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Long-term Durability of FRP Bond in the Midwest United States for Externally-Strengthened Bridge Components

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Abstract

In this study, the bond strength of a typical FRP system subjected to long-term natural weathering in the Midwest United States is experimentally investigated, and the rate of degradation is estimated. To do this, the bond strength of an FRP system exposed to over fifteen years of weathering is determined with pull-off testing, and a relationship between strength reduction and exposure time is developed using regression analysis. For unweathered specimens, it was found that the attachment strength of the FRP system was governed by the concrete substrate, while for weathered specimens, the FRP system could detach by either a failure of the substrate, at the FRP/concrete interface, or FRP failure. It was found that a logarithmic curve best matches bond deterioration.

Author Keywords:

durability, fiber reinforced polymer (FRP), deterioration, reduction factor, bond strength

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Introduction

Over the past few decades, the use of fiber reinforced polymer (FRP) materials to strengthen highway bridges has gained in popularity. Reasonable cost, speed and ease of installation, and limited disruption of the use of the structure have contributed to the adoption of FRP systems over other strengthening options.

Among the various possibilities to strengthen concrete structures with FRP, the scope of this research concerns the strengthening of reinforced concrete structures using externally bonded carbon FRP (CFRP) sheets. Although externally-bonded FRP has been in use for several decades and a multitude of guidelines concerning this topic exist, it remains a relatively new material in civil engineering applications. As a result, limited data are available for the assessment of long-term bond durability between the FRP and concrete substrate, a critical parameter for the system to remain effective. Although the term 'durability' is widely used, its meaning and implications are often ambiguous, and the lack of information and uncertainty associated with the durability of FRP systems has been recognized as an impediment to wider adoption of FRP in civil infrastructure applications (Cromwell et al. 2011; ACI 2007). Durability has been defined broadly as the ability of the system to resist detrimental strength, stiffness, and other undesired performance changes caused by various mechanisms such as cracking, oxidation, chemical degradation, and delamination, for a specific period of time and under specific load and environmental conditions (Karbhari et al. 2003; Al-Tamimi et al. 2015).

In this study, a more narrow definition of durability is considered, where the degradation of bond strength between the concrete and FRP interface over time is of concern. The specific environment considered is exposure of a typical highway bridge element in the State of Michigan. This is a relatively harsh climate in the United States, due to the many yearly freeze-thaw cycles that civil infrastructure components experience. Subjected to this environmental exposure, the focus of this study is to determine a relationship describing the loss of bond strength between a typical highway bridge element and the FRP system as a function of time. For structural applications, the integrity of the bond between the structure and the external FRP strengthening system under adverse environmental conditions are issues of prime importance (Hollaway and Leeming 1999; Mikami et al. 2015). This study is concerned not only with the deterioration of the epoxy used to bond the FRP, but rather any mechanism that causes delamination of the system from the concrete, as in practice, any such failure will govern the strength of the system. Thus, failures may include that of the epoxy as well as that of the concrete substrate to which the FRP is bonded.

Numerous factors affect bond durability, including the initial materials and methods used for construction, the quality of workmanship, the loads imposed on the structure, the implementation of a maintenance program, as well as environmental exposure (Sen 2015).

Most FRP durability information has been gathered from laboratory simulations of harsh environments (Dutta and Hui 1996; Toutanji and Balaguru 1999; Karbhari et al. 2003). In these studies, it was found that freeze-thaw exposures can lead to significant material degradation through matrix cracking and fiber-matrix debonding as well as increased brittleness, resulting in a substantial change in the damage mechanisms commonly observed under ambient conditions (Dutta 1989, 1996; Haramis 2003; Karbhari 1994, 2000, 2003; Rivera and Karbhari 2002). More recently, Pan et al. (2018) examined the effect of environmental conditions on the bond behavior of CFRP applied to concrete and found that freeze-thaw cycles reduce fracture energy, interfacial stiffness, and ultimately bond stress. In addition, a combination of freeze-thaw cycling and relative humidity was found to contribute to a change in failure mode from concrete substrate failure to adhesive/concrete interfacial debonding. A similar result was found by Tuakta and Büyüköztürk (2011) who examined the effect of moisture cycling on the fracture toughness of a concrete/FRP bonded system. A detailed review of FRP bond durability research is given by Cabral-Fonseca et al. (2018) and Böer et al. (2013), who discuss the effects of environmental and other factors on bond performance. Although abundant laboratory studies are available, very few data exist concerning FRP durability in actual in-situ conditions. Results from one of the longest exposure periods considered is presented by Allen and Atadero (2012), who evaluated the performance of FRP bond strength on a concrete bridge in Colorado 8 years after installation. Their data indicated a significant reduction in mean bond strength, although some uncertainty existed with the as-installed material properties. Prior to their study, the authors reported that the longest durability data available considered no more than 3 years of exposure.

In design practice, the effects of environmental exposure are handled by applying specified environmental reduction factors on FRP material properties. In ACI 440.2R (2017), for example, the environmental reduction factor (C_E) is applied to reduce FRP strength and strain capacity, depending on the environment and fiber type. The origin of these reduction values, however, does not appear to be well-documented within the ACI 440.2R commentary. Moreover, such factors are intended for reduction of FRP material and resin strength rather than concrete-FRP bond strength, the concern of this study. Moreover, ACI allowed a lower reduction factor if the FRP system is located in an aggressive environment where prolonged exposure to high humidity, freezing-and-thawing cycles, salt water, or alkalinity is expected.

ACI does recommend that FRP systems are further investigated for the effects of environmental degradation, including freeze-thaw behavior. In contrast to ACI 440.2R, AASHTO guidelines (AASHTO FRP Guide 2013) do not explicitly specify environmental reduction factors.

However, to account for possible bond degradation, AASHTO provides an upper limit to the usable FRP-concrete interface shear transfer strength (τ_{int}). This limit is based on the work of Naaman and Lopez (1999) and represents a lower bound of the experimental data found from the bond strength of FRP-strengthened concrete specimens after subjected to a series of accelerated freeze-thaw cycles. Using tests similar to those conducted by Naaman and Lopez (1999) and others, degradation rates can be fundamentally calculated from the change in strength or stiffness as a function of time. However, as these laboratory tests use accelerating mechanisms to artificially increase the rate of degradation beyond which would be expected in the natural environment, the expected in-situ deterioration is unknown.

With this background, the objectives of this study are to determine the bond strength of a typical FRP system after relatively long-term (15 year) exposure to Michigan weather and to estimate the rate of degradation as a function of time.

Field Specimens

Although actual service life may vary significantly, the assumed design life of a highway bridge designed according to the AASHTO LRFD Bridge Design Specifications is 75 years (AASHTO 2017). Here it should be noted that other sources consider different lengths of service life specifically for FRP strengthening systems; for example, the British Design Manual for Roads and Bridges (Volume 1, Part 16 (2002) and Part 18 (2008)), considers this to be 30 years, while the UK FRP structural strengthening guideline, TR-55 (2013), considers at least a 40-year service life to be appropriate. Although the collection of actual weathering data over 40 - 75 years would be ideal, such information for modern, externally-bonded FRP systems does not exist. Moreover, conducting such a test program may not be particularly useful, as at its conclusion, the technologies tested may be obsolete. Therefore, expected long-term effects of deterioration are generally extrapolated from tests conducted over much shorter periods of time.

Although deterioration information is typically gathered from short term accelerated laboratory testing, in this study, data from a relatively long test program which exposed specimens to actual in-situ weathering up to approximately 15.5 years were obtained. These data are from two FRP-wrapped test columns constructed by the Michigan Department of Transportation (MDOT) in July, 1999 and tested in May, 2015. These free-standing columns were placed near the piers of an existing bridge located south-east of Lansing, Michigan, a region which experiences an annual average of approximately 84 freeze-thaw cycles (MDOT 2014). The columns are adjacent to a secondary road of moderate traffic volume (posted speed limit of 55 MPH (90 KPH) with three lanes of traffic in each direction), in partial shade conditions (Figure 1). The columns were cast from a standard MDOT concrete mix resulting in a compressive strength of approximately 38 MPa (5500 psi) at the time of testing. The columns were wrapped with CFRP using a hand-applied, wet lay-up system and painted in accordance to the manufacturer's directions (Harichandran and Baiyasi 2000; MBT 1998). The average ambient temperature in Lansing, MI in the month of construction of the columns was approximately 21˚ F. As specified by the manufacturer, the CFRP sheets have a nominal ultimate tensile strength of 3792 MPa (550 ksi,) rupture strain of 1.67%, and thickness of 0.165 mm (0.0065 in).

Bond Strength Testing

Prior to testing, it was found that the column faces had different degrees of observable deterioration. In particular, corrosion stains from the internal steel reinforcement and other discoloration was visible only on Faces 1 and 2 of the columns (see Figure 2). This is not unexpected, as these faces have the highest level of exposure to adverse environmental conditions.

In particular, as shown in Figure 2, these sides face the approaching vehicles from the roadway, where traffic may splash rainwater, and in the winter months, deicing contaminants, primarily on these column faces. Due to this observed level of increased deterioration, these three column faces (Face 1 of Column 2 and Face 2 of both columns) were taken as the critical locations for further consideration.

Bond strength was measured with a pull-off adhesion test conducted with a portable automatic adhesion tester (DeFelsko 2016), in accordance with ASTM D4541-09 (ASTM 2009). In this test, the end surface of a 20 mm (0.79 in.) diameter cylindrical metal test dolly and the FRP test specimen are cleaned, then the dolly is bonded to the FRP surface with epoxy. After the epoxy cures, a drill press equipped with a 23 mm (0.91 in.) diamond-tipped core bit is used to cut the FRP around the edge of the dolly, to prevent the bond of the surrounding fibers from influencing test results. As detailed in ASTM D7234 (ASTM 2012), the FRP must be completely cut through, slightly scoring the surface of the concrete. However, it was found that great care must be taken to avoid over-cutting, as deep scoring may cause premature failure of the substrate, leading to unreliable results. As suggested by Mikami et. al. 2015, scoring was limited to a depth no more than 1 mm (0.04 in.). The hydraulic test machine then pulls up upon the dolly until the dolly separates from the concrete specimen, and the required separation force is recorded (note a similar, but alternative standard for pull-off testing, ASTM D7522, is also available).

On the test columns shown in Figures 1 and 2, 8 dollies were installed on each of the three tested faces. During testing, it was found that Face 1 of Column 2 had a substantially lower bond strength than the remaining column faces. This is not surprising, as it is the most exposed face, as shown in Figures 1 and 2. Therefore, in addition to presenting results for all tests combined, the data were also separated into two groups for further consideration: Group 1, which consists of Face

1 of Column 2 only (highest deterioration), and Group 2, which is composed all three faces considered; Face 1 of Column 1 and Face 2 of both columns (lower deterioration).

Several failure modes were observed. These include failure in the concrete substrate, where a thin layer of concrete separates from the specimen and remains attached to the FRP; failure at the adhesive interface, where the concrete and FRP cleanly separate; and combined concrete/adhesive failures, where failure occurs in the substrate as well as at the concrete/FRP interface (Figure 3). In general, failure modes were approximately equally split between substrate and combined substrate/FRP interface failures. Specifically, for Group 2, 50% of the results were substrate failures, 8% were concrete/FRP failures, and 42% were FRP failures. For Group 1, 57% of failures were substrate failures, 14% were concrete/FRP failures and 29% were FRP failures.

Results for the columns after 15.5 years (186 months) of exposure are given in the last two rows of Table 1, where the mean and coefficient of variation (COV; standard deviation divided by mean value) of bond strength are provided.

Estimation of Initial Strength

It is of substantial interest to know not only deteriorated strength, but original strength as well, such that a rate of deterioration can be determined. As bond tests were not conducted by the DOT at the time of FRP application, prior non-deteriorated data do not exist. However, the expected as-built (i.e. non-deteriorated) pull-off strength can be determined by testing a set of re-created specimens formed using a similar mix design, FRP system, and application technique as used for the weathered columns. Such specimens can provide a reasonable approximation of unweathered system strength.

These test specimens consisted of small concrete beams with dimensions of 406 x 51 x 104 mm (16 x 2.0 x 4.1 in.), which were cast in March, 2013 using an MDOT-certified ready mix design representative of that of the field columns. Test specimens were wet-cured for 28 days under an average temperature of 22 °C (72 °F). Average 28-day compressive strength of the test specimens was found to be 39.5 MPa (5700 psi) from 3 cylinder tests, while average compressive strength of the field columns was approximately 38 MPa (5500 psi). Comparing values of $\sqrt{f'_c}$, more relevant for substrate tensile strength (ACI 318 2014), results in similar values of 6.28 MPa and 6.16 MPa for the test specimens and field columns, respectively. The test specimens were thus taken as a good representation of the original column mix design.

One month after the specimens were cast, a nominally similar MBrace FRP system that was recently obtained from the original manufacturer was applied on the broad (104 x 406 mm (4.1 x 16 in.)) face of the beam specimens at a room temperature of 23˚ C, as shown in Figure 4, in accordance with MDOT surface preparation and FRP application practice, which follows the FRP manufacturer's instructions. One week after FRP application (where the specimens remained under a constant temperature of approximately 23˚ C), the specimens were tested for bond strength in the same manner as the field columns. Mean bond strength is shown in Table 1 as the zero-time result. This value is substantially higher than the bond strength found in the weathered field columns at 186 months. Note that for the test specimens, bond failure in every case was found to be a concrete substrate failure, indicating that the unweathered FRP bond strength is greater than the substrate strength. It should be emphasized that, although effort was made to replicate the existing columns and FRP system with laboratory specimens as closely as possible, the actual materials, construction methods, and initial bond strength of the columns cannot be known with certainty, and thus the initial strength provided by the recreated test specimens is an estimation only.

To better understand how this strength deteriorated over time, additional test specimens were prepared to simulate in-situ weathered results at times prior to 186 months of exposure. These additional specimens were left outdoors under exposure conditions similar to Face 1 of Column 2, and tested at 9, 14, and 28 months of exposure. Note that months 9 and 14 were used as "spot checks", where few sample tests were conducted; the longer-term 28 month results were deemed more important and thus most specimens were tested here. As shown in Table 1, mean bond strength drops steadily from 6.27 MPa (910 psi) (time = 0; unweathered) to 4.24 MPa (615 psi) for Group 2 and to 3.41 MPa (495 psi) for Group 1 (at 186 months of weathering), representing a loss in strength of about 33% for Group 2 and 42% for Group 1. Also note that COV is inconsistent as well, ranging from 0.09 to 0.40 across the different weathering times considered, with no clear pattern from 0 to 28 months of weathering. However, it is clear that the test results at 186 months have the highest COV, nearly double that of any earlier times considered. A significant contributor to this increased variation at 186 months is the occurrence of different failure modes for these tests, as noted above.

Characterizing Bond Loss as a Function of Time

In the section above, bond strength is determined at several discrete points in time. However, it may be worthwhile to develop a relationship approximating bond strength reduction at any point in time. Various models have been proposed to predict deterioration rates of composites. One of the earliest was that by (Phani and Bose 1987), which concerned the degradation of flexural strength of composite laminates. The degradation mechanism for this model is assumed to be debonding at the fiber/matrix interface, and is given as: $\sigma(t) = (\sigma_0 - \sigma_\infty)\, exp\left(-\frac{t}{\tau}\right) + \sigma_\infty$, where σ_0 and σ_∞ are the composite strengths at time 0 and ∞, respectively, and τ is a characteristic time parameter dependent on temperature, which is determined from: $\frac{1}{\tau} =$

$\frac{1}{\tau_0} exp\,(\frac{-E_d}{RT})$. Here, E_d is the activation energy, *R* the universal gas constant, *T* the temperature of the exposure environment (Kelvin), and τ_0 is a constant. Later, Katz and Berman (2000) studied the degradation effect of high temperature on the bond between FRP bars and concrete. It was found that the effect of temperature on the average bond strength could be described by: $y = a\,tanh[-b(x - k_1 c)] + d$, where *a, b, c, d* and k_1 are coefficients related to the bar properties, *y* represents the bond strength normalized to room temperature, and *x* represents the temperature. Although not specifically focused on bond, at about the same time, Bank et al. (2003) developed a model to describe the residual strength of FRP composites over time. The model is given as: *Y = a log(t) +b* where *Y* is the percent of property retention, *t* is the exposure time, and *a* and *b* are regression constants. This expression is perhaps the most widely used degradation model for FRP bars (Davalos et. al. 2012). More recently, Davalos et. al. (2012) suggested that the percentage of tensile capacity retention of FRP bars over time can be determined from: $Y = 100(1 - jt^{\alpha+1})^2$, where α is a material constant and *j* is a factor accounting for temperature, solution concentration, and other experimental conditions.

Given the multiple deterioration models that exist, in this research, a regression analysis was conducted on the deterioration data to determine a best-fit deterioration curve. Various alternatives were considered including the forms proposed above, including linear, logarithmic, inverse, quadratic, cubic, power, compound, logistic, growth, and exponential functions. Of these, it is found that a logarithmic curve best fit the degradation of bond strength over time. When selecting the best fit curve, particular attention was given to matching long-term deterioration (at 186 months), rather than short-term (up to 28 months) changes, the latter of which are of less concern for long-term structural performance. The results of all pull-off tests as a function of weathering time, as well as the best-fit logarithmic curve, are plotted in Figure 5 (note time zero is taken as t = 1 month to allow a logarithmic fit to the data, as *log(0)* cannot be evaluated). In the figure, curves are presented separately for Groups 1 and 2, as defined earlier. Note that a distinction between Group 1 and Group 2 data only appears at the t = 186 month results, which are associated with the test columns, whereas the shorter term results (0-28 months) are the same for both groups. In the upper right corner of Figure 5, the curve prediction is extended to 900 months (75 years) for illustration. Note that beyond 186 months, this graph represents a possible outcome based on extrapolation from the logarithmic curve fit.

For Group 1, the best-fit regression curve predicting bond strength over time is given as:

$$b = -80 ln(t) + 921 \qquad \text{(eq. 1, psi)}$$

$$b = -0.55 ln(t) + 6.35 \qquad \text{(eq. 1, MPa)}$$

whereas for Group 2, the curve is:

$$b = -56 ln(t) + 911 \qquad \text{(eq. 2, psi)}$$

$$b = -0.40 ln(t) + 6.28 \qquad \text{(eq. 2, MPa)}$$

where b is bond strength (MPa/psi) and t time in months. For wider applicability, normalizing these curves such that they provide a unitless reduction factor (r) as a function of time rather than direct bond strength (and t=1 provides a reduction factor of 1.0 to represent the initial strength), results in:

$$r = -0.084 ln(t) + 1.0 \qquad \text{(Group 1)} \qquad \text{(eq. 3)}$$

$$r = -0.066 ln(t) + 1.0 \qquad \text{(Group 2)} \qquad \text{(eq. 4)}$$

Using these curves, the resulting reduction factors are given in Table 2. The reduction factor is defined here as the ratio of strength at a given time to the original strength. Predicted reduction factors at 50 years were 0.46 and 0.58, and at 75 years, were 0.43 and 0.55, for Groups 1 and 2, respectively.

Existing design guides provide environmental reduction factors to account for environmental degradation of FRP material strength. Although not specifically meant for FRP-concrete bond, these factors practically result in a reduction of system design strength regardless of failure mode. As such, it may be worthwhile to examine how these existing factors compare to the reduction in strength found in this study. ACI 440.R2 (ACI 2017) as well as CNR (CNR-DT 200 2013) suggest an environmental reduction factor of 0.85 for CFRP in an aggressive exposure environment. Other design guides, such as TR55 (2013) and ISIS (2008), recognize that different variabilities may be associated with different application methods. For example, TR55 (2013) presents a reduction factor of 0.83 for wet lay-up applications and 0.95 for machine-controlled applications. Similarly, ISIS (2008) applies a total reduction factor of 0.75 for pultruded CFRP and 0.5625 for hand applied, wet lay-up CFRP (including both material strength uncertainties as well as consideration of environmental degradation). As shown, the values presented in Table 2 are substantially more aggressive than the reduction factors of ACI, CNR, and TR55 when moderate lengths of time are considered (i.e. 10 years or more). It should be noted that the factors given in Table 2 account for failures beyond FRP deterioration. Rather, as discussed above, these factors also account for substrate failure, which frequently controlled the bond strength of the system. It should also be emphasized that these reduction factors correspond to the environment in which the structure was exposed; less or more severe reductions may of course result for other environmental conditions.

Conclusion

In this study, the bond strength of a typical FRP system exposed to approximately 15.5 years of in-situ weathering were analyzed, and expressions to predict bond deterioration as a function of time were developed. Here bond failure is considered broadly to include any type of separation between the FRP system and the structure, and includes FRP/concrete interface failures as well as failure of the concrete substrate. It was found that the resulting reduction in strength is best described logarithmically, with 15.5 year strength reduction factors from 0.56-0.65, assuming that initial specimen strength is accurately modeled.

Due to the general lack of long-term FRP deterioration data, a significant amount of additional work is recommended to better characterize bond deterioration, including consideration of other climate and chemical exposure conditions, FRP system construction, and types of substrate material.

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Table 1. Bond Strength Test Results.

Time (months)	Mean bond strength, MPa (psi)	Sample size	COV
0	6.28 (910)	37	0.23
9	5.98 (867)	3	0.14
14	5.89 (854)	4	0.21
28	4.49 (651)	13	0.09
186 (Group 1)	3.41 (495)	7	0.40
186 (Group 2)	4.24 (615)	24	0.36

Table 2. Bond Strength Reduction Factors.

Time		Reduction Factor	
Years	Months	Group 1	Group 2
0	0	1.00	1.00
0.75	9	0.82	0.85
1.17	14	0.78	0.83
2.33	28	0.72	0.78
10	120	0.60	0.68
15.5	186	0.56	0.65
Extrapolated:			
30	360	0.51	0.61
40	480	0.48	0.59
50	600	0.46	0.58
75	900	0.43	0.55

Fig. 1. Test Columns Under Westbound Interstate 96 Over Lansing Road.

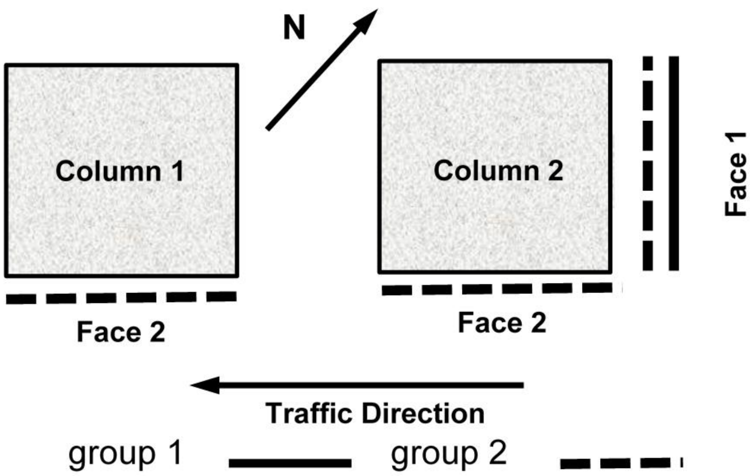

Fig. 2. Column Orientation.

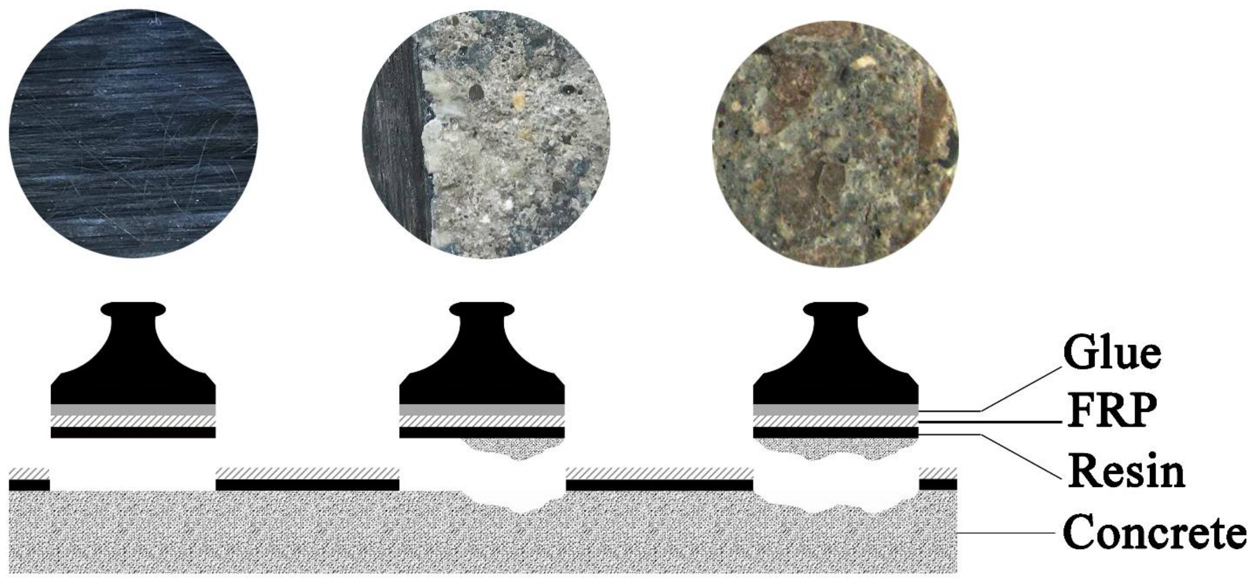

Fig. 3. Pull-off Test Failure Modes: (a) FRP adhesive failure; (b) Mixed concrete/FRP failure; (c) Concrete substrate failure

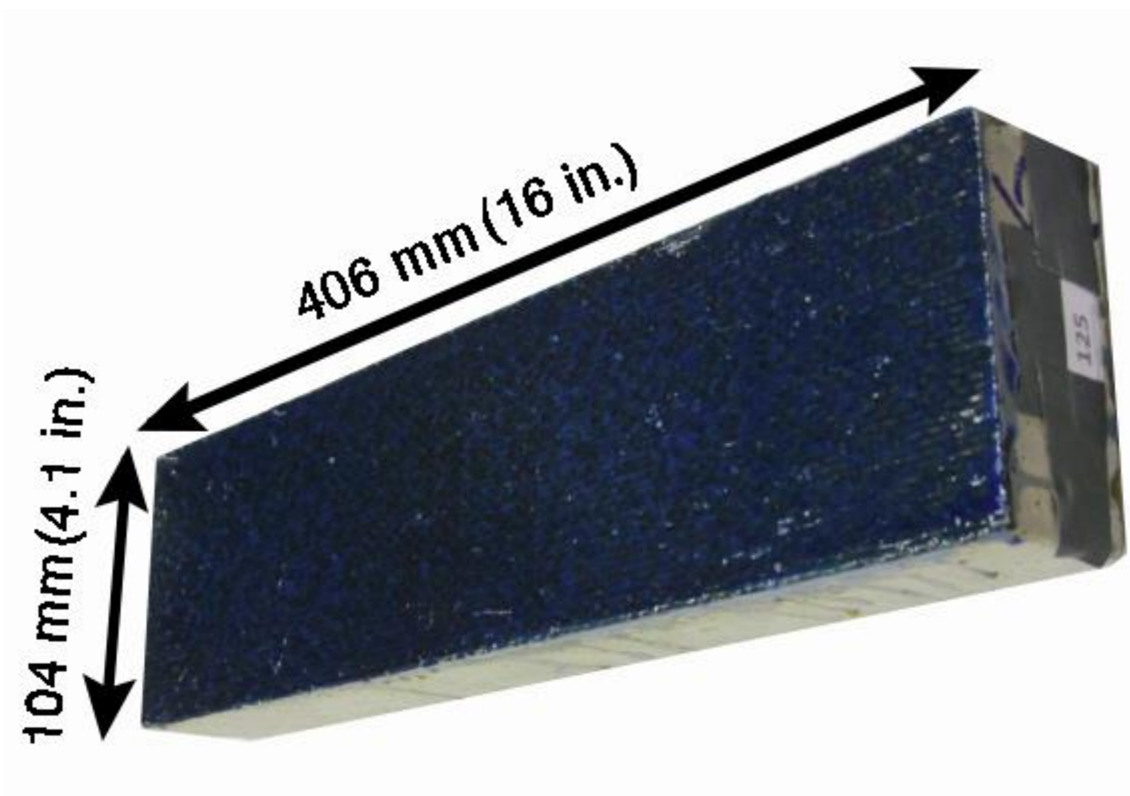

Fig. 4. Pull-off Test Specimen.

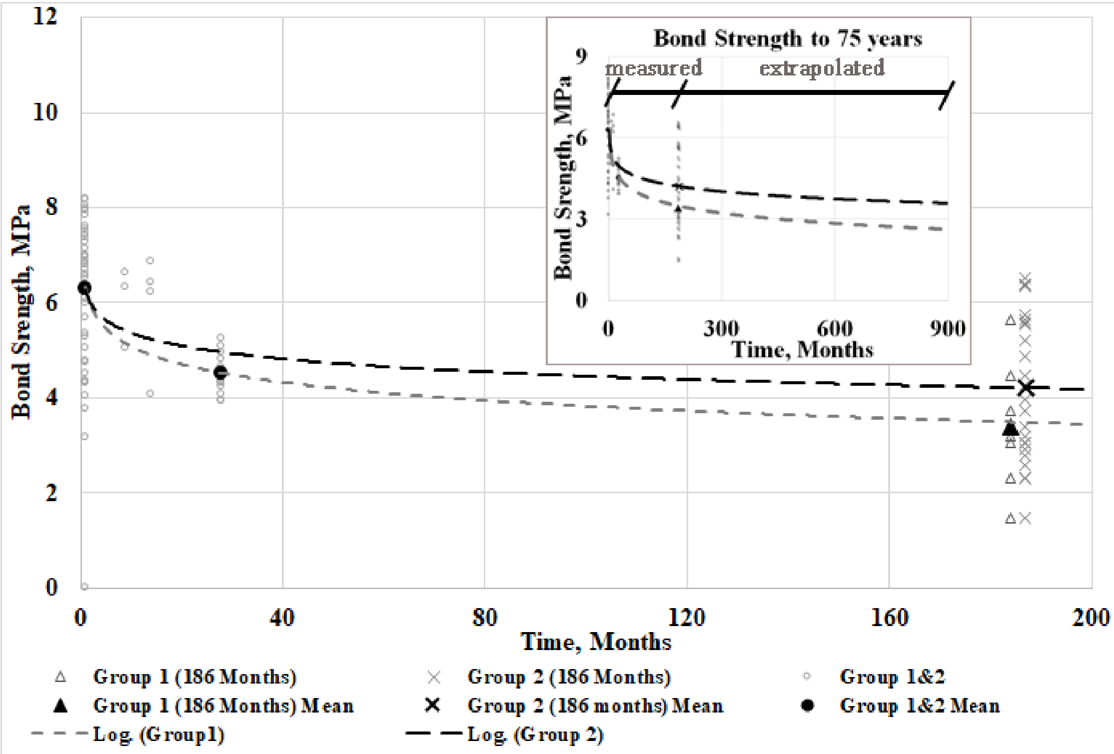

Fig. 5. Bond Strength as a Function of Weathering Time.