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7. Author(s) Monique Head, PhD, Devin Harris, PhD, Mohamad Shawki Amine, Jonathon Tanks, Steve Efe, Ajibola Dehinbo, Emani Evans, Tyrone Hansboro, Jr., Kyle Edmonds, and Camille Smith		8. Performing Organization Report No.
9. Performing Organization Name and Address Morgan State University Department of Civil Engineering 1700 E. Cold Spring Lane CBEIS 209 Baltimore, MD 21251 University of Virginia Department of Civil and Environmental Engineering 351 McCormick Road Thornton Hall, D216 Charlottesville, VA 22904-4742		10. Work Unit No. (TRAIS)
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16. Abstract Corrosion-induced deterioration of steel rebar in concrete structures often demands costly repair and maintenance, where the steel rebar swells and increases the tensile load in concrete resulting in cracks, spallings and openings that increase its susceptibility to corrosion. Previous research has shown the validity, deformability and suitability of aramid fiber reinforced polymer (AFRP) bars used in prestressed, precast concrete deck panels (PCPs). However, research is still needed to monitor and assess the long-term behavior of AFRP bars due to creep, shrinkage and prestress losses when exposed to thermal and sustained loads similar to "in-situ" bridge conditions. The research will be divided into two phases: 1) a laboratory-scale investigation for accelerated degradation and time-dependent behavior, and 2) an experimental investigation of 7-foot concrete beams reinforced with AFRP bars and evaluated for long-term performance under natural environmental conditions. Phase I will examine effects of freeze-thaw, creep, and shrinkage effects of concrete components, and Phase II will focus on testing of prestressed beams with FRP bars (flexural reinforcement only). For both phases instrumentation (internal and external measures) will be deployed for measuring strain response of the specimens. State-of-the-art digital imaging correlation (DIC), a non-contact optical based deformation measurement technique, is used for monitoring specimen behavior. This study will also serve as a testbed for deploying DIC for performance monitoring of concrete structure and finite element analysis (FEA) to numerically compare system performance to conventional designs.		
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DISCLAIMER

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Table of Contents

LIST OF FIGURES	5
LIST OF TABLES	6
PROBLEM	7
APPROACH.....	7
METHODOLOGY	8
FINDINGS	9
Task 1: Literature Review of AFRP, Bridge Decks, Prestressing and Anchorage of AFRP Bars	9
Task 2 – Specimen Design.....	12
Materials	12
Specimens.....	12
Environmental Exposures.....	13
Task 3 – Experimental Testing and Analysis.....	15
Pullout Testing.....	15
Analysis of Results from Pullout Tests.....	16
Beam Testing.....	19
Analysis of Results from Beam Testing	22
Task 4 – Summary and Recommendations.....	22
FUTURE WORK	24
REFERENCES.....	25

LIST OF FIGURES

Fig. 1: Formwork for 7' beams to be prestressed with AFRP bars.....	8
Fig. 2: Images from DIC component used for measuring strains on surface a) reference image, b) grid pattern for correlation, and c) calculated displacement field	9
Fig. 3: Specimen design for bond pullout testing (inches)	13
Fig. 4: Representative thermal fatigue cycles within a 48 hour period	15
Fig. 5: Setup for bond pullout testing with the optical DIC system	16
Fig. 6 Bond stress-slip curves from 2205, CFRP, and AFRP bars for (a) control, (b) saltwater, and (c) thermal fatigue conditions.....	17
Fig. 7: Condition of bars after pullout testing, showing (a) 2205, (b) CFRP, and (c) AFRP	18
Fig. 8: Residual performance of 2205, CFRP, and AFRP for bond strength	19
Fig. 9: Beams in the wet phase of the wet/dry cycle.	21
Fig. 10: Beam test setup for 3-point bending testing	21
Fig. 11: ANSYS modeling of a concrete beam with a concentrated load at midpoint.....	22
Fig. 12: Inconsistent rebar alignment and bonded length within most specimens	23
Fig. 13: Concrete failures during testing due to concrete quality and embedded rebar alignment.....	24

LIST OF TABLES

Table 1. AFRP, CFRP, and 2205 Material Properties	12
Table 2: Previously studied environmental conditions that could potentially affect the long-term behavior of FRP materials.....	14
Table 3: Beam Description and Instrumentation Scheme.....	19
Table 4: Concrete Compressive Strength Data from Pour #1.....	20
Table 5: Concrete compressive strength data from Pour #2.....	20

PROBLEM

Using composite materials instead of conventional steel rebar in bridges will address the critical problem of corrosion-induced deterioration, thereby increasing the service life and life-cycle cost savings (even after higher initial costs of composite materials) for concrete structures. Such developments are needed to minimize future investments for repair, maintenance, asset management, and overall sustainability of transportation infrastructure. Advances in nonmetallic materials such as aramid fiber reinforced polymer (AFRP) composites show promise for civil engineering applications, particularly in concrete bridge decks. The research will address knowledge gaps due to lack of sufficient data on the long-term performance of AFRPs.

The research goal addressed by this problem statement is to investigate the long-term performance of aramid fiber reinforced polymer (AFRP) bars used in prestressed, precast concrete deck panels. In parallel with the primary research objective, the project team will also investigate the feasibility of a non-contact optical method, digital image correlation (DIC), and long-term performance monitoring. In order for a paradigm shift in the design of concrete transportation structures using composites for improved structural sustainability and design, monitoring and testing of such structures are needed. The anticipated impact of this research has the potential to lead to a new class of precast concrete panels (PCPs) and/or components like beams that are prestressed with AFRP bars (and non-prestressed AFRP bars) to provide longer service life for bridge decks, which will be more sustainable and durable.

The expected benefits will be preliminary results on the long-term performance of aramid fiber reinforced polymer bars for prestressed bridge deck panel applications. While the study will be limited to 2 years, the monitoring will continue beyond the study period and serve as a performance measure of the concept for future studies.

APPROACH

To address the research objective, this project is divided into four (4) research tasks, where Morgan State University (MSU) and the University of Virginia (UVA) worked together to merge efforts:

- Task 1 – Literature Review of AFRP, Bridge Decks, Prestressing and Anchorage of AFRP Bars
- Task 2 – Specimen Design
- Task 3 – Experimental Testing and Analysis
- Task 4 – Summary and Recommendations

METHODOLOGY

For each task, a description of the methodology applied is outlined herein:

Task 1 – Literature Review of AFRP, Bridge Decks, Prestressing and Anchorage of AFRP Bars

The research team will compile a literature review, using the Transportation Research Information Service, TRIS, as well as other library sources of reference material to fully document the state-of-the practice and state-of-the-art on the use of AFRP bar for prestressed, precast concrete panels (PCPs) and beams used for bridge decks. The research team has significant experience and expertise with the AFRP material, structural modeling, experimental design and testing, and structural design.

Task 2 – Specimen Design

Phase I of this task will focus on simulating effects of freeze-thaw, creep, and shrinkage effects on the bond strength of individual AFRP bars embedded within concrete cubes (component specimens) that will be monitored and tested by the UVA team. Phase II consists of six (6) beams prestressed and non-prestressed with AFRP and GFRP bars will be designed and constructed (Fig. 1), where specific design issues focused on serviceability will be investigated. Also, for the design, load-deflection and moment-curvature relationships, post-cracking flexural stiffness, prestress loss in AFRP tendons, effect of tension stiffening in post-serviceability regions, and crack width versus the stress level in AFRP bars will be studied. FEA models will be developed in parallel with the specimens designed for correlation purposes. UVA will be instrumental in providing the expertise from the digital correlation imaging (DIC) system for monitoring specimen behavior.



Fig. 1: Formwork for 7' beams to be prestressed with AFRP bars

Task 3 – Experimental Testing and Analysis

For both phases instrumentation (internal and external measures) will be deployed for measuring strain response of the specimens. An example of the capabilities of the DIC component is shown in some beam samples in Fig. 2.

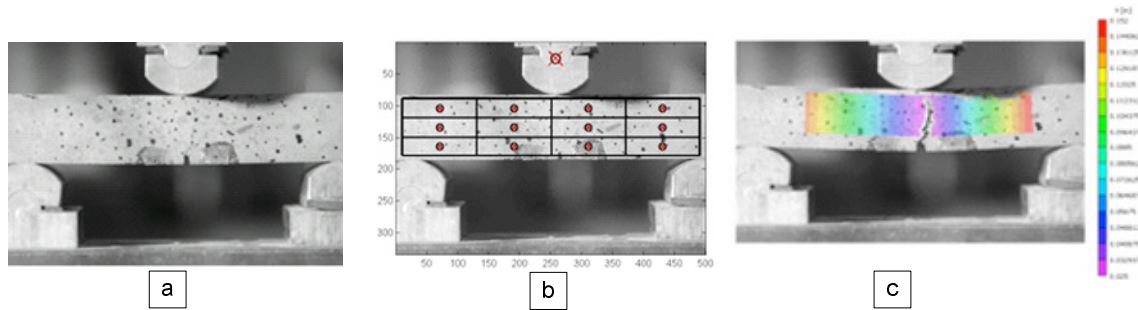


Fig. 2: Images from DIC component used for measuring strains on surface a) reference image, b) grid pattern for correlation, and c) calculated displacement field

Task 4 – Final Report

The final tasks consists of documenting lessons learned and details from Tasks 1-3, thereby revealing the long-term performance and specimen behavior of non-prestressed and prestressed components (or elements) with AFRP bars.

FINDINGS

Task 1: Literature Review of AFRP, Bridge Decks, Prestressing and Anchorage of AFRP Bars

Transportation agencies have been challenged for years with early deterioration of concrete structures due to corrosion of steel reinforcement, mainly in bridge structures (Koch et al., 2002; Toutanji and Saafi, 1999; Okelo and Yuan, 2005; Myers and Viswanath, 2006; El-Hacha et al., 2010). The annual cost of corrosion in the infrastructure industry in the United States, according to the Federal Highway Administration, is \$22.6 billion, and 37% of this cost is contributed by highway bridges (Koch et al., 2002). The expansion of steel reinforcement due to corrosion exerts an enough force to defeat the tensile capacity of concrete causing cracking (Toutanji and Saafi, 1999). In order to prevent any potential damage to structures caused by steel corrosion, agencies have looked for solutions such as galvanization, using epoxy coated steel and stainless steel, cathodic protection systems, and modified concrete mixes, to name a few (Koch et al., 2002). Those protection methods proved to be effective in mild environments however they failed to eliminate the problem of corrosion and deterioration of concrete in severe conditions (Toutanji and Saafi, 1999; Okelo and Yuan, 2005).

Another solution was to replace steel with alternative materials, for reinforcement, with similar tensile capabilities but that do not corrode. For number of years, Fiber Reinforced Polymer (FRP) composite materials have been considered as viable options to serve such a purpose due to their high tensile strength and durability.

Compared to steel, FRP has significantly higher tensile strength and lower modulus of elasticity which makes deflection and crack widths control design (Okelo and Yuan, 2005). On the other hand, FRP behaves linearly-elastic to failure, which displays no ductility so brittle failure can raise concerns for their use as reinforcing materials; serious design considerations should be taken for this mode of failure (Toutanji and Saafi, 1999; Myers and Koenigsfeld, 2006). Design codes for reinforced and prestressed concrete structures are based on extensive research done on the bonding durability of steel in concrete (Achillides and Pilakoutas, 2004). Due to the physical and mechanical differences between FRP and steel, a direct substitution between the two is not ideal (Okelo and Yuan, 2005; Stoll et al., 2000). Therefore it is of a great interest for designers to predict the bond behavior between FRP materials and concrete in order to effectively use it in concrete structures for both reinforced and prestressed applications.

This study evaluates the bond durability of unidirectional pultruded FRP bars—made with carbon (CFRP) and aramid (AFRP) fibers—in concrete after exposure to two different environmental conditions: temperature cycling and immersion in saltwater. Several state departments of transportation (DOTs), such as Maine, Michigan, Missouri, Ohio, and Virginia, have recently used CFRP tendons in prestressed bridge elements in an effort to reduce corrosion damage (FHWA, 2014). The benefits of CFRP include low density, high strength, and high fatigue-resistance (Dolan et al., 2001), and relatively good resistance to chemical attack; it is one of the most durable composites available (Dolan et al., 2001). Nonetheless, in order to increase reliability and implementation of CFRP, durability under environmental conditions must be studied (Gar, 2012). Benefits of AFRP include good creep-rupture and fatigue features, large tensile capacities, and reasonable pricing which makes them appealing to DOTs (Gar, 2012). AFRP has not been used as much as CFRP by transportation agencies but has a great potential to be deployed for field applications. Further experimental investigations need to be performed on AFRP to increase reliability of the material.

Early deterioration of concrete structures with steel reinforcement has been a major problem for structures that are exposed to marine environments due to steel corrosion. It is evident that the exposure to solutions containing chlorides causes accelerated corrosion of steel reinforcement and the deterioration of concrete structures, but the effects of that exposure on FRP-concrete bond durability has yet to be determined. Work by Micelli and Nanni (Micelli and Nanni, 2004), Chin et al. (Chin et al., 1999; Chin et al., 2001), Scott and Lees (Scott and Lees, 2009; Scott and Lees, 2012) confirm that in the case of undamaged resin, moisture absorption is governed by Fickian diffusion. However, after a certain degree of absorption is reached and the fluid has penetrated the composite sufficiently, damage occurs from swelling strains and the diffusion behavior changes from linear to nonlinear (Micelli and Nanni, 2004). Microscopic examination has also indicated that these matrices are susceptible to bond degradation at the fiber/matrix interface, while degradation of the fibers themselves depends largely on their type (Ray,

2006). Karbhari and Xian (Karbhari and Xian, 2009) studied moisture absorption in FRP composites, with a focus on measuring diffusion coefficients for absorption, desorption, and re-absorption at 23, 37.8, and 60 °C. Higher immersion temperatures lead to higher diffusion rates and equilibrium absorption.

Reinforced and prestressed concrete is a composite system, so sufficient bond strength between the FRP and the concrete is needed for the system to achieve the design requirements. Studies have shown that bonding is controlled by the following factors: chemical bond, friction (surface roughness of FRP), mechanical interlock of FRP against concrete, hydrostatic pressure against FRP (shrinkage of hardened concrete), and swelling of FRP (temperature change, moisture absorption) (Cosenza, Manfredi, and Realfonzo, 1997). Initial pull-out is mainly resisted by chemical bond, while intermediate and final pull-out is resisted by friction and mechanical interlock (Cosenza, Manfredi, and Realfonzo, 1997). According to Kanakubo et al. (1993), smooth- and strand-shaped (undeformed) tendons exhibit a dominant friction-resistance, while deformed bars bond more through bearing-resistance (mechanical interlock).

For the undeformed bars, the surface treatment has a noticeable effect on the chemical bond and friction bond, with smooth having the worst bond strength and grain-coated having the best. However, coatings (such as sand grains) tend to detach abruptly and cause a sudden, brittle failure (Cosenza, Manfredi, and Realfonzo, 1997). The traditional assumption that bond strength varies linearly with the square-root of concrete's compressive strength is incorrect for FRP, since the bond strength usually depends solely on the bar's surface treatment and resin matrix (Cosenza, Manfredi, and Realfonzo, 1997).

The effects of higher temperatures on FRP-concrete bond, and cyclic temperature, have been studied with respect to geographical locations that experience a wide variation in temperature, such as deserts or even some so-called temperate regions. The difference in thermal expansion coefficients between FRP and concrete creates a strain-incompatibility that can lead to bond degradation (Belarbi and Wang, 2012; Ceroni et al., 2006; Maluk et al., 2010). Additionally, elevated temperatures (greater than 40 °C) tend to soften the polymer matrix of most FRP, which can cause a loss in bond stiffness and thus a potential decrease in performance (Katz et al., 1999). The amount of softening depends on the glass transition temperature (T_g). More work is needed to understand the effects of temperature alone, given the well-known thermal incompatibility between FRP and concrete.

Task 2 – Specimen Design

Materials

In order to fully understand the bond behavior of AFRP and CFRP bars under the exposure of environmental conditions, the bond performance of 2205 stainless steel was also investigated. The bond behavior of 2205 and that of pultruded, unidirectional AFRP and CFRP composite materials are compared. The characteristics of AFRP, CFRP, and the 2205 bars are presented in Table 1 below.

Table 1. AFRP, CFRP, and 2205 Material Properties

Parameter	Unit	Pultruded AFRP Bars	Pultruded CFRP Bars	2205 Stainless Bars
Diameter	<i>mm (in)</i>	13 (0.5)	12.7 (0.5)	13.3 (0.5)
Surface Finish	-	Smooth, helical groove	Smooth, helical groove	Deformed (ribbed)
Fiber Type	-	Technora aramid	Tenax PAN	-
Fiber Content (vol)	-	0.64	0.65	-
Resin Type	-	Epoxy	Epoxy	-
Yield Strength	<i>MPa (ksi)</i>	-	-	448 (65)
Tensile Strength	<i>MPa (ksi)</i>	1,516 (220)	1,695 (246)	621 (90)
Tensile Modulus	<i>GPa (Msi)</i>	47.5 (6.9)	131 (19)	190 (27.6)
Specific Gravity	-	1.3	1.5	7.8

For the experimental plan, the same concrete mix was intended for casting all the specimens; however during the casting process and after all the steel specimens were cast, some logistical problems arose and forced an interruption. Six weeks later, the AFRP and CFRP specimens were then cast with an identical concrete mix. All specimens were then exposed for the same exposure periods before testing them. The 28-day concrete strengths were 36.1 MPa (5,249 psi) and 36.6 MPa (5,315 psi) for the first and second mixes, respectively.

Specimens

For the purpose of our investigation, 150 mm (6 in) concrete cube specimens containing a single reinforcing bar were fabricated (Fig. 3), according to the RILEM pullout style (RILEM, 1978), and exposed to either conditions of warm saltwater or thermal fatigue, and then tested using the direct-pullout method.

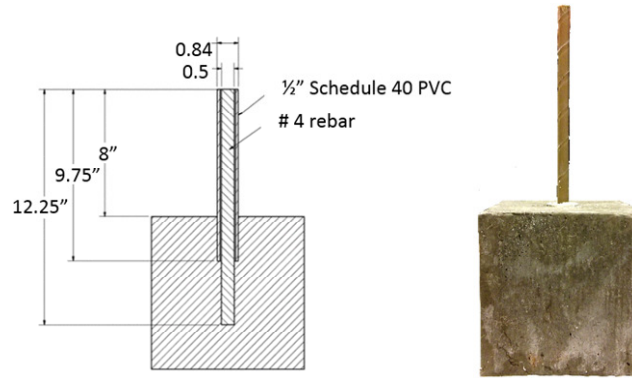


Fig. 3: Specimen design for bond pullout testing (inches)

The bonded length was nominally five times the bar diameter all specimens, of all bar types. Results of performed work by Okelo and Yuan (Okelo and Yuan, 2005) showed that 5db for bonded length is the most appropriate for bond testing out of those they studied, between three and nine times the bar diameter. Bond stresses are mostly evenly distributed during testing with a 5db bonded length, compared to a range of three to five times the bonded length (Okelo and Yuan, 2005).

During casting, PVC pipes were used as bond-breakers, as presented in Figure 3, to create an unbonded region separating the embedded bars from concrete allowing a bonded length of $5d_b$. This is to prevent “pop-out” failure, wherein the concrete surface cracks at the loaded end and is pulled out along with the bar. After the specimens were left to cure, the PVC was cut and removed for all specimens except for those which were exposed to the saltwater; it was left for these, in order to protect the bare bars from being directly affected. Furthermore, insulated sleeves with high thermal resistance were used to replace the PVC pipe for the thermal fatigue specimens in order to protect the bare bars from higher temperatures.

Environmental Exposures

Previous Work

Aramid fibers have a considerable propensity to absorb moisture (up to 8 percent by weight) which leads to swelling causing a development of bond problems between the composite and concrete. It's evident that moisture absorption is a critical factor that affects AFRP/concrete bonding in the long term. The exposure of the material to wet/dry cycles in salt water has also been highly recommended to evaluate in order to assess the integrity of the material's bond under such an exposure. Additionally, previous studies had shown that AFRP material has a significant resistance to concrete Alkalinity (ACI Structural Journal, V.95, No. 5, 1998). Based on our literature review, table 2 below represents some of the previously studied environmental conditions that could potentially affect the long term behavior of the examined FRP materials.

Considering real life scenarios as well as previous studies on FRP reinforcing materials, the two environmental conditions chosen for this study were (1) salt solution,

at elevated temperature to accelerate degradation, and (2) thermal fatigue, through cycling between lower and higher temperatures. Both environmental conditions were simulated in our laboratories at Virginia Center for Transportation Innovation and Research and at the University of Virginia.

Table 2: Previously studied environmental conditions that could potentially affect the long-term behavior of FRP materials

	Environmental Conditions		
	Aramid Fiber	CFRP	GFRP
Internally Bonded	Tidal/thermal cycle in Salt Water (daily & Annual)		Freeze-Thaw
			Air (Laboratory AC)
	Simulated Tidal		Ca(OH) ₂
	Wet-Dry Cycles		NaCl + MgCl ₂
Externally Bonded		Wet-dry salt water cycles	Fire
		(Synthetic) sea water	Freeze-Thaw
		Fresh Water	
		Thermal Expansion Cycles	Wet-dry salt water cycles
		Freeze-Thaw cycles in salt water	
		Humidity	
Material Alone	Water	UV	Salt Solution
	UV		NH ₄ OH
	Wet/Dry cycles	Alkaline	Deionized Water
	Alkaline		UV
	Sodium Hydroxide	Air	Sea Water
			Alkaline
			NaCl ₂ + CaCl ₂

Salt Solution

The salt solution (saltwater) environment was simulated using a commercially available sea salt mixture that was produced and prepared according to the “Sea-salt” ASTM D1141-98 (ASTM International, 2013). It was added to a large Plexiglas tub along with the specimens for this exposure condition. An immersion heater with an integrated thermostat control was used to maintain the solution’s temperature at 60 °C, for a period of three months.

Thermal Fatigue

All specimens were subjected to thermal fatigue by placing them in a Despatch[®] Ecosphere[™] environmental chamber for prescribed durations and conditions. Temperature range cycled at 4.5 and 49 °C (40 and 120 °F), at 25% relative humidity. The specimens were exposed to 90 cycles, where each cycle represented an approximation to one day in real-time, shown in Figure 4.

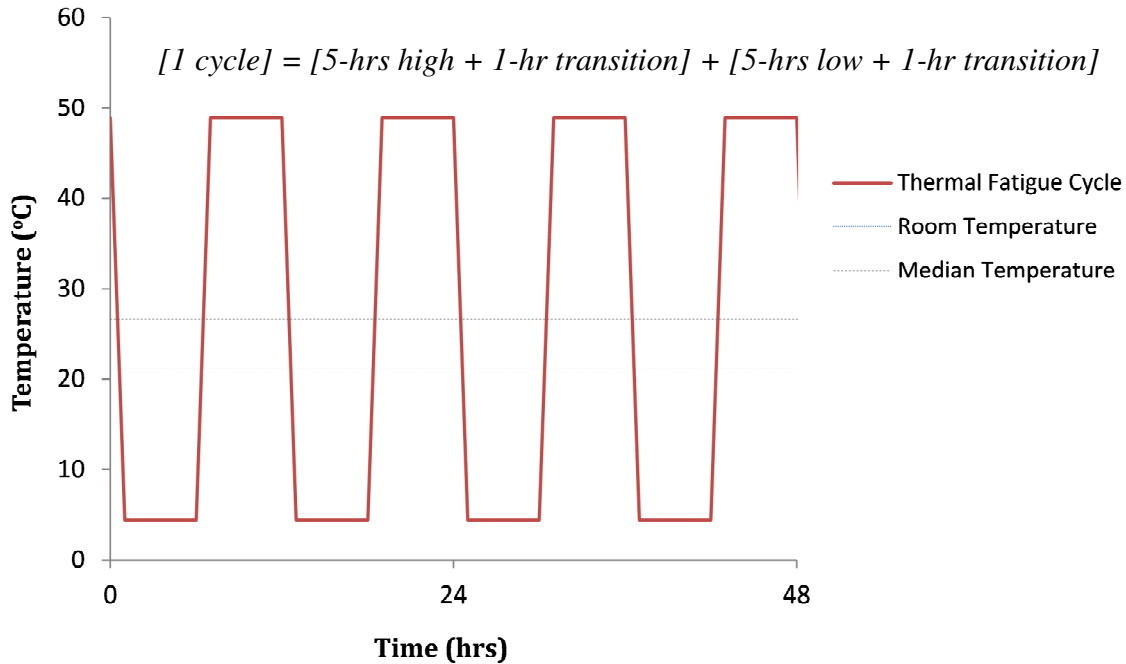


Fig. 4: Representative thermal fatigue cycles within a 48 hour period

Task 3 – Experimental Testing and Analysis

Pullout Testing

For the purpose of our study, displacement-controlled direct-pullout tests were performed on all the specimens in order to assess the bond performance of AFRP and CFRP bars in concrete and compare it to that of 2205 stainless steel. The pullout method has been adopted for years to examine the bond performance of reinforcing bars due to its simplicity and economy even though the stress conditions developed in the specimen during testing are rarely encountered in practice (Achillides and Pilakoutas, 2004). A digital image correlation (DIC) system was used to measure bar deformation and displacement during testing, providing non-contact measurements of deformation and slip.

Figure 5 below presents the experimental set ups for both kinds of specimens, with FRP as well as steel bars. A servohydraulic MTS testing machine with 100 kN capacity was used for pulling the embedded bars out of the concrete. For each test, the concrete cube was placed in a customized steel cage that was positioned in the MTS machine. The

cage consisted of two steel plates where the bottom plate (50 mm thickness) and the top plate (100 mm thickness) were connected at the four edges using four steel threaded rods. Specimens with steel bars were tested by directly gripping the bar using wedge grips and pulling; however, a special gripping mechanism was used to accommodate specimens with embedded FRP bars. The FRP gripping mechanism utilized a clamped anchor, made of steel plates connected with four bolts and a small steel frame positioned in the MTS grips.

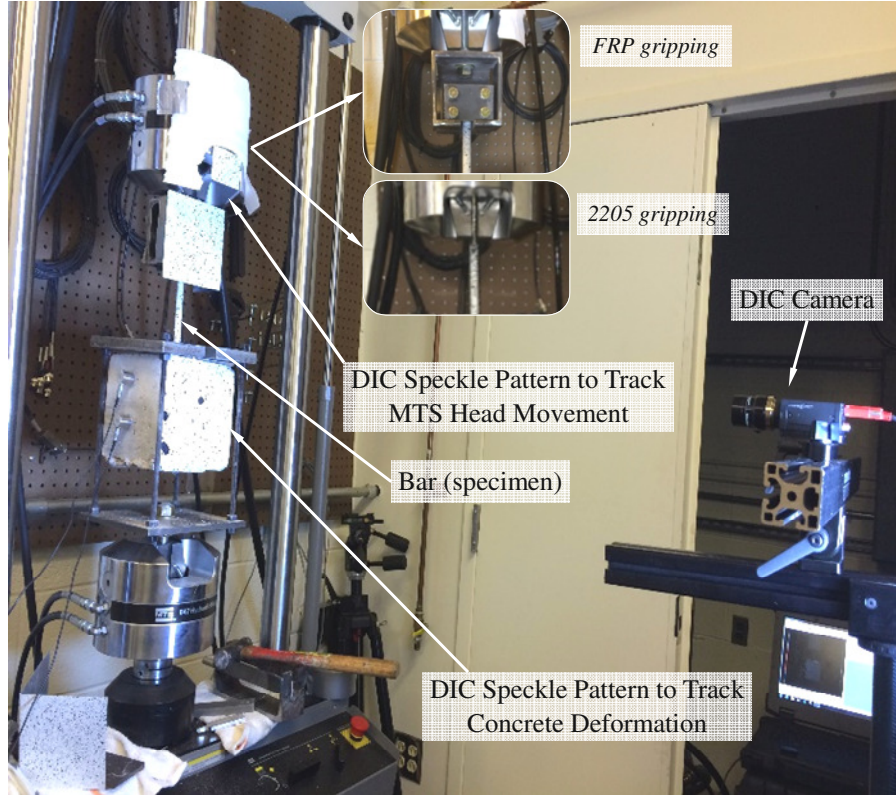


Fig. 5: Setup for bond pullout testing with the optical DIC system

Analysis of Results from Pullout Tests

After exposing all the bond specimens – six inch cube specimens with FRP and steel embedded bars- for three months under the previously specified environmental exposures, the pullout test was performed. All specimens were tested under the same experimental procedure as described in the experimental testing section of this paper. At any stage of testing, the bond stress, τ_b , was calculated using Eq. (1):

$$\tau_b = \frac{F}{A} = \frac{F}{\pi d_b L} = \frac{F}{\pi 5 d_b^2} \quad (1)$$

where F is the applied load, A is the contact surface area, d_b is the bar diameter, and L is embedded length of the bar. Representative bond stress-slip behavior for all control and exposed specimens for all rebar type material are presented in Figure 6 below.

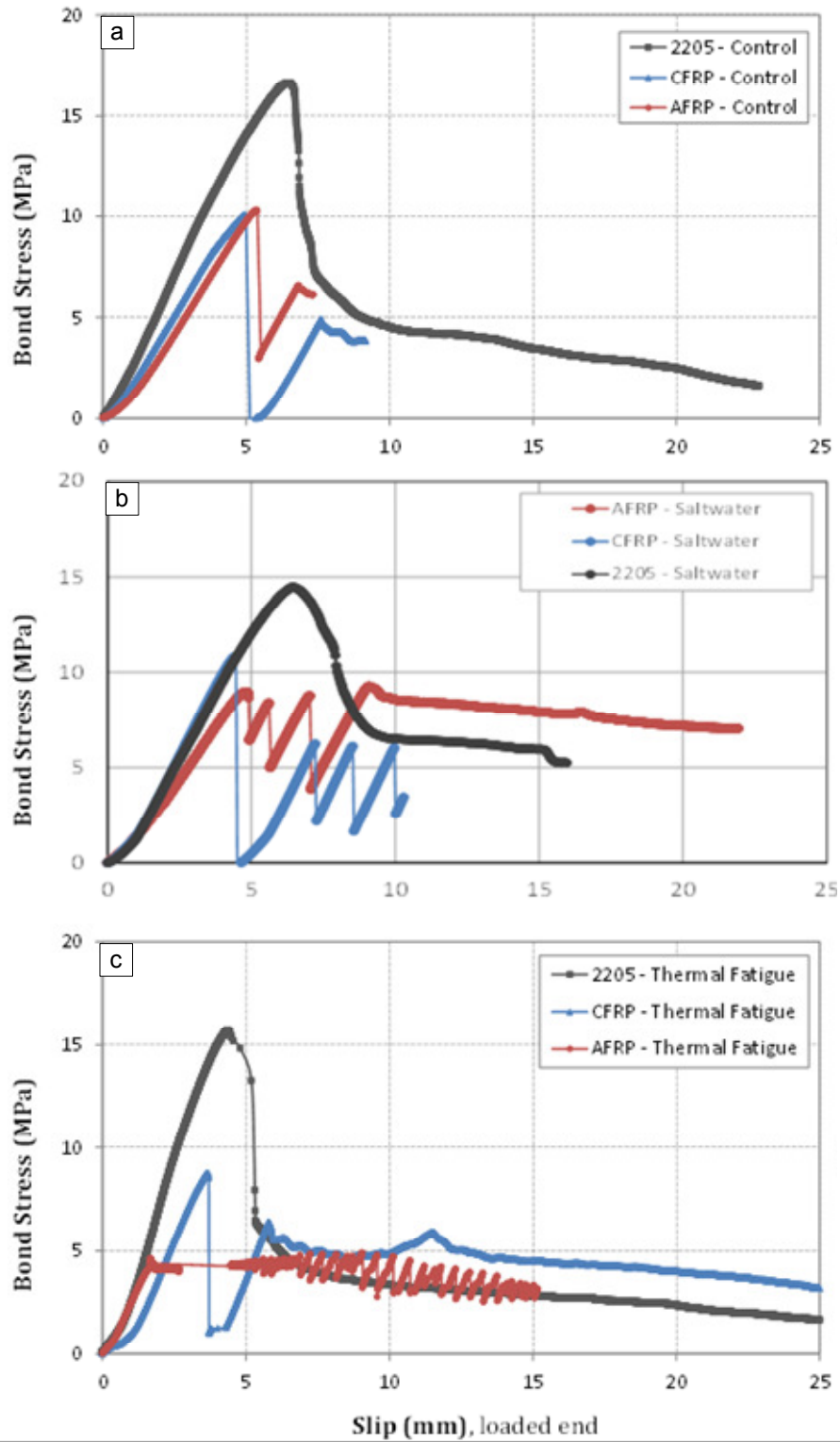


Fig. 6: Bond stress-slip curves from 2205, CFRP, and AFRP bars for (a) control, (b) saltwater, and (c) thermal fatigue conditions

It is clear that the 2205 steel bars exhibit higher bond strength than either FRP, approximately 60% more, and the bond stiffness is roughly 33% more. In this study, bond stiffness refers to the linear ratio of stress-to-slip prior to peak bond stress. Based on the literature presented earlier, it seems that this large difference is due mostly to the fact that the 2205 bars have a deformed shape whereas the FRP are straight, smooth bars with only slight helical grooves. It is difficult to separate the chemical, friction, and mechanical-interlocking portions of the bond, but previous work shows that smooth FRP bars primarily resist initial slip through chemical bond, with friction comprising the majority of resistance after very small displacements, while the deformed steel shears the concrete located between lugs. Thus, the nature of the stress-slip curves after the peak stress (bond strength, τ_b) is reached varies between materials. The steel shows a smooth decay, while both AFRP and CFRP experience jumping—but overall decreasing—stress as slip increases. This cyclic stress-slip behavior after bond breakage is characteristic of friction-dominated bond mechanisms, wherein debris from the FRP that has peeled away accumulates to wedge the gap between the bar and concrete, increasing the stress. Once the debris is overcome, stress drops and debris accumulates again as the slip increases. Conversely, the steel pulls out smoothly because the sheared concrete between lugs offers little change in friction. Figure 7 illustrates the bar condition after pullout, with debris clearly visible on the AFRP and some signs of material loss on the CFRP. The shear concrete between the lugs on the 2205 matches the test data and the literature.

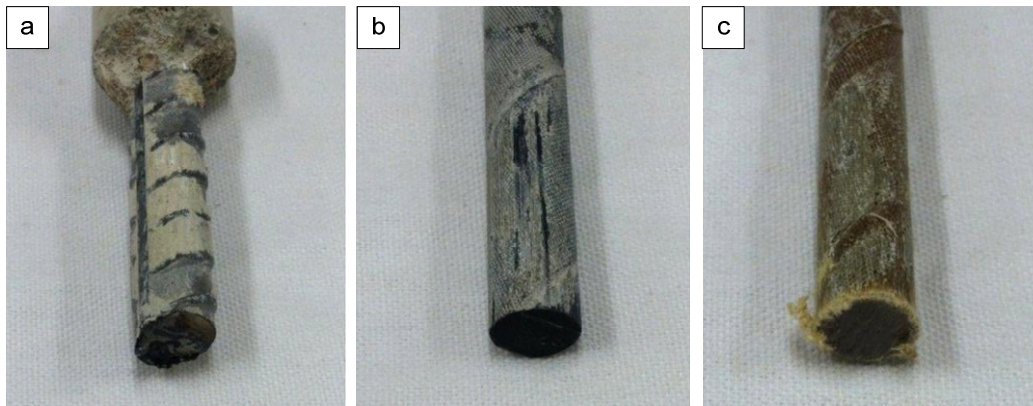


Fig. 7: Condition of bars after pullout testing, showing (a) 2205, (b) CFRP, and (c) AFRP

Regardless of the difference in magnitude of bond strength and stiffness between materials, the effect of environmental exposure (i.e., degradation) is made apparent in Figure 6. There appears to be an interesting trend showing that while saltwater harshly affects bond stiffness, thermal fatigue actually causes an increase. There is little evidence in the literature of why this might be, but it is very likely that changes in the chemical interface between reinforcement-concrete are responsible. Further work at smaller length scales is needed to determine the mechanism here. Thermal fatigue causes a 55% loss in bond strength for AFRP compared to 13% for CFRP. Unsurprisingly, saltwater lowers the bond strength of 2205, but for CFRP and AFRP, this value slightly increases. This is promising for FRP applications in marine environments, where steel typically corrodes at an accelerated rate.

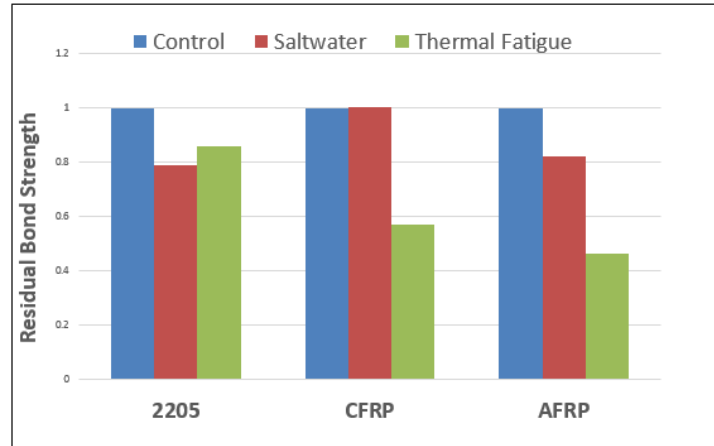


Fig. 8: Residual performance of 2205, CFRP, and AFRP for bond strength

Beam Testing

To investigate bond integrity or failure, long-term effects of aqueous and alkaline exposure and moisture absorption, an experiment using 6 concrete beams with various internal reinforcements as described in Table 3 were explored.

Table 3: Beam Description and Instrumentation Scheme

Description	Bar No.	VWG Instrumentation
Non-Prestressed AFRP	4	YES
Prestressed AFRP	4	YES
Prestressed AFRP	5	YES
Non-Prestressed AFRP	6	YES
Non-Prestressed AFRP	4	NO
Non-Prestressed AFRP	4	NO

Two of the beams were prestressed using AFRP and GFRP bars. The remainder were non-prestressed beams while 2 of those were fitted with stainless steel and black steel as control samples. All FRP beams were wired with variable wire gauges (VWG) to collect continuous strain data on any changes within the beams. To evaluate the strength of the concrete 6 x 12 cylinders were tested 7-day intervals as shown in Table 4 and 5.

Table 4: Concrete Compressive Strength Data from Pour #1

Date	Days	Maximum compressive strength f'_c (psi)
21- March	1	1111.12
7- April	14	1698.86
14- April	21	4613
21-April	28	4912.54

Table 5: Concrete compressive strength data from Pour #2

Date	Days	Maximum compressive strength f'_c (psi)
5- May	1	2547
14- May	14	3200
21- May	21	6548

All 6 beams were subjected to a wet/dry cycle in a tank as shown in figure 1. with the intention of mimicking the natural tide cycle of a marine environment. After a 6 week 3-day wet and 4-day dry wet/dry cycle the beam were then exposed an alkaline environment using sea-salt according the ASTM specification for marine water (according to the “Sea-salt” ASTM D1141-98 [ASTM International, 2013] like the cube specimens tested). After a 6-week (3-day wet and 4-day dry) wet/dry cycle in saline-like solution the beams were then exposed to an alkaline environment using sea-salt according to the ASTM specification for marine water for a continued duration of 6 weeks.



Fig. 9: Beams in the wet phase of the wet/dry cycle

For the ultimate strength tests, a three-point flexural test was established to apply the load as shown in Figure 10. To apply the required force, a hydraulic ram was used to load the specimen within the HPM Magnus frame.

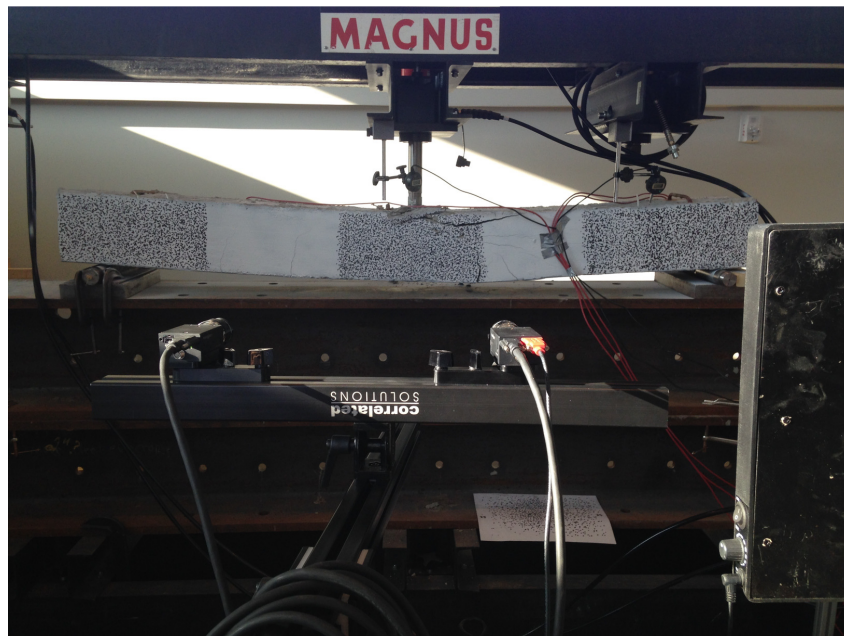


Fig. 10: Beam test setup for 3-point bending testing

Analysis of Results from Beam Testing

The beam test results showed that all specimens failed in shear due to the lack of shear reinforcement, which was expected. The cracks in the beam indicated that the beam experienced compression under the load and tension at the bottom of the beam as confirmed by finite element modeling using ANSYS as shown in Fig. 11. More data reduction is needed to process all of the results from the DIC to determine the effect of the accelerated aging on the actual beam performance for all of the 6 beams tests. The anticipated results will provide indicators as to the bond performance of the FRP bars to the concrete which will largely determine its effect on the ultimate load capacity of the beam.

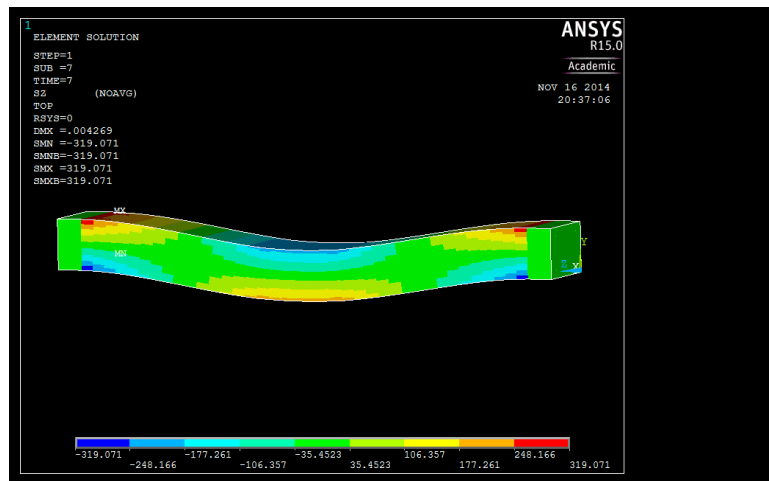


Fig. 11: ANSYS modeling of a concrete beam with a concentrated load at midpoint

Task 4 – Summary and Recommendations

From the experimental study presented here, the following conclusions regarding bond durability for AFRP and CFRP in concrete have been made:

- 2205 steel bars exhibit higher bond strength and stiffness than both AFRP and CFRP due mostly to the deformed shape of the 2205 bars.
- The previously described bond behavior of smooth FRP bars, consisting of initial slip resistance through chemical bond and friction resistance after very small displacements, was confirmed from direct pullout testing.
- 2205 steel bars with its deformed shape shears the concrete located between lugs to resist slippage and then pulls out smoothly because the sheared concrete offers little change in friction.
- AFRP and CFRP show a cyclic stick-slip behavior after bond breakage as a characteristic of friction-dominated bond mechanisms.
- Thermal fatigue causes a greater loss in bond strength for AFRP (55%) compared to CFRP (13%), and both lost more than 2205. This is attributed to the larger

difference in thermal expansion between FRP and concrete. Interestingly, this exposure condition increases bond stiffness, and while the reason is not yet known, it may be due to a thermally-enhanced chemical bonding mechanism at the bar-concrete interface.

- Saltwater affects bond strength for 2205, but appears to have little influence on CFRP and AFRP, even showing a slight increase. It also decreases bond stiffness for all bar types.

During this experimental investigation, there were a number of challenges that we encountered. The quality of the specimens did not allow us to take advantage of all the fabricated specimens especially that there was inconsistency in some of the parameters that were originally designed to be fixed such as bonded length and strength of concrete. The quality of the concrete differed greatly where poor consolidation and bad finishing at the time of pouring were commonly found within the specimens (Fig. 12). Additionally, and for an evenly distributed bond stress at the time of performing the pull-out test, the specimens were originally designed for the bar to be embedded straight and perpendicular to the surface of the concrete cube with a constant $5d_b$ bonded length. The bonded length varied greatly from one specimen to another, where only selected few specimens had a constant $5d_b$ bonded length. Additionally the bars were not aligned straight which caused failure in concrete, instead of bond, in many cases (Fig. 13).



Fig. 12: Inconsistent rebar alignment and bonded length within most specimens



Fig. 13: Concrete failures during testing due to concrete quality and embedded rebar alignment

FUTURE WORK

Further work is needed—and is in progress—at smaller length scales to understand the mechanisms of all results presented here, including a parallel assessment of the bar and concrete materials for each environment. We are currently in the process of performing combined macro- and microscopic investigations to understand the behavior of the FRP, concrete, and the interface region between both under the exposure of environmental conditions. Additionally, specimens with cylindrical shape with a constant 5db rebar embedment length, were fabricated, exposed to the same environmental conditions as presented in this report, and tested following the same experimental procedure. Data was collected for all specimens, and we are currently in the process of analyzing it. Furthermore, longer exposure durations are recommended to be considered in any future work in order to better understand the long term performance of AFRP and CFRP as reinforcing materials. It is worth noting that this work is part of a larger study on the durability of FRP bond in concrete for prestressing applications.

As for the beam testing, further reduction of the data collected is needed—and is in progress to understand the structural degradation in the ultimate strength capacity of the beam compared to theory. Moreover, the "long-term" monitoring of the beams via the vibrating wire gauges (VWG) that were embedded in the beams needs to be further analyzed to understand patterns and various behaviors during the monitoring period. For the prestressed beams, the data collected by the VWGs embedded in the instrumented beams will be used to calculate transfer lengths and track any prestress losses. Changes in the concrete strain as indictable by the data collected from the internal instrumentations over time can only be explained by an elastic shortening, creep, and shrinkages of the concrete and relaxation of the FRP strains. This can be associated with prestress losses due to an imperfect bond between the strands and cementitious matrix.

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