease. Lines were drawn on the concrete surface centered on the saw-cut, where the composite would be applied. The properties of each component and the composite system, as well as the detailed construction procedures are given in the subsequent sections.

Composite A

Composite A was comprised of a high strength unidirectional carbon fiber fabric impregnated with an epoxy resin. The epoxy resin was a two-component 100% solids, moisture tolerant, high strength and modulus epoxy. The system was sealed with a protective coating that had high resistance to carbon dioxide, chlorides and salts; low temperature crack-bridging abilities; and excellent UV light resistance. The material properties of each component of the composite system, as well as the constructed composite are given in Table 6-9.

Table 6-9. Material properties for Composite A

Component	Tensile Strength (ksi)	Tensile Modulus (ksi)	Elongation (%)
Fiber Weave	550.0	34000	1.5
Epoxy Saturant	8.0	250	3.0
Composite	123.2	10240	1.12

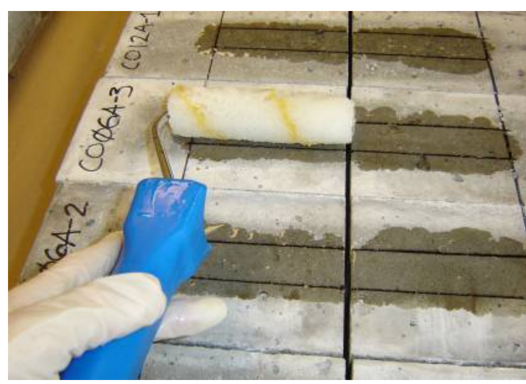
Composite A was constructed in four layers. First, a small batch of two-part saturant was mixed. Part A was weighed into a plastic beaker, and Part B was then added at a ratio of 1.0:0.345 A:B by weight. The two components were then hand mixed for 3-minutes with a paddle until a uniform clear amber color was reached. The mixed saturant was then applied to the concrete surface in the marked areas using a nap roller, making sure all crevices were adequately filled.

The first saturant coat was allowed to rest for approximately 1-hour until a tacky consistency was reached. Another batch of saturant was then mixed and applied to the first layer using the same nap roller, as shown in Figure 6-11b. The saturant was then used to impregnate the pre-cut 8-in x 1-in carbon fiber weave. The 8-in length was cut in the direction of the fibers.

The fibers were laid out on a piece of plastic and saturant was drizzled over them with a ratio of 1:1 by weight. A nap roller was rolled in the direction of the fibers, distributing the saturant along and between the fibers. The fibers were flipped, and this process was repeated on the other side. The pressure of the roller ensured that the saturant fully penetrated the depth of the fiber weave.

The impregnated fibers were then placed on the concrete on top of the saturant layers. The fiber was then rolled in the direction of the fibers to ensure bonding between the fibers and saturant layers. Figure 6-11c shows the composite after it was allowed to rest overnight for initial cure. The topcoat was then applied in three layers to the surface of the composite, until uniform covering occurred (Figure 6-11d). The previous layer was allowed to completely dry before subsequent layer was applied. Layers 1 and 2 were applied on same day, while layer 3 was applied on the following day.

A 



B

Figure 6-11. Application of Composite A A) sandblast surface prepared specimens B) application of prime coat C) application of cut to length fiber fabric D) application of top coat

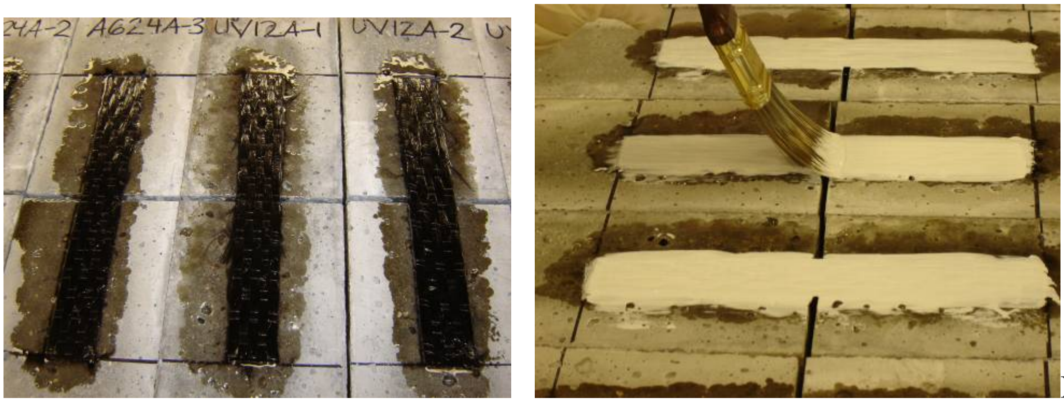
C  D

Figure 6-11. Continued.

Composite B

Composite B consisted of epoxy primer, epoxy putty, epoxy saturant, fiber weave, and protective top coat. The fiber weave was unidirectional carbon fiber with high strength and stiffness, lightweight, highly durable, and non-corrosive. 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 was a coating used to protect against UV radiation and mild abrasion. Table 6-10 gives the material properties for the components of Composite B.

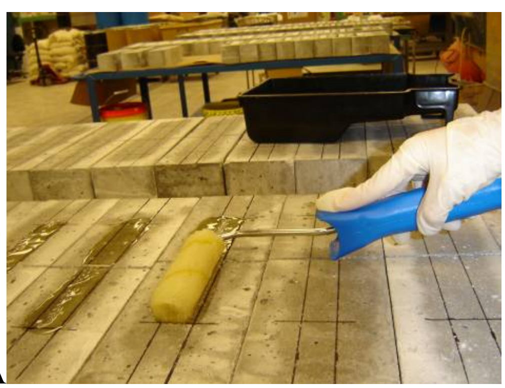
Table 6-10. Material properties for Composite B

Component	Tensile Strength	Tensile Modulus	Elongation	Tg	CTE
	ksi	ksi	%	°C	10^{-6}/°C
Fiber Weave	550.0	33000	1.67	-	-.38
Epoxy Primer	2.5	105	2.0	77	35
Epoxy Putty	2.2	260	1.5	75	35
Epoxy Saturant	8.0	440	2.5	71	35

The five components of Composite B were applied in a layered fashion. The primer, putty, and saturant were 2-part epoxies made by hand mixing appropriate amounts of parts A and B in a plastic beaker for 3 minutes until a uniform color and viscosity were reached. The proportions of A to B by weight for each component are as follows: primer 1.0:0.30, putty 1.0:0.30, saturant 1.0:0.34.

First, the primer was applied to the surface with a nap roller to fill all crevices, Figure 6- 12a. The primer was allowed to set for approximately one hour on the concrete surface until a tacky consistency was reached. The putty was then applied over the prime coat with a spatula, as shown in Figure 6- 12b, to smooth the surface and fill any remaining voids.

The prepared saturant was then rolled onto the fiber strips in the direction of the fibers to squeeze the saturant between the roving of fabric. The saturation was performed on both sides of the fiber strip so that the entire fabric was coated. The saturated fibers were then placed on the putty and a nap roller was used to promote adhesion as shown in Figure 6- 12c. The composite was allowed to dry overnight and then two layers of topcoat were applied to a uniform consistency with a brush (Figure 6- 12d). The first layer was allowed to completely dry before application of the second layer.

A 

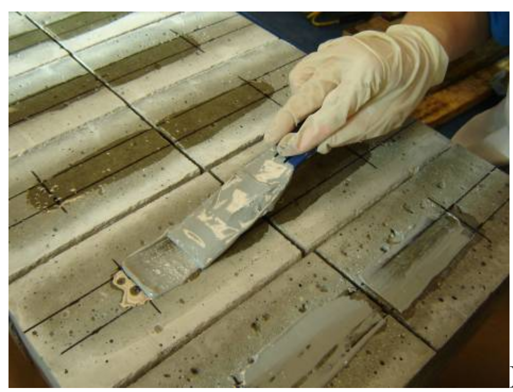
 B

Figure 6- 12. Application of Composite B. A) application of prime coat with a nap roller B) application of putty with spatula C) application of saturated fiber fabric with roller D) application of top coat with brush


C


D

Figure 6-12. Continued

Composite C

Composite C consisted of a pre-cured laminate and epoxy putty. The laminate was a unidirectional pultruded carbon reinforced polymer laminate. The putty used was a 100% solids, moisture tolerant, high modulus and strength structural epoxy paste adhesive that conformed to the current ASTM C-881 and AASHTO M-235 specifications. Table 6-11 lists material properties for both components of composite C.

Table 6-11. Material properties for Composite C

Component	Tensile Strength	Tensile Modulus	Elongation
	(ksi)	(ksi)	(%)
Fiber Laminate	406.0	23900	1.69
Epoxy Putty	3.6	650	1.0

The laminate came as a 40-foot long piece 1.97-in wide. It was cut to 8-in by 1-in strips using a razor, with the 8-in dimension was along the direction of the fibers. The cutting was done so not to cause cracking or splitting in the laminate. The surface of the laminate was then cleaned of any debris and grease before bonding.

Each part of the putty was mixed separately for three minutes before batching. Part A was weighed into a plastic beaker, and part B was then added as 30% by weight. The epoxy paste was then mixed for a minimum of three minutes until a uniform thick gray color was obtained. The putty had a short working time, so the construction of the specimens was done with four batches of putty, with each batch making between 20 and 30 specimens.

The putty was first smoothed with a uniform thickness onto the concrete substrate using a spatula, sufficiently filling all voids as shown in Figure 6-13a. The putty was then applied in a uniform thickness to the laminate using a spatula, Figure 6-13b. The side of the laminate not labeled ‘do not bond’ was covered by applying the paste in the direction of the fibers. The laminate was then placed on the concrete, putty side down as shown in Figure 6-13c. Pressure was applied to the surface of the laminate to allow adhesion between the puttied substrates. Excess putty squeezed from the sides of the laminate and was removed with the spatula (Figure 6-13d).

A  B

Figure 6-13. Construction of Composite C A) application of putty to concrete surface B) application of putty to laminate C) placing of laminate on concrete (putty to putty) D) completed construction of composite C

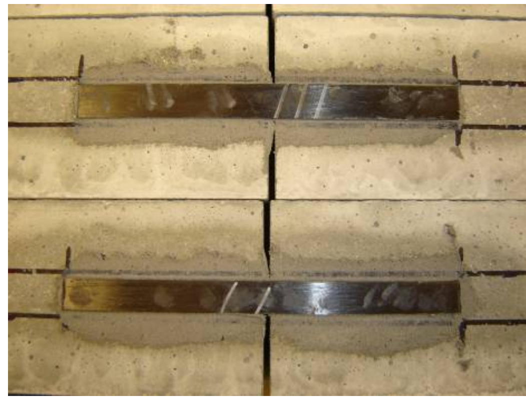
C   D

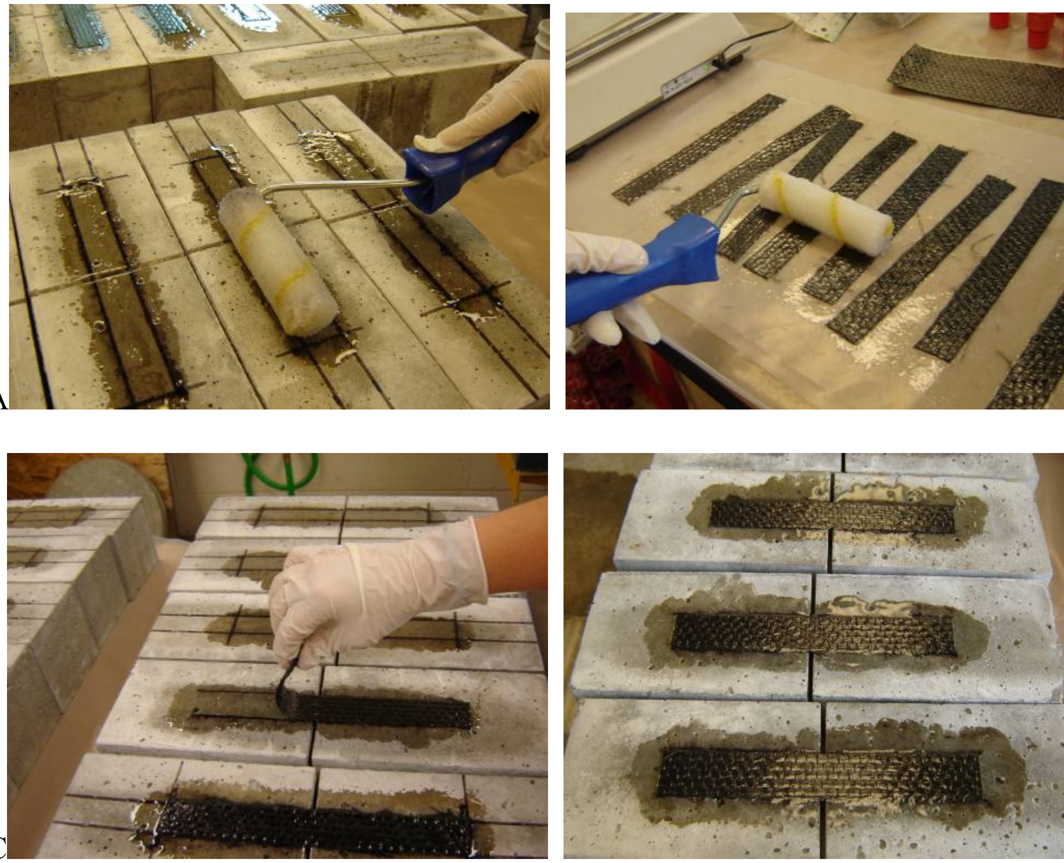
Figure 6-13. Continued

Composite D and E

Composites D and E consisted of the same components, but different mixing ratios. The composite consisted of a 2-part epoxy resin and a fiber fabric. The epoxy was mixed in the manufacturers specified proportions for composite D. This mixture allowed for equal number of reaction sites for both components of the saturant. Composite E used an altered ratio of the two parts of the epoxy. This caused the number of reaction sites for the two parts to be different, allowing for un-reacted sites.

The saturants were made by mixing an appropriate amount of part A with a specified weight ratio of part B in a plastic beaker. The weight ratios of part A to part B for composites D and E were 1.0:0.345 and 1.0:0.439 respectively. The two parts were mixed by hand with a paddle for 3-minutes until a uniform consistency and color were achieved.

The saturant was used to fill all voids on the concrete substrate using a nap roller as shown in Figure 6- 14a. The first coat of saturant was allowed to tack, and a second coat was applied. The saturant was then applied to the 8-in x 1-in fiber weave strips. Both sides of the fabric were then coated with saturant, and a roller was used to force the saturant between the fiber weave, Figure 6- 14b. The saturated fibers were then placed on the saturant covered concrete surface and the roller was used to ensure adhesion to the concrete as shown in Figure 6- 14c.



A B

C D

Figure 6- 14. Application of Composites D and E. A) application of prime coat to concrete surface using nap roller B) saturation of fiber fabric C) placing of saturated fabric on concrete surface D) completed construction of composites D and E

Other specimens

Epoxy samples were made at the time of composite construction for analysis during exposure. Samples were made by pouring each two-part epoxy used during the composite construction process into rubber stoppers. One sample was made for every temperature and time period of the Arrhenius exposure.

Composite sheets consisting of the fiber and impregnating resin used for composite construction were also constructed. The composite sheets were made for the wet lay-up composites (Composites A, B, D, and E). A sheet was made for each temperature in the Arrhenius exposure (30°C, 40°C, 50°C, 60°C).

Exposure Tank Set-up

The environments constructed were alkali solution, chloride solution, sustained loading, real time exposure, UV exposure, and Arrhenius correlation heated water bath exposure. The environments, with exception to the real time exposure, were established in cooler systems located at the Coastal Engineering Laboratory at the University of Florida.

Description of Exposure Systems

Salt and high pH solutions have been reported to decrease durability of CFRP composite bonded concrete. The effect of these solutions was investigated by exposing 12 specimens to each for 12 months. The solutions were held at 50°C.

The salt solution was created by adding water softening salts to water. The water softening salt was pure NaCl crystals (Figure 6-15) and was added at 5% the water weight.

A


B

Figure 6-15. Salt used for Chloride Solution. A) Product description B) close-up of salt granules

Calcium Hydroxide powder was added to water to create an alkali solution (Figure 6-16). The calcium hydroxide was dissolved into the water until a pH of 11.5 was reached. The pH was maintained throughout the exposure period.

Figure 6-16. Calcium Hydroxide used for Alkali Solution

Sustained load combined with hygrothermal exposure was investigated by immersing loaded specimens in 50°C water. The sustained load frames were constructed so as to apply a constant load at 50% of the ultimate capacity of the specimen. The frames consisted of two specimens joined by all-thread bars supporting the load of a compressed spring, as shown in Figure 6-17.

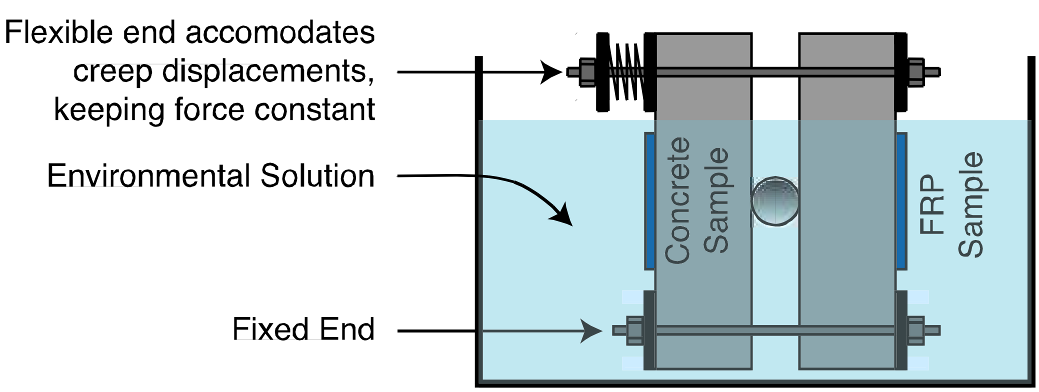


Figure 6-17. Schematic of sustained load frame

To create the sustained load frames, holes were drilled in each specimen from the tension face to the compression face approximately 1.5 inches from the edge. All-thread bars were then inserted into the holes so that two specimens were joined at the compression face, the composite facing outwards. A pivot was placed on the compressive faces between the two specimens at mid-span to act as a third-point load. Washers and bolts on the tension face connected the beams to the all-thread. A spring was placed between the washers and concrete surface on one end of a concrete beam and compressed using torque applied through a hex nut. The springs were compressed to 50% of the ultimate strength determined from previous flexural test results, as shown in Figure 6-18. The springs for the fiber composites (A and B) were loaded to 750 lb, while the springs for the laminate composite (C) were loaded to 1000 lb. These spring loads correspond to pivot loads of 1500 and 2000 lbs for fiber and laminate composites respectively. The specimens were then placed in a 50°C water bath.

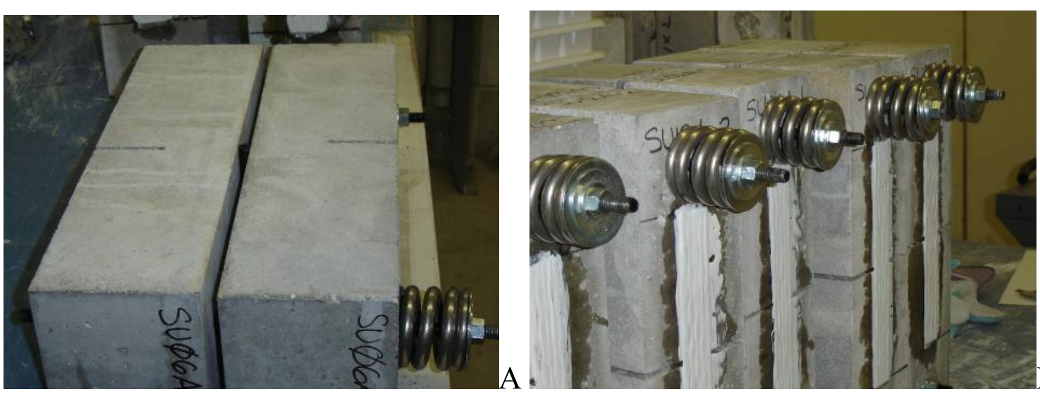

A B

Figure 6-18. Sustained load exposure set-up. A) Single sustained load frame B) loaded springs in a row of sustained load frames

With the cooperation of the FDOT, 29 beams were hung from the fender system of the SR 206 bridge in Crescent Beach, Florida (Figure 6-19). Five fender beams on the northeast fender were utilized, as shown in Figure 6-20.

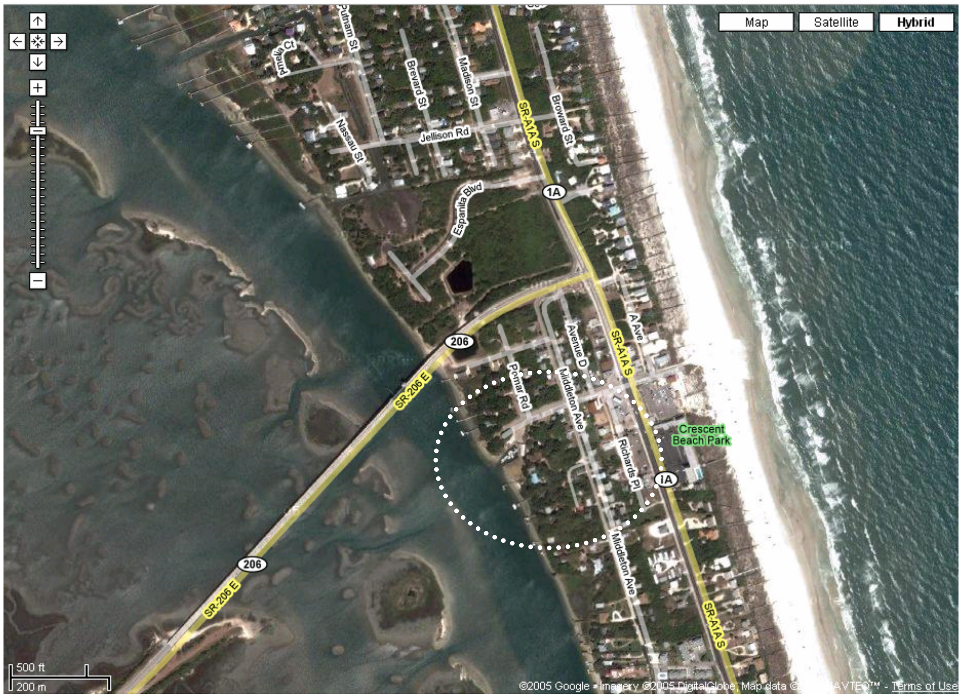


Figure 6-19. Location of SR 206 bridge

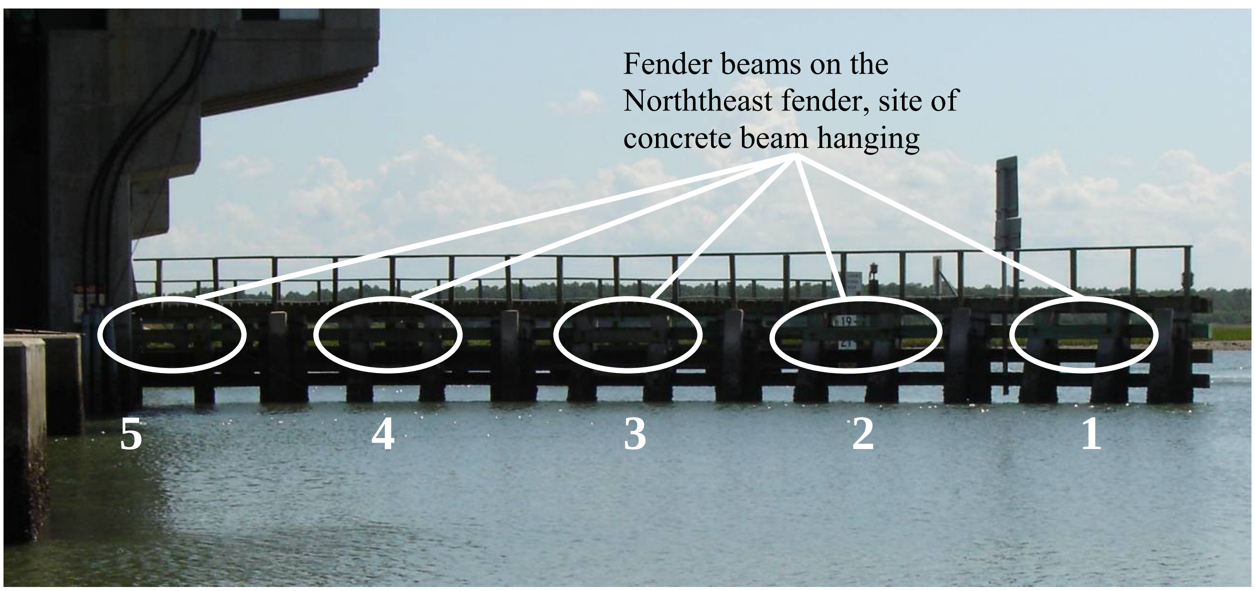


Figure 6-20. Fender beams to be used to hang concrete beams

Six concrete beams were hung from each fender beam using stainless steel cable and clamps. The specimens hung from each fender beam are listed in Table 6-12.

Table 6-12. List of specimens hung from each fender beam

Fender beam	1	2	3	4	5
Specimens hung from fender beam	RF120B-1	RF60B-1	RF24A-1	RF60A-1	RF24B-1
	RF120B-2	RF60B-2	RF24A-2	RF60A-2	RF24B-2
	RF120B-3	RF60B-3	RF24A-3	RF60A-3	RF24B-3
	RF120C-1	RF60C-1	RF24C-1	RF60M-1	RF120A-1
	RF120C-2	RF60C-2	RF24C-2	RF60M-2	RF120A-2
	RF120C-3	RF60C-3	RF24C-3	RF60M-3	

Twelve specimens were exposed to UV light cycled with immersion in 50°C water. The UV light was provided by a 4-ft long Phillips TL60W/10R UVA reflector lamp. UVA light was used for exposure as suggested for accelerated weathering tests by ASTM standard G154-06. Figure 6-21 shows the UVA-340 spectrum compared to sunlight spectrum.

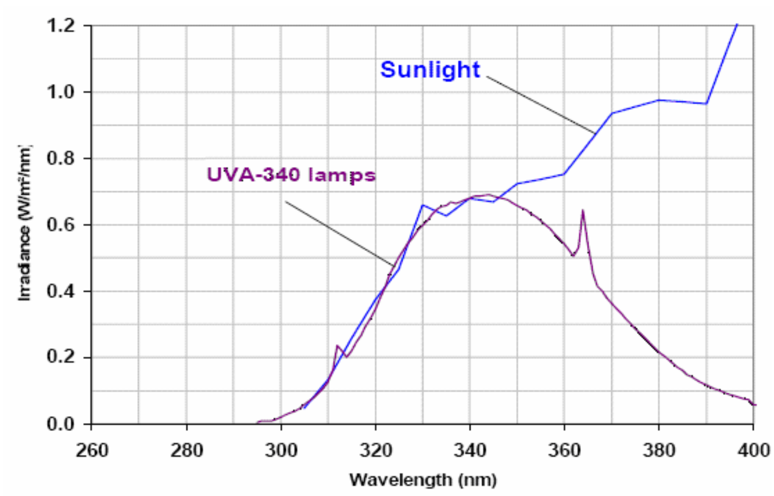


Figure 6-21. UVA-340 spectrum vs. Sunlight spectrum

The specimens were rotated between UV exposure and hygrothermal exposure, having 2 weeks of exposure for each cycle. The UV lamp was placed 6-in away from the center of the CFRP so that the whole length was exposed. The specimen positions were rotated with every cycle to ensure consistent exposure among CFRP types.

The Arrhenius exposure involved four different temperature water baths. The specimens were immersed in 30°C, 40°C, 50°C, and 60°C water.

Procedures for Installation

The nine exposure conditions consisted of six systems of 120-qt insulated coolers. The coolers allowed heat equilibration and retention. Systems that contained more than one tank were connected with ¾-in PVC plumbing. Each system was equipped with a pump and a heater connected to the coolers via 5/8-in heater hose. The systems, the number of tanks involved, and specimens in each tank are listed in

Table 6-13.

Systems 1 and 2 were heated by Tiny Titan 2.5-gal point of use heaters, while systems 3-6 were heated with Whirlpool 6-gal electric residential water heaters. All systems but system 2 had water circulation from Little Giant 1-MD magnetic driven pumps. System 2 used a Little Giant 2-MD magnetic driven pump due to the high pH and corrosive nature of the solution. The pumps ran continuously, while the heaters were self-regulating and turned on once the temperature of the water dropped below the programmed temperature.

Each cooler had a one-way ball valve at the inlet that allowed all coolers in a system to be adjusted to have the same water flow. All tanks in a system maintained consistent temperatures with fluctuations of plus or minus 1.5°C of the desired temperature. A plan view of the systems including heaters and plumbing is shown in Figure 6-22 and pictures of the activated systems are shown in Figure 6-23.

Table 6-13. Specimen location in exposure tanks

System	Exposure	Tank	Specimens		
1	Chloride	1	TC12A-1,2,3	TC12B-1,2,3	TC12C-1,2,3
2	Alkaline	1	TA12A-1,2,3	TA12B-1,2,3	TA12C-1,2,3
3	Arrhenius 30°C	1	A324A-1,2,3	A324B-1,2,3	A306C-1,2,3
			A312C-1,2,3	A324C-1,2,3	-
		2	A306D-1,2,3	A306E-1,2,3	A306M-1,2,3
			A312M-1,2,3	A324M-1,2,3	
		3	A312D-1,2,3	A324D-1,2,3	A312E-1,2,3
			A324E-1,2,3	-	-
4	Arrhenius 40°C	1	A424A-1,2,3	A424B-1,2,3	A406C-1,2,3
			A412C-1,2,3	A424C-1,2,3	-
		2	A406D-1,2,3	A412D-1,2,3	A424D-1,2,3
		3	A406E-1,2,3	A412E-1,2,3	A424E-1,2,3
5	Arrhenius 50°C, Sustained Load, UV	1	SU06A-1,2,3,4	SU12A-1,2,3,4	SU24A-1,2,3,4
		2	SU06B-1,2,3,4	SU12B-1,2,3,4	SU24B-1,2,3,4
		3	SU06C-1,2,3,4	SU12C-1,2,3,4	SU24C-1,2,3,4
		4	UV12A-1,2,3	UV12B-1,2,3	UV12C-1,2,3
			A512M-1,2,3	A524E-1,2,3	-
		5	A524A-1,2,3	A524B-1,2,3	A506C-1,2,3
			A512C-1,2,3	A524C-1,2,3	-
		6	A506D-1,2,3	A512D-1,2,3	A524D-1,2,3
			A506E-1,2,3	A512E-1,2,3	-
6	Arrhenius 60°C	1	A624A-1,2,3	A624B-1,2,3	A606C-1,2,3
			A612C-1,2,3	A624C-1,2,3	-
		2	A606D-1,2,3	A606E-1,2,3	A606M-1,2,3
			A612M-1,2,3	A624M-1,2,3	-
		3	A612D-1,2,3	A624D-1,2,3	A612E-1,2,3
			A624E-1,2,3	-	-

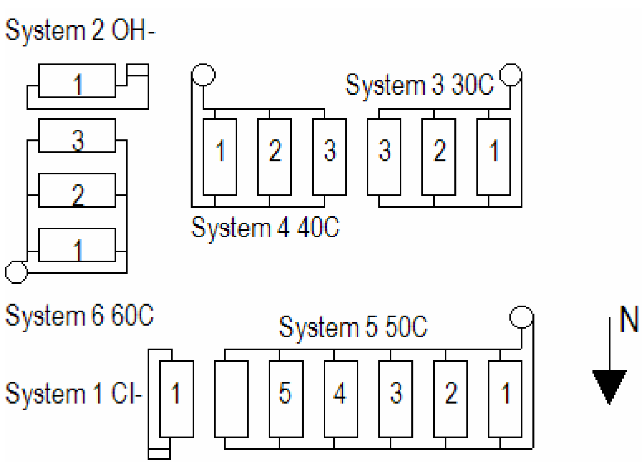


Figure 6-22. Layout of exposure tanks in plan view

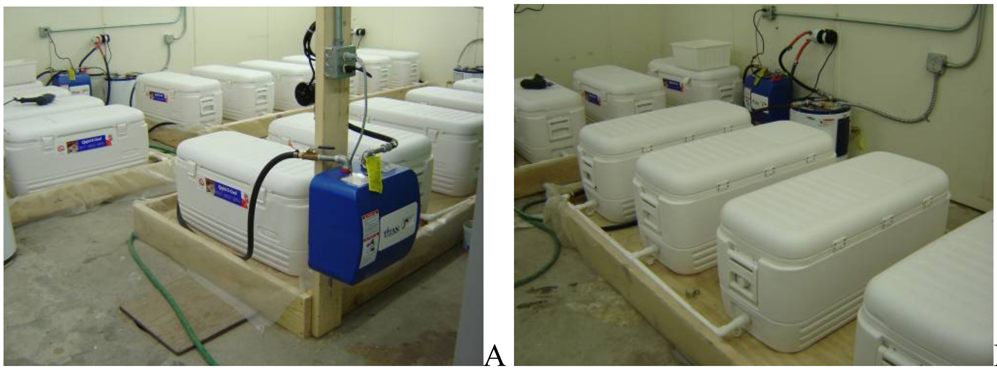
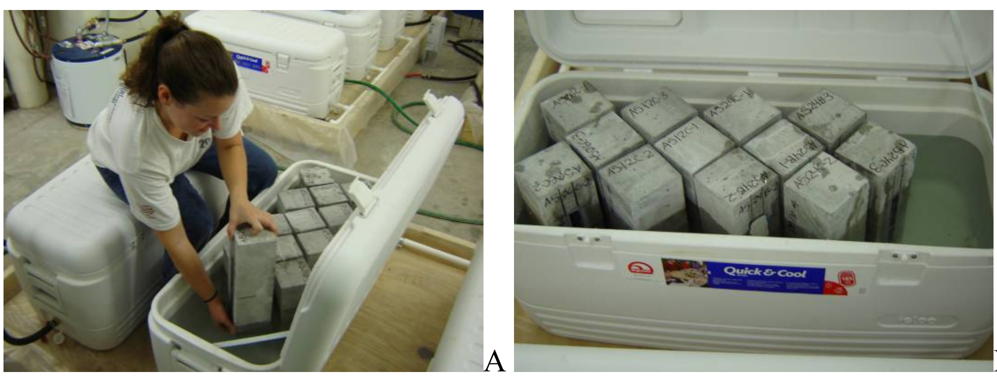

A B

Figure 6-23. Exposure tank set-up. A) picture of all 6 systems B) close up of plumbing for system 4

The specimens were added 9-15 per tank and were positioned on their sides so the CFRP could be exposed directly to the moisture. The water was filled to completely cover the CFRP, as shown in Figure 6- 24. The specimens were added at different times through a four-week period, with exposure dates ranging from April 18th to May 4th 2006.



A B

Figure 6- 24. Addition of beams to exposure tanks. A) Installation of beams in tank B) Placement of beams in tank

Infrared Scanning of Specimens

Ninety-three specimens underwent infrared (IR) scanning before exposure to detect any defects or voids in the composite construction. The specimens will also be scanned after exposure to see if any difference in bonding can be seen. Three specimens were positioned on their ends and put side by side for filming. They were heated for 60-

seconds by two 500-W halogen lamps, as shown in Figure 6-25. The lamps were then turned off, and the specimens were allowed to cool for 3 minutes while being filmed with the IR camera at a speed of one frame per second.

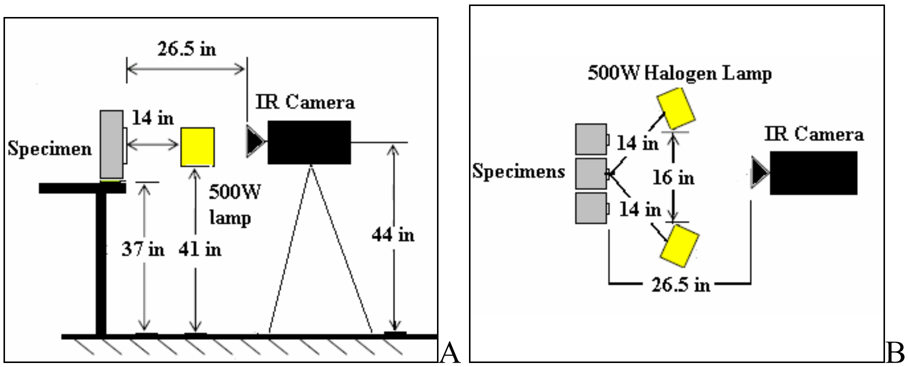


Figure 6-25. Set-up of IR scans A) elevation view B) plan view

CHAPTER 7
ENVIRONMENTAL EXPOSURE: RESULTS AND DISCUSSION

Preliminary results from the effect of the environmental exposure showed a premature loss in capacity upon exposure to the synergistic effects of moisture and elevated temperature. It was found that the specimens lost 50% of their original strength after two weeks of exposure to elevated temperatures. Two weeks after exposure of the sustained load specimens to the 50°C water, it was noticed that the springs had uncompressed. The specimens were removed from the water for inspection, and it was found that at least one specimen in each frame had failed, as shown in Figure 7-1.

Figure 7-1. A sustained load frame with 2 failed specimens

The failure mode of the specimens was the same as that observed from testing with the flexural testing machine. The specimens had a crack initiating from the pivot, continuing to the saw-cut, and ending in adhesive failure of the composite on one side of the saw-cut. Adhesive failure mode as seen in Figure 7-2 was observed for all specimens that had complete failure. Some specimens had hairline cracks from the pivot to the saw-cut, while the composite remained intact (Figure 7-3). The failure load and mode for each sustained load specimen is given in Table 7-1.

The failure of the specimens at the reduced load can be attributed to the effects of moisture and increased temperature on the CFRP composite/concrete bond. The specimens were loaded at 50% of their strength when tested at ambient conditions. Once the bond strength was effectively zero, the concrete had no tensile reinforcement and could not support the applied load from the spring. .

The loads applied corresponded to failure loads recorded from concrete specimen testing. The failure loads for the plain concrete MOR tests performed on specimens without saw-cuts ranged from 5500 to 6000 lbs. Once the saw-cut was induced, the mid-span cross-section reduced by half. Based on Table 7-1, a 50% reduction in cross-section relates to a 75% reduction in load, giving a concrete failure load of approximately 1500-lbs, which is consistent with the applied sustained loads.

The other specimens in the test matrix do not involve flexural testing at an elevated temperature. The test procedure requires a 24-hour immersion in room temperature water before testing so the specimens will all be tested at the same temperature. This ensures that the effects of hygrothermal exposure will be compared based on their effect on the composite properties, and not a function of test temperature.

The specimens that did not fail in the initial loading were reloaded to 500-lbs (25% of the control strength). Specimens SU24A-4, SU12B-2, SU12C-4, SU06C-3 were immersed in a room temperature water bath, while specimens SU06A-1, SU12C-2, SU24C-1, SU24C-2 were placed in dry ambient conditions. After two months, the specimens remained intact and continued to age in the exposure environment.

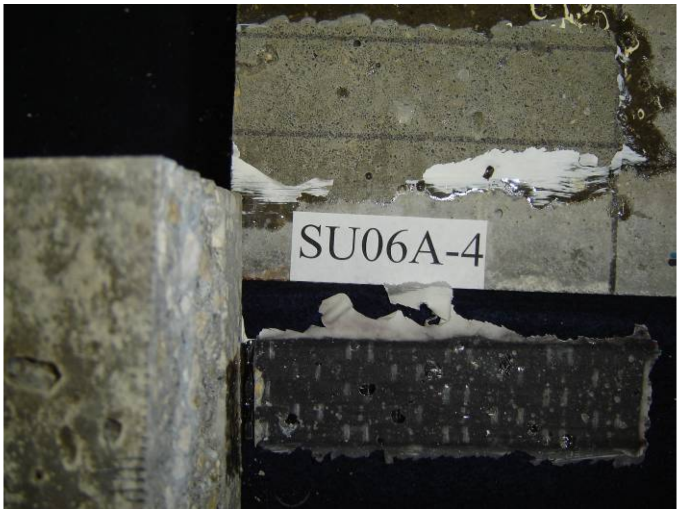


Figure 7-2. Adhesive failure on a sustained load specimen

Figure 7-3. Hairline crack in sustained load specimen

Table 7-1. Load and failure mode of sustained load specimens

Specimen	Composite	Load (lbs)	Failure Mode
SU12A-1	A	1550	adhesive
SU12A-2	A	1550	adhesive
SU12A-3	A	1394	adhesive
SU12A-4	A	1394	hairline
SU6A-1	A	1550	none
SU6A-2	A	1550	adhesive
SU6A-3	A	1547	adhesive
SU6A-4	A	1547	adhesive
SU24A-1	A	1457	hairline
SU24A-2	A	1457	adhesive
SU24A-3	A	1577	hairline
SU24A-4	A	1577	none
SU12B-1	B	1472	adhesive
SU12B-2	B	1472	none
SU12B-3	B	1350	hairline
SU12B-4	B	1350	hairline
SU6B-1	B	1442	hairline
SU6B-2	B	1442	adhesive
SU6B-3	B	1529	adhesive
SU6B-4	B	1529	adhesive
SU24B-1	B	1460	adhesive
SU24B-2	B	1460	adhesive
SU24B-3	B	1490	hairline
SU24B-4	B	1490	adhesive
SU12C-1	C	2087	adhesive
SU12C-2	C	2087	none
SU12C-3	C	1905	adhesive
SU12C-4	C	1905	none
SU6C-1	C	1980	adhesive
SU6C-2	C	1980	adhesive
SU6C-3	C	2021	none
SU6C-4	C	2021	adhesive
SU24C-1	C	1878	none
SU24C-2	C	1878	adhesive
SU24C-3	C	2063	none
SU24C-4	C	2063	adhesive

CHAPTER 8
CONCLUSIONS AND FUTURE WORK

A standard test procedure for evaluating durability of CFRP composite bonded concrete beams was created and implemented to create specimens for the NCHRP durability study. The specimen configuration included a 4-in x 4-in x 14-in concrete beam with a half-depth saw cut at midspan. The concrete strength was targeted at 10-ksi. The specimens incorporated CFRP flexural reinforcement with the dimensions of 8-in long by 1-in wide for wet lay-up composites and 8-in long by 0.75-in wide for procured laminates. The testing procedure chosen was a 3-pt flexure test.

An exposure system was designed and constructed for the accelerated durability study. Insulated coolers were used for immersion of 450 beams to be tested for durability. The exposure systems included hygrothermal (30°C, 40°C, 50°C, and 60°C), alkali (50°C), salt (50°C), UV (50°C), sustained load (50°C), and tidal exposure (ambient). Specimens subjected to the synergistic effects of sustained loading and hygrothermal exposure gave the following preliminary results:

- Sustained load of 50% the control capacity caused failure after two weeks when exposed to 50°C water
- The failure mode for all composites investigated remained adhesive after exposure to 50°C water
- The combination of moisture and elevated temperature reduced the capacity of the CFRP adhesive bond, but the mechanisms underlying this reduction are as of yet unknown

Six month testing will be performed to confirm the degradation results shown from the sustained load specimens. The effect of hygrothermal exposure on the material properties of the CFRP composite will also be investigated. The evaluation of hygrothermal effect on each component of the CFRP will determine the mechanism of degradation, and this mechanism can then be pinpointed and corrected.

APPENDIX A
CONCRETE MIX DESIGNS FOR NCHRP PROJECT 12-73

TRAIL BATCH -- DATA AND CALCULATIONS
(Saturated, Surface-dry Aggregates)

Specification

Cement Content:	846	lbs			Date:	November 1, 2005
W/CM (lbs/lbs):	0.350				Project:	NCHRP Project
C. A. Gradation:	# 89					**Mix 1**
Air Content (%):	0.0	to	5.0		Weights by:	R. Delorenzo/ Gartner
Slump Range (in):	5.5	to	8.5		Mixing By:	R. Delorenzo
Fine Agg. SSD:	0.18	Lab =	0.00		Design By:	
Coarse Agg. SSD:	4.31	Lab =	8.71		Witness By:	
Batch Size (ft^3):	14.0	C.F. =	0.5185			
Ratio of Fine Agg:	43.8 %					

MATERIAL	SOURCE	WT. PER YD^3 (LB)	SPECIFIC GRAVITY	VOL. PER YD^3 (CF)	WT. PER BATCH (LB)	ADJ. WT. PER BATCH (LB)	REMARKS
CEMENT	Cemex	846	3.15	4.30	438.67	438.7	
FLY ASH							
GGBF SLAG							
ULTRA FINE FA							
METAKAOLIN							
SILICA FUME							
WATER	Local	296	1.00	4.74	153.48	121.7	
FINE AGG.	76-137	1262	2.65	7.63	654.37	653.2	
COARSE AGG.	87-089	1446	2.37	9.78	749.78	782.8	
AIR ENTRAINER	WR Grace Daravair 1000	3.0 oz		0.54	46.0 ml		
ADMIXTURE	WR Grace WRDA 60	22.6 oz			346.6 ml		
ADMIXTURE	WR Grace ADVA 140	67.7 oz			1038.1 ml	1200 ml	
TOTAL				27.00			

Plastic Property

Slump (in):	3.0"	Slump By:	
Air (%)	2.80%	Air By:	
Mix Temp (°F):	74 F	Temp By:	
Unit Weight (lb/ft^3):	---	Unit Weight By:	
Workability:	Good	Cylinders By:	
Initial Set (min):		Air Temp (°F):	
Final Set (min):		Final Bleed:	

Figure A- 1. Concrete mix 1 properties

TRAIL BATCH -- DATA AND CALCULATIONS
(Saturated, Surface-dry Aggregates)

Specification

Cement Content:	846	lbs		Date:	November 3, 2005
W/CM (lbs/lbs):	0.350			Project:	NCHRP Project
C. A. Gradation:	# 89				**Mix 2**
Air Content (%):	0.0	to	5.0	Weights by:	R. Delorenzo/ Gartner
Slump Range (in):	5.5	to	8.5	Mixing By:	R. Delorenzo
Fine Agg. SSD:	0.18	Lab =	0.00	Design By:	
Coarse Agg. SSD:	4.31	Lab =	8.58	Witness By:	
Batch Size (ft^3):	14.0	C.F. =	0.5185		
Ratio of Fine Agg:	43.8 %				

MATERIAL	SOURCE	WT. PER YD^3 (LB)	SPECIFIC GRAVITY	VOL. PER YD^3 (CF)	WT. PER BATCH (LB)	ADJ. WT. PER BATCH (LB)	REMARKS
CEMENT	Cemex	846	3.15	4.30	438.7	438.7	
FLY ASH							
GGBF SLAG							
ULTRA FINE FA							
METAKAOLIN							
SILICA FUME							
WATER	Local	296	1.00	4.74	153.5	122.6	
FINE AGG.	76-137	1262	2.65	7.63	654.4	653.2	
COARSE AGG.	87-089	1446	2.37	9.78	749.8	781.8	
AIR ENTRAINER	WR Grace Daravair 1000	3.0 oz		0.54	46.0 ml		
ADMIXTURE	WR Grace WRDA 60	22.6 oz			346.6 ml		
ADMIXTURE	WR Grace ADVA 140	67.7 oz			1038.1 ml	1200 ml	
TOTAL				27.00			

Plastic Property

Slump (in):	3.75"	Slump By:	
Air (%)	3.30%	Air By:	
Mix Temp (°F):	75 F	Temp By:	
Unit Weight (lb/ft^3):	---	Unit Weight By:	
Workability:	Good	Cylinders By:	
Initial Set (min):		Air Temp (°F):	
Final Set (min):		Final Bleed:	

Figure A- 2. Concrete mix 2 properties

TRAIL BATCH -- DATA AND CALCULATIONS

(Saturated, Surface-dry Aggregates)

Specification					Date:	November 8, 2005	
Cement Content:	846	lbs			Project:	NCHRP Project	
W/CM (lbs/lbs):	0.350					**Mix 3**	
C. A. Gradation:	# 89				Weights by:	R. Delorenzo	
Air Content (%):	0.0	to	5.0		Mixing By:	R. Delorenzo	
Slump Range (in):	5.5	to	8.5		Design By:		
Fine Agg. SSD:	0.18	Lab =	0.00		Witness By:		
Coarse Agg. SSD:	4.31	Lab =	8.12				
Batch Size (ft^3):	14.0	C.F. =	0.5185				
Ratio of Fine Agg:	43.8 %						

MATERIAL	SOURCE	WT. PER YD^3 (LB)	SPECIFIC GRAVITY	VOL. PER YD^3 (CF)	WT. PER BATCH (LB)	ADJ. WT. PER BATCH (LB)	REMARKS
CEMENT	Cemex	846	3.15	4.30	438.7	438.7	
FLY ASH							
GGBF SLAG							
ULTRA FINE FA							
METAKAOLIN							
SILICA FUME							
WATER	Local	296	1.00	4.74	153.5	126.1	
FINE AGG.	76-137	1262	2.65	7.63	654.4	653.2	
COARSE AGG.	87-089	1446	2.37	9.78	749.8	778.3	
AIR ENTRAINER	WR Grace Daravair 1000	3.0 oz		0.54	46.0 ml		
ADMIXTURE	WR Grace WRDA 60	22.6 oz			346.6 ml		
ADMIXTURE	WR Grace ADVA 140	67.7 oz			1038.1 ml	1200 ml	
TOTAL				27.00			

Plastic Property			
Slump (in):	3.50"	Slump By:	
Air (%)	3.30%	Air By:	
Mix Temp (°F):	76 F	Temp By:	
Unit Weight (lb/ft^3):	---	Unit Weight By:	
Workability:	Good	Cylinders By:	
Initial Set (min):		Air Temp (°F):	
Final Set (min):		Final Bleed:	

Figure A- 3. Concrete mix 3 properties

TRAIL BATCH -- DATA AND CALCULATIONS

(Saturated, Surface-dry Aggregates)

Specification

Cement Content:	846	lbs		Date:	November 15, 2005
W/CM (lbs/lbs):	0.350			Project:	NCHRP Project
					Mix 4
C. A. Gradation:	# 89			Weights by:	R. Delorenzo
Air Content (%):	0.0	to	5.0	Mixing By:	R. Delorenzo
Slump Range (in):	5.5	to	8.5	Design By:	
Fine Agg. SSD:	0.18	Lab =	0.00	Witness By:	
Coarse Agg. SSD:	4.31	Lab =	8.50		
Batch Size (ft^3):	14.0	C.F. =	0.5185		
Ratio of Fine Agg:	43.8 %				

MATERIAL	SOURCE	WT. PER YD^3 (LB)	SPECIFIC GRAVITY	VOL. PER YD^3 (CF)	WT. PER BATCH (LB)	ADJ. WT. PER BATCH (LB)	REMARKS
CEMENT	Cemex	846	3.15	4.30	438.7	438.7	
FLY ASH							
GGBF SLAG							
ULTRA FINE FA							
METAKAOLIN							
SILICA FUME							
WATER	Local	296	1.00	4.74	153.5	123.2	
FINE AGG.	76-137	1262	2.65	7.63	654.4	653.2	
COARSE AGG.	87-089	1446	2.37	9.78	749.8	781.2	
AIR ENTRAINER	WR Grace Daravair 1000	3.0 oz		0.54	46.0 ml		
ADMIXTURE	WR Grace WRDA 60	22.6 oz			346.6 ml		
ADMIXTURE	WR Grace ADVA 140	67.7 oz			1038.1 ml	1200 ml	
TOTAL				27.00			

Plastic Property

Slump (in):	3.50"	Slump By:	
Air (%)	3.00%	Air By:	
Mix Temp (°F):	75 F	Temp By:	
Unit Weight (lb/ft^3):	---	Unit Weight By:	
Workability:	Good	Cylinders By:	
Initial Set (min):		Air Temp (°F):	
Final Set (min):		Final Bleed:	

Figure A- 4. Concrete mix 4 properties

TRAIL BATCH -- DATA AND CALCULATIONS

(Saturated, Surface-dry Aggregates)

Specification

Cement Content:	846	lbs	
W/CM (lbs/lbs):	0.350		
C. A. Gradation:	# 89		
Air Content (%):	0.0	to	5.0
Slump Range (in):	5.5	to	8.5
Fine Agg. SSD:	0.18	Lab =	0.00
Coarse Agg. SSD:	4.31	Lab =	8.50
Batch Size (ft^3):	14.0	C.F. =	0.5185
Ratio of Fine Agg:	43.8 %		

Date:	November 17, 2005
Project:	NCHRP Project
	Mix 5
Weights by:	R. Delorenzo
Mixing By:	R. Delorenzo
Design By:	
Witness By:	

MATERIAL	SOURCE	WT. PER YD^3 (LB)	SPECIFIC GRAVITY	VOL. PER YD^3 (CF)	WT. PER BATCH (LB)	ADJ. WT. PER BATCH (LB)	REMARKS
CEMENT	Cemex	846	3.15	4.30	438.7	438.7	
FLY ASH							
GGBF SLAG							
ULTRA FINE FA							
METAKAOLIN							
SILICA FUME							
WATER	Local	296	1.00	4.74	153.5	123.2	
FINE AGG.	76-137	1262	2.65	7.63	654.4	653.2	
COARSE AGG.	87-089	1446	2.37	9.78	749.8	781.2	
AIR ENTRAINER	WR Grace Daravair 1000	3.0 oz		0.54	46.0 ml		
ADMIXTURE	WR Grace WRDA 60	22.6 oz			346.6 ml		
ADMIXTURE	WR Grace ADVA 140	67.7 oz			1038.1 ml	1700 ml	
TOTAL				27.00			

Plastic Property

Slump (in):	3.50"	Slump By:	
Air (%)	3.30%	Air By:	
Mix Temp (°F):	75 F	Temp By:	
Unit Weight (lb/ft^3):	---	Unit Weight By:	
Workability:	Good	Cylinders By:	
Initial Set (min):		Air Temp (°F):	
Final Set (min):		Final Bleed:	

Figure A- 5. Concrete mix 5 properties

APPENDIX B
NCHRP 12-73 UF TESTING MATRIX

Period	Exposure	FRP Type	Location	Replicate	Temperature	Specimen name	Concrete mix	Cast date	28 day strength, $f'_{c,28}$	28 day modulus of rupture f_r	Saw cut date	Sandblast date	flexural FRP Applied date	pull-off FRP apply date	Initial IR Scan Date (before exposure)	Initial IR Scan File Name (block number)	Sustained Load date	Sustained Load Magnitude	Sustained Load reload date	Sustained Load reload length	Sustained Load reload magnitude (lbs)	Sustained Load Reload condition	Exposure initiated date
24	A3	A	F	-1	30	A324A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0008(1)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A3	A	F	-2	30	A324A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0008(2)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A3	A	F	-3	30	A324A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0008(3)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A3	B	F	-1	30	A324B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0009(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A3	B	F	-2	30	A324B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0009(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A3	B	F	-3	30	A324B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0009(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A3	C	F	-1	30	A324C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0011(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A3	C	F	-2	30	A324C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0011(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A3	C	F	-3	30	A324C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0011(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A3	C	F	-1	30	A36C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A3	C	F	-2	30	A36C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A3	C	F	-3	30	A36C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A3	C	F	-1	30	A312C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A3	C	F	-2	30	A312C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A3	C	F	-3	30	A312C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
60	A3	C	F	-1	30	A360C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A3	C	F	-2	30	A360C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A3	C	F	-3	30	A360C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
06	A3	D	F	-1	30	A36D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A3	D	F	-2	30	A36D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A3	D	F	-3	30	A36D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A3	D	F	-1	30	A312D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A3	D	F	-2	30	A312D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A3	D	F	-3	30	A312D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A3	D	F	-1	30	A324D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A3	D	F	-2	30	A324D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A3	D	F	-3	30	A324D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A3	E	F	-1	30	A36E-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A3	E	F	-2	30	A36E-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A3	E	F	-3	30	A36E-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A3	E	F	-1	30	A312E-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A3	E	F	-2	30	A312E-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A3	E	F	-3	30	A312E-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A3	E	F	-1	30	A324E-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A3	E	F	-2	30	A324E-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A3	E	F	-3	30	A324E-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A3	M	F	-1	30	A324M-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A3	M	F	-2	30	A324M-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A3	M	F	-3	30	A324M-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
06	A3	M	F	-1	30	A36M-1	FDOT-3	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
06	A3	M	F	-2	30	A36M-2	FDOT-3	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
06	A3	M	F	-3	30	A36M-3	FDOT-3	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
12	A3	M	F	-1	30	A312M-1	FDOT-2	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
12	A3	M	F	-2	30	A312M-2	FDOT-2	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
12	A3	M	F	-3	30	A312M-3	FDOT-2	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
60	A3	M	F	-1	30	A360M-1	FDOT-5	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A3	M	F	-2	30	A360M-2	FDOT-5	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A3	M	F	-3	30	A360M-3	FDOT-5	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
24	A4	A	F	-1	40	A424A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0013(1)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006

Figure B- 1. University of Florida testing matrix

Period	Exposure	FRP Type	Location	Replicate	Temperature	Specimen name	Concrete mix	Cast date	28 day strength, $f'_{c,28}$	28 day modulus of rupture f_r	Saw cut date	Sandblast date	flexural FRP Applied date	pull-off FRP apply date	Initial IR Scan Date (before exposure)	Initial IR Scan File Name (block number)	Sustained Load date	Sustained Load Magnitude	Sustained Load reload date	Sustained Load reload length	Sustained Load reload magnitude (lbs)	Sustained Load Reload condition	Exposure initiated date
24	A4	A	F	-2	40	A424A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0013(2)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A4	A	F	-3	40	A424A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0013(3)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A4	B	F	-1	40	A424B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0007(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A4	B	F	-2	40	A424B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0007(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A4	B	F	-3	40	A424B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0007(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A4	C	F	-1	40	A424C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0012(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A4	C	F	-2	40	A424C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0012(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A4	C	F	-3	40	A424C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0012(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A4	C	F	-1	40	A46C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A4	C	F	-2	40	A46C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A4	C	F	-3	40	A46C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A4	C	F	-1	40	A412C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A4	C	F	-2	40	A412C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A4	C	F	-3	40	A412C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
60	A4	C	F	-1	40	A460C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A4	C	F	-2	40	A460C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A4	C	F	-3	40	A460C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
06	A4	D	F	-1	40	A46D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A4	D	F	-2	40	A46D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A4	D	F	-3	40	A46D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A4	D	F	-1	40	A412D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A4	D	F	-2	40	A412D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A4	D	F	-3	40	A412D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A4	D	F	-1	40	A424D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A4	D	F	-2	40	A424D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A4	D	F	-3	40	A424D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A4	E	F	-1	40	A46E-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A4	E	F	-2	40	A46E-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A4	E	F	-3	40	A46E-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A4	E	F	-1	40	A412E-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A4	E	F	-2	40	A412E-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A4	E	F	-3	40	A412E-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A4	E	F	-1	40	A424E-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A4	E	F	-2	40	A424E-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A4	E	F	-3	40	A424E-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A5	A	F	-1	50	A524A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0010(1)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A5	A	F	-2	50	A524A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0010(2)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A5	A	F	-3	50	A524A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0010(3)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A5	B	F	-1	50	A524B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0001(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A5	B	F	-2	50	A524B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0001(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A5	B	F	-3	50	A524B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0001(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A5	C	F	-1	50	A524C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0010(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A5	C	F	-2	50	A524C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0010(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A5	C	F	-3	50	A524C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0010(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A5	C	F	-1	50	A56C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A5	C	F	-2	50	A56C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A5	C	F	-3	50	A56C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A5	C	F	-1	50	A512C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A5	C	F	-2	50	A512C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A5	C	F	-3	50	A512C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006

Figure B-1. Continued

Period	Exposure	FRP Type	Location	Replicate	Temperature	Specimen name	Concrete mix	Cast date	28 day strength, $f'_{c,28}$	28 day modulus of rupture f_r	Saw cut date	Sandblast date	flexural FRP Applied date	pull-off FRP apply date	Initial IR Scan Date (before exposure)	Initial IR Scan File Name (block number)	Sustained Load date	Sustained Load Magnitude	Sustained Load reload date	Sustained Load reload length	Sustained Load reload magnitude (lbs)	Sustained Load Reload condition	Exposure initiated date
60	A5	C	F	-1	50	A560C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A5	C	F	-2	50	A560C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A5	C	F	-3	50	A560C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
06	A5	D	F	-1	50	A56D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A5	D	F	-2	50	A56D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A5	D	F	-3	50	A56D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A5	D	F	-1	50	A512D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A5	D	F	-2	50	A512D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A5	D	F	-3	50	A512D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A5	D	F	-1	50	A524D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A5	D	F	-2	50	A524D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A5	D	F	-3	50	A524D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A5	E	F	-1	50	A56E-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A5	E	F	-2	50	A56E-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A5	E	F	-3	50	A56E-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A5	E	F	-1	50	A512E-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A5	E	F	-2	50	A512E-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A5	E	F	-3	50	A512E-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A5	E	F	-1	50	A524E-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A5	E	F	-2	50	A524E-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A5	E	F	-3	50	A524E-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A5	M	F	-1	50	A512M-1	FDOT-1	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
12	A5	M	F	-2	50	A512M-2	FDOT-1	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
12	A5	M	F	-3	50	A512M-3	FDOT-1	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A6	A	F	-1	60	A624A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0011(1)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A6	A	F	-2	60	A624A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0011(2)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A6	A	F	-3	60	A624A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	Tue 3/14/2006	2/3/2006	NCHRP_A0011(3)	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A6	B	F	-1	60	A624B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0010(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A6	B	F	-2	60	A624B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0010(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A6	B	F	-3	60	A624B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0010(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A6	C	F	-1	60	A624C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0013(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A6	C	F	-2	60	A624C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0013(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
24	A6	C	F	-3	60	A624C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0013(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A6	C	F	-1	60	A66C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A6	C	F	-2	60	A66C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
06	A6	C	F	-3	60	A66C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A6	C	F	-1	60	A612C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A6	C	F	-2	60	A612C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	A6	C	F	-3	60	A612C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
60	A6	C	F	-1	60	A660C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A6	C	F	-2	60	A660C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A6	C	F	-3	60	A660C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
06	A6	D	F	-1	60	A66D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A6	D	F	-2	60	A66D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A6	D	F	-3	60	A66D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A6	D	F	-1	60	A612D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A6	D	F	-2	60	A612D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A6	D	F	-3	60	A612D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A6	D	F	-1	60	A624D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A6	D	F	-2	60	A624D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006

Figure B-1. Continued

Period	Exposure	FRP Type	Location	Replicate	Temperature	Specimen name	Concrete mix	Cast date	28 day strength, $f_{c,28}$	28 day modulus of rupture f_r	Saw cut date	Sandblast date	flexural FRP Applied date	pull-off FRP apply date	Initial IR Scan Date (before exposure)	Initial IR Scan File Name (block number)	Sustained Load date	Sustained Load Magnitude	Sustained Load reload date	Sustained Load reload length	Sustained Load reload magnitude (lbs)	Sustained Load Reload condition	Exposure initiated date
24	A6	D	F	-3	60	A624D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A6	E	F	-1	60	A66E-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A6	E	F	-2	60	A66E-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
06	A6	E	F	-3	60	A66E-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A6	E	F	-1	60	A612E-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A6	E	F	-2	60	A612E-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
12	A6	E	F	-3	60	A612E-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A6	E	F	-1	60	A624E-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A6	E	F	-2	60	A624E-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A6	E	F	-3	60	A624E-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Tue 5/2/2006
24	A6	M	F	-1	60	A624M-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A6	M	F	-2	60	A624M-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
24	A6	M	F	-3	60	A624M-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
06	A6	M	F	-1	60	A66M-1	FDOT-3	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
06	A6	M	F	-2	60	A66M-2	FDOT-3	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
06	A6	M	F	-3	60	A66M-3	FDOT-3	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
12	A6	M	F	-1	60	A612M-1	FDOT-2	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
12	A6	M	F	-2	60	A612M-2	FDOT-2	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
12	A6	M	F	-3	60	A612M-3	FDOT-2	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Mon 4/24/2006
60	A6	M	F	-1	60	A660M-1	FDOT-5	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A6	M	F	-2	60	A660M-2	FDOT-5	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
60	A6	M	F	-3	60	A660M-3	FDOT-5	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
12	CO	A	F	-1	RT	CO12A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0001(1)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	A	F	-2	RT	CO12A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0001(2)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	A	F	-3	RT	CO12A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0001(3)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	A	F	-1	RT	CO6A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	A	F	-2	RT	CO6A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	A	F	-3	RT	CO6A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	A	F	-1	RT	CO24A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	A	F	-2	RT	CO24A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	A	F	-3	RT	CO24A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	A	F	-1	RT	CO60A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	A	F	-2	RT	CO60A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	A	F	-3	RT	CO60A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	A	F	-1	RT	CO120A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	A	F	-2	RT	CO120A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	A	F	-3	RT	CO120A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	B	F	-1	RT	CO12B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0008(1)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	B	F	-2	RT	CO12B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0008(2)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	B	F	-3	RT	CO12B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0008(3)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	B	F	-1	RT	CO6B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	B	F	-2	RT	CO6B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	B	F	-3	RT	CO6B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	B	F	-1	RT	CO24B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	B	F	-2	RT	CO24B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	B	F	-3	RT	CO24B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	B	F	-1	RT	CO60B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	B	F	-2	RT	CO60B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	B	F	-3	RT	CO60B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	B	F	-1	RT	CO120B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Figure B-1. Continued

Period	Exposure	FRP Type	Location	Replicate	Temperature	Specimen name	Concrete mix	Cast date	28 day strength, $f'_{c,28}$	28 day modulus of rupture f_r	Saw cut date	Sandblast date	flexural FRP Applied date	pull-off FRP apply date	Initial IR Scan Date (before exposure)	Initial IR Scan File Name (block number)	Sustained Load date	Sustained Load Magnitude	Sustained Load reload date	Sustained Load reload length	Sustained Load reload magnitude (lbs)	Sustained Load Reload condition	Exposure initiated date
120	CO	B	F	-2	RT	CO120B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	B	F	-3	RT	CO120B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	C	F	-1	RT	CO12C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0009(1)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	C	F	-2	RT	CO12C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0009(2)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	C	F	-3	RT	CO12C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0009(3)	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	C	F	-1	RT	CO6C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	C	F	-2	RT	CO6C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	C	F	-3	RT	CO6C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	C	F	-1	RT	CO24C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	C	F	-2	RT	CO24C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	C	F	-3	RT	CO24C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	C	F	-1	RT	CO60C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	C	F	-2	RT	CO60C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	C	F	-3	RT	CO60C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	C	F	-1	RT	CO120C-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	C	F	-2	RT	CO120C-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	C	F	-3	RT	CO120C-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	D	F	-1	RT	CO6D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	D	F	-2	RT	CO6D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	D	F	-3	RT	CO6D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	D	F	-1	RT	CO12D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	D	F	-2	RT	CO12D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	D	F	-3	RT	CO12D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	D	F	-1	RT	CO24D-1	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	D	F	-2	RT	CO24D-2	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	D	F	-3	RT	CO24D-3	FDOT-3	Tue 11/8/05	9258	1091	Mon 11/28/05	Mon 12/12/05	Wed 4/12/2006	Thurs 4/13/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	E	F	-1	RT	CO6E-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	E	F	-2	RT	CO6E-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	E	F	-3	RT	CO6E-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	E	F	-1	RT	CO12E-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	E	F	-2	RT	CO12E-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	E	F	-3	RT	CO12E-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	E	F	-1	RT	CO24E-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	E	F	-2	RT	CO24E-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	E	F	-3	RT	CO24E-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 4/12/2006	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	M	F	-1	RT	CO12M-1	FDOT-2	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	M	F	-2	RT	CO12M-2	FDOT-2	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12	CO	M	F	-3	RT	CO12M-3	FDOT-2	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	M	F	-1	RT	CO6M-1	FDOT-3	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	M	F	-2	RT	CO6M-2	FDOT-3	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
06	CO	M	F	-3	RT	CO6M-3	FDOT-3	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	M	F	-1	RT	CO24M-1	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	M	F	-2	RT	CO24M-2	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
24	CO	M	F	-3	RT	CO24M-3	FDOT-4	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	M	F	-1	RT	CO60M-1	FDOT-5	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	M	F	-2	RT	CO60M-2	FDOT-5	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
60	CO	M	F	-3	RT	CO60M-3	FDOT-5	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	M	F	-1	RT	CO120M-1	FDOT-1	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	M	F	-2	RT	CO120M-2	FDOT-1	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
120	CO	M	F	-3	RT	CO120M-3	FDOT-1	Tue 11/15/05	9429	1053	Wed 11/30/05	Fri 12/16/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Figure B-1. Continued

Period	Exposure	FRP Type	Location	Replicate	Temperature	Specimen name	Concrete mix	Cast date	28 day strength, $f'_{c,28}$	28 day modulus of rupture f_r	Saw cut date	Sandblast date	flexural FRP Applied date	pull-off FRP apply date	Initial IR Scan Date (before exposure)	Initial IR Scan File Name (block number)	Sustained Load date	Sustained Load Magnitude	Sustained Load reload date	Sustained Load reload length	Sustained Load reload magnitude (lbs)	Sustained Load Reload condition	Exposure initiated date
24	RF	A	F	-1	FL	RF24A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0014(1)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
24	RF	A	F	-2	FL	RF24A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0014(2)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
24	RF	A	F	-3	FL	RF24A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0014(3)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	A	F	-1	FL	RF60A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	A	F	-2	FL	RF60A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	A	F	-3	FL	RF60A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
120	RF	A	F	-1	FL	RF120A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
120	RF	A	F	-2	FL	RF120A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
120	RF	A	F	-3	FL	RF120A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
24	RF	B	F	-1	FL	RF24B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0002(1)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
24	RF	B	F	-2	FL	RF24B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0002(2)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
24	RF	B	F	-3	FL	RF24B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0002(3)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	B	F	-1	FL	RF60B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	B	F	-2	FL	RF60B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	B	F	-3	FL	RF60B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
120	RF	B	F	-1	FL	RF120B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
120	RF	B	F	-2	FL	RF120B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
120	RF	B	F	-3	FL	RF120B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
24	RF	C	F	-1	FL	RF24C-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0008(1)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
24	RF	C	F	-2	FL	RF24C-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0008(2)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
24	RF	C	F	-3	FL	RF24C-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0008(3)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	C	F	-1	FL	RF60C-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	C	F	-2	FL	RF60C-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	C	F	-3	FL	RF60C-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
120	RF	C	F	-1	FL	RF120C-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
120	RF	C	F	-2	FL	RF120C-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
120	RF	C	F	-3	FL	RF120C-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	M	F	-1	FL	RF60M-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	M	F	-2	FL	RF60M-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
60	RF	M	F	-3	FL	RF60M-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 6/22/2006
12	SU	A	F	-1	50	SU12A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0005(1)	Wed 5/3/2006	1549.72	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	SU	A	F	-2	50	SU12A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0005(2)	Wed 5/3/2006	1549.72	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	SU	A	F	-3	50	SU12A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0007(1)	Thur 5/4/2006	1394.45	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	SU	A	F	-4	50	SU12A-4	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0007(1)	Thur 5/4/2006	1394.45	N/A	N/A	N/A	N/A	Thur 5/4/2006
06	SU	A	F	-1	50	SU6A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	Wed 5/3/2006	1549.72	6/16/2006	1.8125	500	ambient	Thur 5/4/2006
06	SU	A	F	-2	50	SU6A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	Wed 5/3/2006	1549.72	N/A	N/A	N/A	N/A	Thur 5/4/2006
06	SU	A	F	-3	50	SU6A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	Wed 5/3/2006	1546.73	N/A	N/A	N/A	N/A	Thur 5/4/2006
06	SU	A	F	-4	50	SU6A-4	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	Wed 5/3/2006	1546.73	N/A	N/A	N/A	N/A	Thur 5/4/2006
24	SU	A	F	-1	50	SU24A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	Wed 5/3/2006	1457.15	N/A	N/A	N/A	N/A	Thur 5/4/2006
24	SU	A	F	-2	50	SU24A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	Wed 5/3/2006	1457.15	N/A	N/A	N/A	N/A	Thur 5/4/2006
24	SU	A	F	-3	50	SU24A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	Wed 5/3/2006	1576.59	N/A	N/A	N/A	N/A	Thur 5/4/2006
24	SU	A	F	-4	50	SU24A-4	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	N/A	N/A	Wed 5/3/2006	1576.59	6/16/2006	1.8125	500	RT water	Thur 5/4/2006
12	SU	B	F	-1	50	SU12B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0012(1)	Thur 5/4/2006	1472.08	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	SU	B	F	-2	50	SU12B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0012(2)	Thur 5/4/2006	1472.08	6/16/2006	1.8125	500	RT water	Thur 5/4/2006
12	SU	B	F	-3	50	SU12B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0013(1)	Thur 5/4/2006	1349.66	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	SU	B	F	-4	50	SU12B-4	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0013(2)	Thur 5/4/2006	1349.66	N/A	N/A	N/A	N/A	Thur 5/4/2006
06	SU	B	F	-1	50	SU6B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	Thur 5/4/2006	1442.22	N/A	N/A	N/A	N/A	Thur 5/4/2006
06	SU	B	F	-2	50	SU6B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	Thur 5/4/2006	1442.22	N/A	N/A	N/A	N/A	Thur 5/4/2006
06	SU	B	F	-3	50	SU6B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	Thur 5/4/2006	1528.81	N/A	N/A	N/A	N/A	Thur 5/4/2006
06	SU	B	F	-4	50	SU6B-4	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	Thur 5/4/2006	1528.81	N/A	N/A	N/A	N/A	Thur 5/4/2006

Figure B-1. Continued

Period	Exposure	FRP Type	Location	Replicate	Temperature	Specimen name	Concrete mix	Cast date	28 day strength, $f'_{c,28}$	28 day modulus of rupture f_r	Saw cut date	Sandblast date	flexural FRP Applied date	pull-off FRP apply date	Initial IR Scan Date (before exposure)	Initial IR Scan File Name (block number)	Sustained Load date	Sustained Load Magnitude	Sustained Load reload date	Sustained Load reload length	Sustained Load reload magnitude (lbs)	Sustained Load Reload condition	Exposure initiated date
24	SU	B	F	-1	50	SU24B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	Thur 5/4/2006	1460.14	N/A	N/A	N/A	N/A	Thur 5/4/2006
24	SU	B	F	-2	50	SU24B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	Thur 5/4/2006	1460.14	N/A	N/A	N/A	N/A	Thur 5/4/2006
24	SU	B	F	-3	50	SU24B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	Thur 5/4/2006	1490.00	N/A	N/A	N/A	N/A	Thur 5/4/2006
24	SU	B	F	-4	50	SU24B-4	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	N/A	N/A	Thur 5/4/2006	1490.00	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	SU	C	F	-1	50	SU12C-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0004(1)	Thur 5/4/2006	2087.19	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	SU	C	F	-2	50	SU12C-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0004(2)	Thur 5/4/2006	2087.19	6/16/2006	1.8125	500	ambient	Thur 5/4/2006
12	SU	C	F	-3	50	SU12C-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0003(1)	Thur 5/4/2006	1905.05	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	SU	C	F	-4	50	SU12C-4	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0003(2)	Thur 5/4/2006	1905.05	6/16/2006	1.8125	500	RT water	Thur 5/4/2006
06	SU	C	F	-1	50	SU6C-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	Thur 5/4/2006	1979.70	N/A	N/A	N/A	N/A	Thur 5/4/2006
06	SU	C	F	-2	50	SU6C-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	Thur 5/4/2006	1979.70	N/A	N/A	N/A	N/A	Thur 5/4/2006
06	SU	C	F	-3	50	SU6C-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	Thur 5/4/2006	2021.50	6/16/2006	1.8125	500	RT water	Thur 5/4/2006
06	SU	C	F	-4	50	SU6C-4	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	Thur 5/4/2006	2021.50	N/A	N/A	N/A	N/A	Thur 5/4/2006
24	SU	C	F	-1	50	SU24C-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	Thur 5/4/2006	1878.17	6/16/2006	1.8125	500	ambient	Thur 5/4/2006
24	SU	C	F	-2	50	SU24C-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	Thur 5/4/2006	1878.17	N/A	N/A	N/A	N/A	Thur 5/4/2006
24	SU	C	F	-3	50	SU24C-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	Thur 5/4/2006	2063.30	6/16/2006	1.8125	500	ambient	Thur 5/4/2006
24	SU	C	F	-4	50	SU24C-4	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	Thur 5/4/2006	2063.30	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	A	F	-1	50	TA12A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0003(1)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	A	F	-2	50	TA12A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0003(2)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	A	F	-3	50	TA12A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0003(3)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	B	F	-1	50	TA12B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0003(1)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	B	F	-2	50	TA12B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0003(2)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	B	F	-3	50	TA12B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0003(3)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	C	F	-1	50	TA12C-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0002(1)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	C	F	-2	50	TA12C-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0002(2)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	C	F	-3	50	TA12C-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0002(3)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	M	F	-1	50	TA12M-1	FDOT-1	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	M	F	-2	50	TA12M-2	FDOT-1	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TA	M	F	-3	50	TA12M-3	FDOT-1	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	A	F	-1	50	TC12A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0004(1)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	A	F	-2	50	TC12A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0004(2)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	A	F	-3	50	TC12A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0004(3)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	B	F	-1	50	TC12B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0006(1)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	B	F	-2	50	TC12B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0006(2)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	B	F	-3	50	TC12B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0006(3)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	C	F	-1	50	TC12C-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0005(1)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	C	F	-2	50	TC12C-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0005(2)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	C	F	-3	50	TC12C-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0005(3)	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	M	F	-1	50	TC12M-1	FDOT-1	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	M	F	-2	50	TC12M-2	FDOT-1	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	TC	M	F	-3	50	TC12M-3	FDOT-1	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Thur 5/4/2006
12	UV	A	F	-1	50	UV12A-1	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0009(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	UV	A	F	-2	50	UV12A-2	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0009(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	UV	A	F	-3	50	UV12A-3	FDOT-1	Tue 11/1/05	9858	1034	Wed 11/16/05	Mon 12/5/05	Thur 12/15/05	N/A	2/3/2006	NCHRP_A0009(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	UV	B	F	-1	50	UV12B-1	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0005(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	UV	B	F	-2	50	UV12B-2	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0005(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	UV	B	F	-3	50	UV12B-3	FDOT-2	Thur 11/3/05	9813	1058	Fri 11/18/05	Thur 12/8/05	Mon 12/19/05	N/A	2/8/2006	NCHRP_B0005(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	UV	C	F	-1	50	UV12C-1	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0006(1)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	UV	C	F	-2	50	UV12C-2	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0006(2)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
12	UV	C	F	-3	50	UV12C-3	FDOT-5	Thur 11/17/05	10429	1095	Mon 12/5/05	Mon 12/19/05	Wed 1/4/06	N/A	2/13/2006	NCHRP_C0006(3)	N/A	N/A	N/A	N/A	N/A	N/A	Tue 4/18/2006
x	x	x	F	x	x	xxxx	FDOT-6	Thurs 8/3/2006															

Figure B-1. Continued

APPENDIX C
STANDARD TEST METHOD FOR FLEXURAL STRENGTH OF CFRP COMPOSITE BONDED CONCRETE (USING SIMPLE BEAM WITH THREE-POINT LOADING)

1. Scope

1.1 This test method covers the determination of the flexural strength of fiber reinforced polymer (CFRP) composites bonded to concrete by the use of a simple beam with three-point loading.

1.2 The values stated in inch-pound units are to be regarded as the standard. The SI equivalent of inch-pound units has been rounded where necessary for practical application.

1.3 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.

2. Referenced Documents

2A *ASTM Standards:*

C;31 Practice for Making and Curing Concrete Test Specimens in the Field2

C 42 Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete2

C 192 Practice for Making and Curing Concrete Test Specimens in the Laboratory2

C 617 Practice for Capping Cylindrical Concrete Specimens2

C 1077 Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Laboratory Evaluation2

E 4 Practices for Force Verification of Testing Machines3

3. Significance and Use

3.1 This test method is used to determine the flexural strength of the CFRP bonded to the tensile face of plain concrete beam specimens. The concrete beams shall be prepared and cured in accordance with Test Methods C42 or Practices C31 or C 192. The CFRP shall be prepared and cured in accordance with NCHRP Report 514 and the manufacturer's specifications. The stress determined will vary where there are differences in specimen size, preparation, moisture condition, curing, or where the beam has been molded or sawed to size.

3.2 The results of this test method may be used to determine compliance with specifications or as a basis for selection and application of CFRP.

4. Apparatus

4.1 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 are not permitted. Motorized pumps or hand operated positive displacement pumps having sufficient volume in one continuous stroke to complete a test without requiring replenishment are permitted and shall be capable of applying loads at a uniform rate without shock or interruption.

4.2 Loading Apparatus-The three point loading method shall be used in making flexure tests of concrete employing bearing blocks which will 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 Fig. 1.

4.2.1 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. (±1.3 mm).

4.2.2 If an apparatus similar to that illustrated in Fig. 1 is used: the load-applying and support blocks should not be more than 2½ in. (64 mm) 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. (0.05 mm) 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° (0.79 rad). The load-applying and support blocks

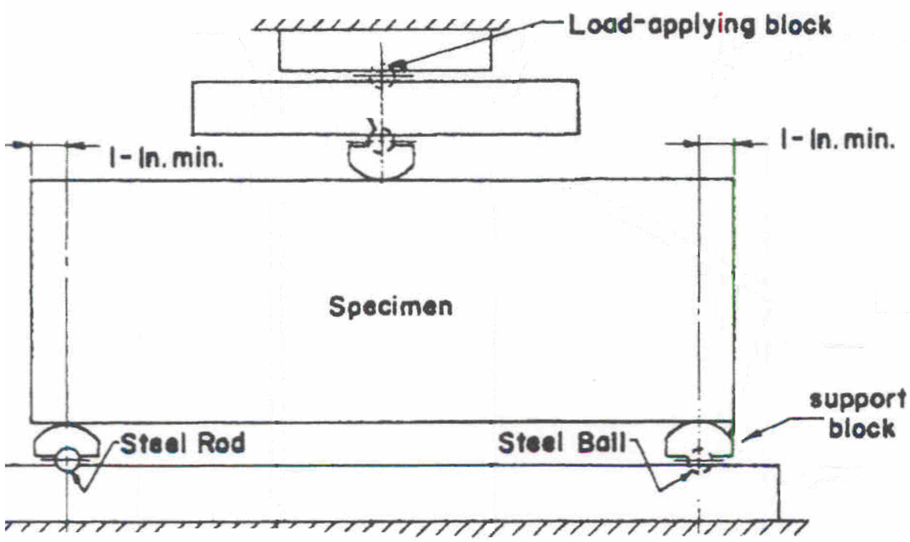


Figure C- 1. Diagrammatic View of a Suitable Apparatus for Flexure Test of Concrete by Three-Point Loading Method

NOTE I-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.
NOTE 2-1 in. = 25.4 mm

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 Fig. 1 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.

5. Testing

5.1 The test specimen shall conform to all requirements of Test Method C 42 or Practices C 31 or 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.

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

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

6. Procedure

6.1 Specimens shall be removed from exposure condition and immersed in room temperature (75 F) water 24 hours before testing. Specimens shall be removed from water immersion, surface dried, and allow to air dry for at least one hour, but no more than two hours before flexural testing.

6.2 When using molded specimens, turn the test specimen on its side with respect to its position as molded and center it on the support blocks. When using sawed specimens, position the specimen so that the tension face corresponds to the top or bottom of the specimen as cut from the parent material. Center the loading system in relation to the applied force. 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. (0.10 mm) and 0.015 in. (0.38 mm) 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. (25 mm) or more. Grind, cap, or use leather shims on the specimen contact surface to eliminate any gap in excess of 0.004 in. (0.10 mm) in width. Leather shims shall be of uniform 1/4 in. (6.4 mm) thickness, 1 to 2 in. (25 to 50 mm) width, and shall extend across the full width of the specimen. Gaps in excess of 0.015 in. (0.38 mm) 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.

6.3 Load the specimen continuously and without shock. The load shall be applied at a constant rate to the breaking point. Apply the load so that the specimen will reach ultimate capacity between 1-min and 2-min after reaching half capacity. A displacement rate of .01-in/min has been found to be acceptable for concrete strengths between 5-ksi and 10-ksi.

7. Report

7.1 Report the following information:

7.1.1 Load at failure,

7.1.2 Maximum deflection,

7.1.3 Fiber failure stress,

7.1.4 Fiber shear stress

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BIOGRAPHICAL SKETCH

Amber Lee Gartner is daughter to Gary and Linda Paul, and sister to Erin Paul. She grew up in Cape Coral, Florida where she completed her elementary and secondary education. Amber began studying at the University of Florida in August, 2000. She pursued engineering because she enjoyed math and science classes throughout her education. Her undergraduate degree was in Materials Science and Engineering, specializing in polymer science. Throughout her undergraduate degree, Amber participated in programs such as Integrated Product and Process Design at UF and Research Experiences for Undergraduates at Northwestern University. Although she carried and interest in polymer science, she felt her career goals had her heading towards the field of civil engineering.

After some post-baccalaureate work in civil engineering, Amber began the Civil Engineering graduate program in the Spring semester of 2005. Her background in polymer science proved helpful as she began work with Dr. Hamilton on CFRP research. The research combined polymer science and civil engineering. Amber received the title of an engineering intern upon passing the fundamentals of engineering exam in October 2005.

Throughout her graduate studies Amber's husband Mike has been a constant support. She will be graduating with a Masters of Engineering Degree, specializing in structures. She will continue to use her education as she joins an engineering firm in Ocala, Florida upon graduation.