

Assessment of GFRP Properties: A Literature Review

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Original Submittal: October 19, 2018
Revised Submittal 1: January 21, 2019
Revised Submittal 2: June 19, 2019

Executive Summary

There has been significant development in the design and use of GFRP reinforcing bars. This report provides an overview of the literature on the properties, characteristics, and performance of GFRP bars. This literature review indicates that when compared with steel reinforcement, GFRP reinforcing bars exhibit lower modulus of elasticity values, lower ductility, and lower bar-concrete bond. The literature also indicates that structures reinforced with GFRP can exhibit larger deflections and larger crack widths. GFRP bars are also lighter than steel bars and are non-conductive and non-magnetic, which provide some potential benefits for specific situations. However, one characteristic that has not achieved consensus in the engineering community is the durability of GFRP when embedded in concrete. In the large majority of cases concrete has a high relative humidity within its pore system and this moisture consists of a high pH solution. When GFRP reinforcing bars are embedded in concrete, the composite surrounding the glass fibers is supposed to protect the glass fibers from potential deterioration. However, the high pH pore solution can penetrate this composite material. As the high pH pore solution penetrates the composite it eventually reaches the glass fiber and these fibers are susceptible to etching and leaching. This etching and leaching of the glass fibers in the GFRP can result in loss of bond between the glass fibers and composite material or can result in weakening of the glass fibers. Both debonding and loss of glass fiber strength result in loss of strength in GFRP reinforcing bars. Loss of strength in GFRP reinforcing bars has been reported throughout the literature. Unlike steel reinforcement, which when corroded exhibits signs of degradation (e.g., rust stains or concrete delamination), when GFRP degrades there are no visual signs of this degradation.

Some recent research indicates that GFRP reinforcing bars embedded in field structures do not exhibit degradation or loss of strength. However, these research studies contained no direct measurements of the residual tensile strength of GFRP reinforcing bars. Although indirect measures of GFRP degradation are improving, direct measurements of GFRP reinforcement degradation provide a clear and unambiguous measure of performance. Because the literature indicates that GFRP reinforcing bars do lose strength with time and because degrading GFRP bars provide no visible warning of this degradation, the engineering community must move forward in using this reinforcement with caution.

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1. Introduction and Objectives

Significant efforts have been and are currently underway to replace conventional construction materials (e.g., steel and concrete) with composite materials. Although these composite products do have several positive attributes, there is considerable concern regarding the long-term performance of these materials. Long-term performance is a legitimate concern as infrastructure systems are generally designed and constructed to serve the public for 75 to 125 years, depending on the type of infrastructure system. Trejo and Reinschmidt (2007) proposed an economic analysis method to assess the value of using alternative materials and concluded that some materials can provide economic benefits if these materials can provide long-term performance. Alternatively, the authors reported that some materials do not provide value when they are not durable and do not provide long-term durability. Understanding the durability and long-term performance characteristics of a material, especially a newer material being introduced for infrastructure systems, is essential as the cost of designing and constructing these infrastructure systems is significant. This paper will provide an overview of the literature and challenges associated with the implementation of composites, specifically glass fiber reinforced polymer (GFRP) reinforcing bars for concrete reinforcement, into the construction industry.

2. Literature Review

The use of composites in the construction industry has been relatively limited. However, in the 1990s significant research was initiated to assess if GFRP reinforcing bars could be used as an alternate material for steel reinforcement in concrete. Because of the low modulus and low ductility of GFRP, significant efforts were expended in developing new design methodologies for these materials and design methodologies are now available (ACI 440.1R). One major claim of producers and some researchers is that composites do not corrode and therefore, reinforced concrete structures made with these materials would have longer service life than a structure made with conventional steel reinforcement. This literature review will clearly show that GFRP bars do indeed degrade, resulting in a reduction in tensile capacity. This degradation of the GFRP is reportedly dependent on the exposure conditions of the concrete. This section will provide a review of literature, providing a brief history of FRP, a brief overview of the fabrication process for GFRP,

and will provide an overview of the properties, with emphasis on the durability characteristics of GFRP reinforcing bars.

2.1. History

One relatively new product introduced to the engineering and construction market is fiber reinforced polymers (FRP) and specifically GFRP for concrete reinforcement. Although not new, the introduction of glass fibers and composites to the construction industry has been relatively recent. The patent for “glass wool” was granted in 1933 and fiberglass (this was the original spelling in the patent) was patented in 1936. Significant efforts were expended in developing prototype automobiles and aircraft components soon after the patent was assigned and the use of composites in these industries has been significant. The first introduction of FRP as a construction material for concrete applications, as published in the American Concrete Institute’s (ACI) journal, was in 1981 (Fardis and Khalili 1981). The authors proposed using FRP for stay-in-place concrete forms. No other publications on FRP were published in the ACI journals in the 1980s. However, in 1991, Bunea proposed using GFRP as a replacement for steel reinforcement but focused on using the material for lunar settlements or habitats. The number of published papers on FRP increased significantly in the 1990’s and over 200 manuscripts were published in the ACI journals. Because of GFRP’s low modulus and low ductility many of these publications focused on developing methodologies for the design of GFRP-reinforced concrete members (Brown and Bartholomew 1993, Rahman et al. 1993, Eshani et al. 1993, Tottori and Wakui 1993). Many of the publications claimed that GFRP was more durable and free from deterioration yet very little research had been performed on assessing the longer-term performance and potential mechanisms of deterioration of GFRP reinforcement in concrete systems. Although research has been performed since, more research is needed to assess the long-term characteristics and performance of GFRP reinforcing bars.

2.2. Fabrication of GFRP Reinforcement and Potential Challenges

GFRP reinforcement consists of continuous glass fiber filaments embedded in a composite matrix, typically polyester or vinylester. A schematic of a typical cross sectional view of a bar is shown in Figure 1. The glass filaments, or roving, provides the strength while the polyester or vinylester composite binds these fibers together to provide composite action within the bar. The vinylester

or polyester composite material is also supposed to protect the glass fibers from deteriorating by removing and protecting these fibers from solutions that may be aggressive or corrosion to these fibers. The composite action, i.e., the bond between the polyester or vinylester and glass fibers, is critical to the long-term performance of the FRP system.

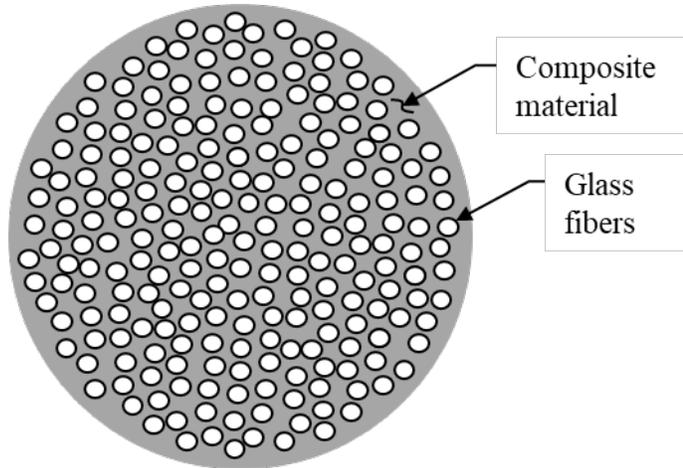


Figure 1 Typical cross-section of GFRP reinforcing bar (not to scale).

The general process of producing GFRP reinforcing bars is to pull the filaments

through a resin bath, preform the bar, then pass the product into a heated die where the resin polymerizes to form the final product. Busel (2012) reported that most FRP products are manufactured with the process shown in Figure 2. Because the glass filaments are the load-bearing components and these glass filaments can be susceptible to degradation, it is critical that these filaments or fibers are embedded within the composite matrix. The composite matrix can slow the ingress of water or aggressive ions that can degrade the fibers. However, even if the fibers are embedded in the composite matrix, moisture or other aggressive ions can migrate into the composite matrix, reducing the bond between the glass fiber and composite matrix, and/or reducing the load carrying capacity of the fibers and eventually the FRP bar.

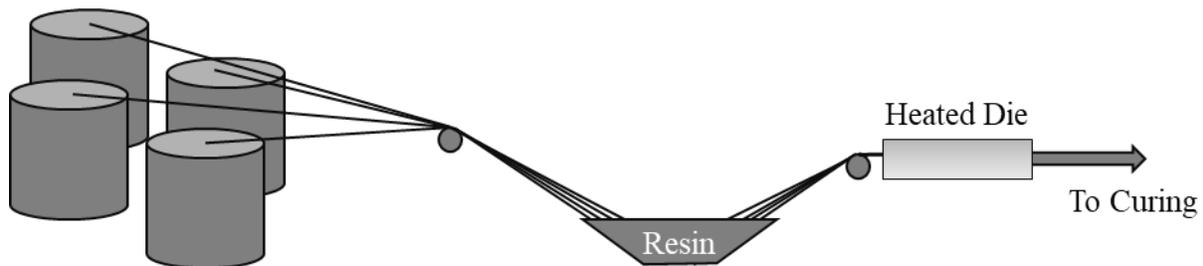


Figure 2 General manufacturing process of FRP reinforcing bars (after Busel 2012).

2.3. GFRP Manufacturers

Several manufacturers produce GFRP in North America. Table 1 provides a summary of manufacturers that have been identified. Contact information for each producer is also provided.

Table 1 List of Manufacturers of GFRP Reinforcement in North America

1.	Marshall Composite Technologies, LLC 2873 22nd Street SE Salem, Oregon 97302
2.	TUF-BAR Inc. #900 111 2nd Avenue NE St Petersburg, FL 33701
3.	TUF-BAR Inc. 5522 36th Street NW Edmonton, Alberta Canada, T6B 3P3
4.	TUF-BAR Canada Inc. 7 Erin Park Drive Erin, Ontario Canada N0B 1T0
5.	Hughes Brothers, Inc. 210 N. 13th Street Seward NE 68434
6.	Pultrall 700 9th Street North Thetford Mines (Quebec) Canada G6G 6Z5
7.	VROD Canada 53 Woodstream Blvd. Unit 7A Woodbridge, ON L4L 7Y8
8.	Kodiak Fiberglass Rebar Katy, Texas 77450
9.	American Fiberglass Rebar 1191 Center Point Drive Henderson, NV 89074
10.	B&B FRP Manufacturing 40 Millwick Drive, Unit 9 Toronto, Ontario Canada M9L 1Y3
11.	Nycon Headquarters 300 Ben Fairless Drive Fairless Hills, PA 19030 USA

2.4. GFRP Characteristics: Manufacturer Reported Characteristics

Some manufacturers of GFRP reinforcement report that GFRP reinforcing bars are impervious to chloride ions and low pH chemical attack, are not susceptible to corrosion, have tensile strengths greater than steel, have modulus of elasticity values of 5800 and 8700 ksi, are one-quarter the

weight of steel reinforcing bars, are transparent to magnetic fields and radio waves, are electrically non-conductive, and are thermally non-conductive. The magnetic transparency and low conductivity GFRP bar characteristics are advantageous in pavement applications where conductive steel reinforcement can alter magnetic signals embedded in the pavement. The low weight has been reported to be beneficial during construction. Design methodologies addressing the higher tensile strengths and lower modulus characteristics have been implemented and with the exception of later-age tensile strengths, are relatively accepted. The claims that the GFRP bars are impervious to chloride ions and have no susceptibility to corrosion are somewhat controversial and significant research has been performed in these areas. Although GFRP does not undergo classical corrosion, the literature contains many examples where GFRP bars exhibited deterioration and loss of tensile strength. This literature will be reviewed and presented later.

2.5. Properties of GFRP Reinforcement

GFRP reinforcement exhibits different mechanical properties than steel reinforcement. Figure 3 shows a typical stress-strain plot of Grade 60 and Grade 80 steel reinforcing bars (meeting ASTM A706 specifications) and a typical stress-strain plot for a new GFRP reinforcement. The GFRP stress and strain data are reported values from a GFRP manufacturer. As can be seen, the modulus of elasticity of the GFRP is significantly lower than that of the modulus of elasticity of the steel reinforcement. Aguiniga (2003) reported that the modulus of GFRP is approximately 1/5 that of steel. Note also from the figures that the ductility of the GFRP is significantly less than the ductility of the steel reinforcement. The manufacturer reports that the guaranteed ultimate tensile strength (GUTS) of the GFRP decreases with increasing diameter, ranging from 130 ksi to 60 ksi. As a result of the difference in properties of GFRP reinforcing bars, modifications to the design of GFRP-reinforced concrete had to be developed. The American Concrete Institute's Committee 440 has taken the lead on developing these design methods. The general methodology of the design process will be discussed later.

Aguiniga (2003) reported that GFRP reinforcing bars exhibit high transverse coefficient of thermal expansion values. However, Schaefer (2002) conducted thermal expansion tests and concluded that a concrete cover to bar diameter ratio of as low as 1.33 would not cause a typical concrete bridge deck with 28-day compressive strength of approximately 5880 psi to crack due to

thermal expansion. Aiello (1999) also reported that thermal expansion of bars would not lead to concrete cracking for concrete cover to bar diameters of 2 or more.

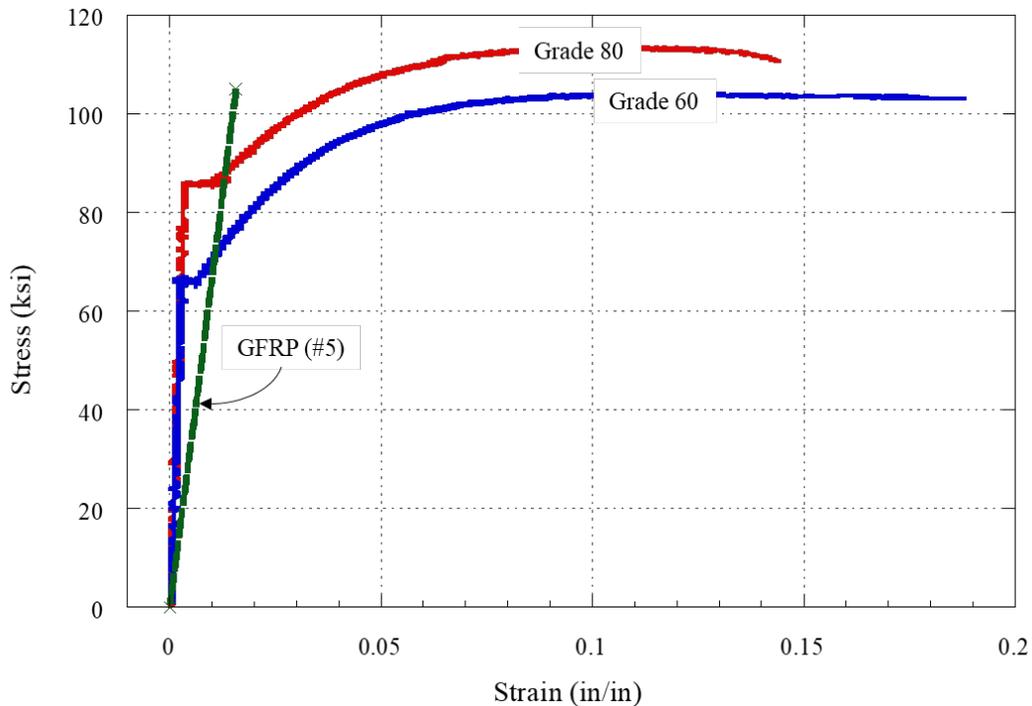


Figure 3 *Stress strain relationship for different reinforcement types.*

Aguiniga (2003) and later Al-Salloum and Almusallam (2007) reported that GFRP exhibits significant creep. Youssef and Benmokrane (2011) reported that creep of GFRP bars was dependent on fiber content and bar diameter and noted that GFRP bars that did exhibit creep experience minimal loss in tensile strength. Aguiniga (2003) proposed a method for evaluating the strains and curvatures of FRP reinforced concrete elements, accounting for creep of the GFRP bars.

2.6. Longer-term GFRP Performance

Figure 3 showed a stress-strain plot for a new GFRP reinforcing bar. Because both composite and glass materials have been reported to degrade when exposed to some environments and because composites do absorb moisture, significant research has been performed to assess the time-variant properties, e.g., the residual tensile strength of GFRP bars. Many researchers have reported significant changes to the properties of GFRP reinforcing bars, mainly tensile strength, after

exposure to various solutions. Early research on assessing the residual tensile strength focused on subjecting the GFRP reinforcing bars to aggressive solutions. In 1994, Sen and Shahawy reported on the durability characteristics of FRP bars and reported that if moisture absorption exceeded 1% the bars exhibited a 20% reduction in strength. The authors also reported that when the relative humidity was greater than 70%, the amount of absorption increased, and this resulted in the “most notable degradation in the matrix.” Pyc (1998) reported that the pore humidity of concrete seldom drops below 72%. Therefore concrete is likely an aggressive environment for GFRP reinforcing bars.

Significant reductions in tensile capacity of GFRP reinforcing bars have been reported throughout the literature (Tannous and Saadatmanesh 1998 and 1999, Sen et al. 2002, Chu and Kharbari 2005, Mukherjee and Arwika 2005, Nkurunziza et al. 2005, Trejo et al. 2005, Debaiky et al. 2006, Chen et al. 2006, and Kim et al. 2012). Tables A1.1 to Table A1.3 in the Appendix list a summary of a comprehensive review of the literature on the time-variant properties of residual tensile properties of GFRP reinforcement. The references only include papers where the tensile capacities of GFRP bars were tested and evaluated or reported. Figure 4 shows data from testing where GFRP bars were immersed in solution and evaluated for residual tensile capacity after exposure. The figure clearly shows that GFRP bars can experience significant reductions in tensile capacity when exposed to water and high pH solutions. It should be noted that these samples were subjected to different exposure temperatures and as a result, the rate of loss of tensile strength and ultimate loss varies. One argument against testing GFRP bars in solution is that this exposure condition, especially at high temperatures and in high pH solutions, is too severe and is not representative of actual capacity loss when GFRP bars are embedded in concrete. Others believe that this could be representative of later-age performance and capacity.

Figure 5 also shows data from the literature on loss of tensile strength of GFRP bars but for GFRP bars embedded in concrete or mortar and subjected to different environments (e.g., moisture, temperature, stress). This figure clearly shows that GFRP bars embedded in concrete or mortar can exhibit considerable loss in tensile capacity. Tables A1.1 through A1.3 show the general exposure conditions reported for each of these conditions. This indicates that the concrete or mortar pore solution can penetrate the composite matrix and degrade the glass fibers or glass-fiber interface, resulting in reduced tensile strengths with increasing exposure times.

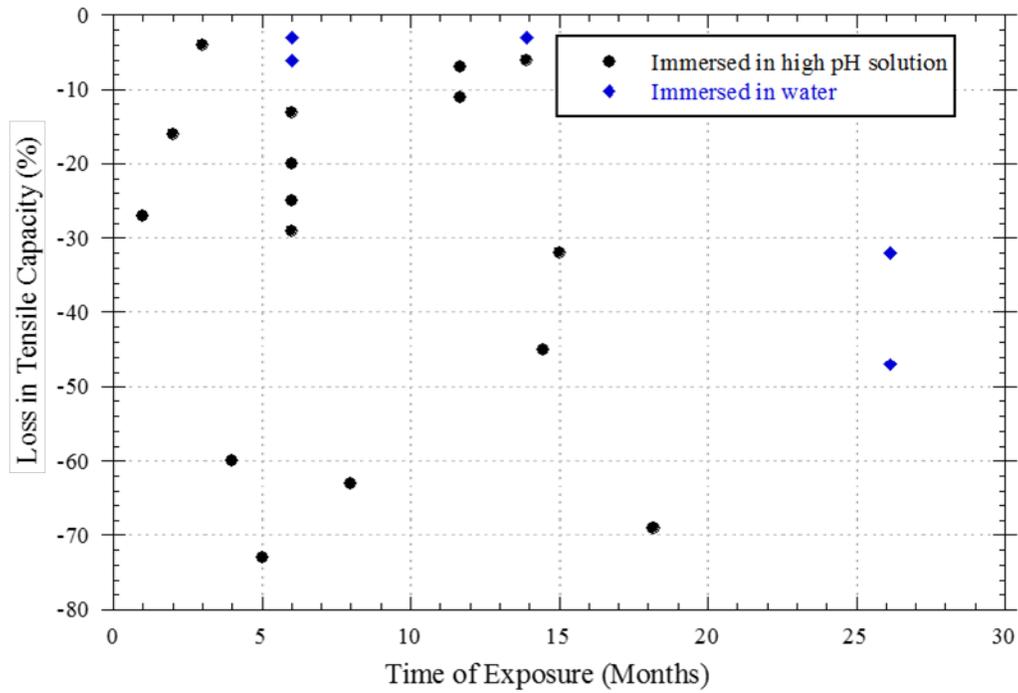


Figure 4 Loss of tensile strength as reported in the literature of GFRP bars immersed in solution.

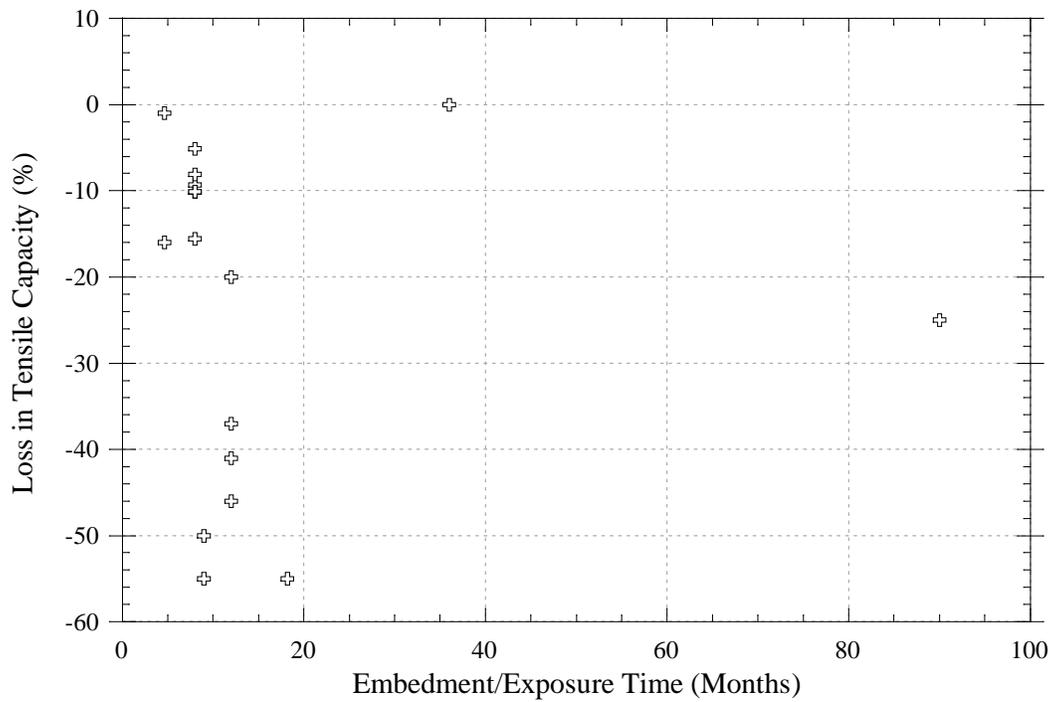


Figure 5 Loss of tensile strength capacity as reported in the literature for GFRP bars embedded in concrete or mortar.

Figure 6 shows a summary of all the data from Table A1.1 through A1.3. The figure shows reported reductions in tensile capacities for GFRP bars immersed in water, immersed in high pH solution, and embedded in concrete. Note that the data shown in Tables A1.1 through A1.3 includes data from different exposure conditions, e.g., exposure temperatures and stresses, and this does influence the rate of deterioration. The influence of temperature is not shown in Figures 4 through 6 and some of these variables have been reported to significantly influence the residual tensile capacity of GFRP bars. Even so, the figure clearly shows that GFRP bars exhibit significant losses in tensile capacity when exposed to water, high pH solutions, and when embedded in concrete. The figure indicates that high pH solution exposure conditions are likely more aggressive than water (neutral pH) exposure conditions. The figure also shows that although high pH solutions are likely more aggressive than direct embedment in concrete (or mortar), there are still significant reductions in tensile capacity when GFRP is embedded in concrete and subjected to different exposure conditions. The data shown in Figure 6 also indicates that direct exposure to high pH solutions can accelerate the rate at which GFRP bars lose capacity and that direct exposure to water can be similar to the loss in capacity when embedded in concrete or mortar. It should be noted that the mechanisms of deterioration could change, but even so, general deterioration rates can be similar. When ranges of capacity losses were reported in the literature, the mean value is shown in the figures.

As new products are introduced to market, many times these products are improved with time. Gremel et al. (2005) reported that even though “short-term material properties” of two different GFRP bars could cause “one to believe they are similar in their constituent make up and suitability for a given use,” there can be a “very wide range in the 'durability performance' of the two bars when subjected to accelerated aging tests.” This indicates that GFRP bars produced at about the same time could exhibit different durability performance but also could indicate that bars produced at different times could also exhibit different durability performance. In fact, if improvements in processing or materials or other factors improve, these changes may improve the durability of the GFRP bars. If this is the case, then the data in the literature could indicate this. Figure 7 shows the loss in tensile capacity as a function of publication date. The objective of this plot is to assess whether the loss in tensile capacity is decreasing with time, which could indicate improvements in some factor that improves the GFRP durability. This assumes that the GFRP production correlates with publication date. The figure shows significant variation in results. More recent results in the

figure show less variation but still significant reductions in tensile capacities. The reduction in variation of the more recent data could be associated with a fewer number of data points. These results indicate that exposure conditions can influence GFRP reinforcement performance and that several exposure conditions can result in deterioration of the tensile strength of these GFRP bars. The figure also indicates that recent studies where the GFRP bars have been assessed for residual tensile strength still show significant losses in tensile strength.

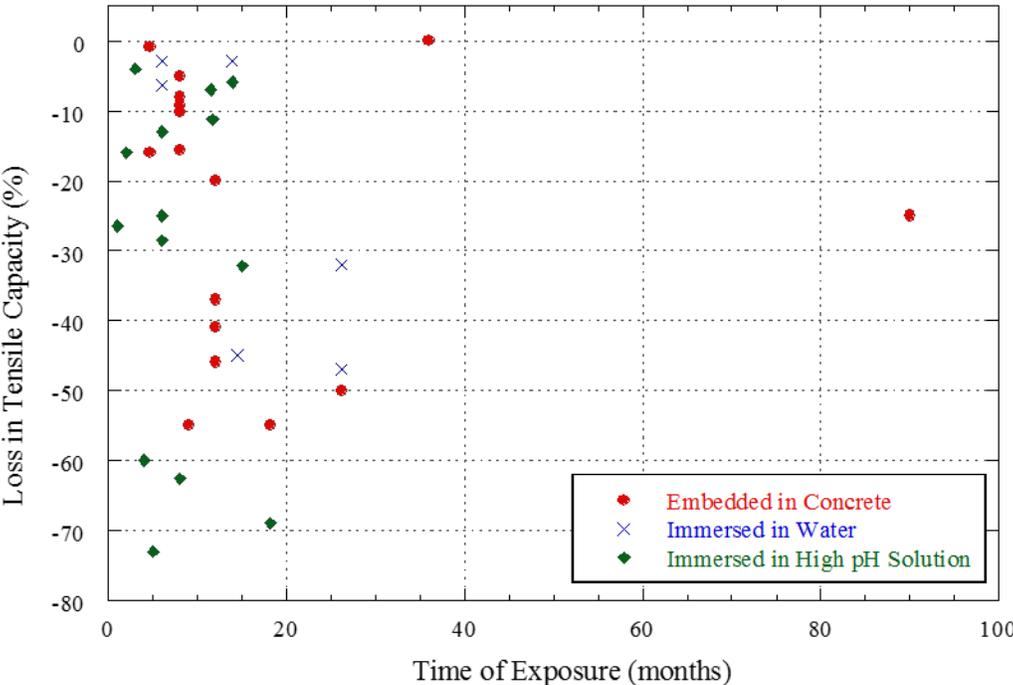


Figure 6 Plot of data from Table A1 showing loss in tensile capacity of GFRP reinforcing bars versus time of exposure.

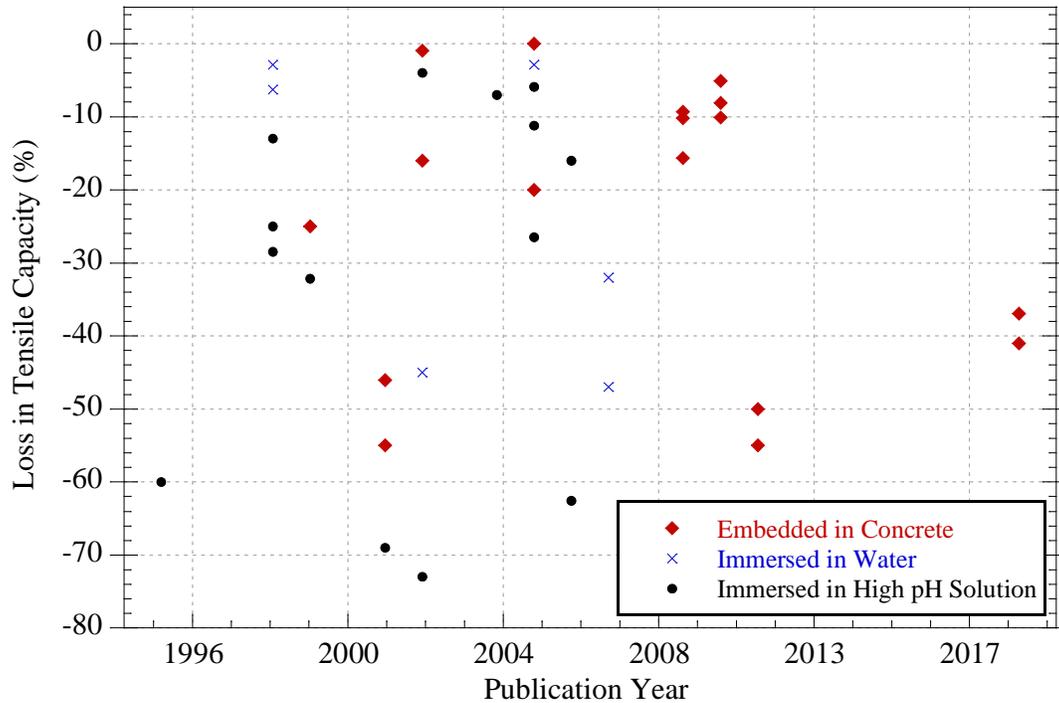


Figure 7 Plot of data from Table A1 showing loss in tensile capacity of GFRP reinforcing bars versus time of published data.

One significant claim by the GFRP industry and/or producers is that GFRP does not corrode. Indeed, GFRP bars do not experience classical corrosion where an electrochemical reaction results in degradation of the base metal. Although corrosion is often perceived as being a disadvantage, when steel reinforcement corrodes it provides the users and owners of steel-reinforced concrete structures with a warning signal of deterioration. That is, when steel corrodes, the corrosion products are often visible within or on the concrete surface and more importantly, these changes in corrosion can be observed and then measured and monitored. As shown in Figures 4 through 6, significant degradation of the GFRP bar capacity does occur. However, unlike steel reinforcement corrosion, there are no indicators of this capacity loss. When GFRP reinforcing bars are embedded in concrete and when these GFRP reinforcing bars undergo degradation, no visible warning signs or visible indicators are produced that indicate the GFRP bar has lost capacity. Also, there are no non-destructive methods to assess the reduction in tensile capacity of GFRP bars embedded in concrete. In engineered structures warning signs of failure are critical and having the ability to visually assess deterioration and potential loss of capacity are advantageous and can assist in identifying end of service life and structure safety. Ideally a structure that is durable and

experiences no deterioration is preferred but when mechanisms of deterioration do occur, having insight into this deterioration and the degree of damage is beneficial. Several researchers have presented information on the potential mechanisms of deterioration of GFRP bars and these mechanisms are presented next.

2.7. Mechanisms and Modeling Degradation in GFRP Reinforcement

Before addressing potential deterioration mechanisms, some definitions on terminology would be beneficial. In general, the loss in tensile capacity is determined as the percent loss in capacity based on the ultimate strength. The ultimate tensile strength, f_{avg} , is the average tensile capacity of a set of reinforcing bars. However, f_{avg} does not consider potential deterioration of the GFRP bars and the resulting reduction in tensile strength. Because of this, the ACI design guide for GFRP reinforced structures (ACI Committee 440.1R 2006) requires that a reduction factor be applied to the tensile strength of GFRP reinforcement. ACI 440.1R-06 reports that the design tensile strength, f_{fu} , should account for the environmental exposure conditions as follows:

$$f_{fu} = C_E f_{fu}^* \quad (\text{Eq. 1})$$

where C_E is the environmental reduction factor and f_{fu}^* is the GUTS of the GFRP bar. The GUTS is defined as the mean tensile strength of a sample of test specimens minus three standard deviations ($f_{fu}^* = f_{avg} - 3 \times SD$). Fergani et al. (2018) reported tensile strength data for GFRP bars and reported a mean and COV of GFRP of 223.6 ksi and 1.8%, respectively. This would indicate that the f_{fu}^* for those bars is $223.6 - 12 = 211.6$ ksi. The value of C_E is 0.7 for GFRP exposed to earth and weather and 0.8 for GFRP not exposed to earth and weather. Using the information from Fergani et al. (2018) and a reduction factor of 0.7 results in a design tensile strength of about 148 ksi, which is approximately 66% of the original mean tensile strength. Using the same data and a reduction factor of 0.8 would result in a design tensile strength of approximately 169 ksi, or almost 76% of the original mean tensile strength. This indicates that the maximum allowable percent loss in tensile strength for GFRP bars exposed to earth and weather would be 34% and for GFRP bars not exposed to earth or weather 24%. Although the reduction factors (0.7 and 0.8) are reported to be conservative estimates based on consensus of the ACI 440 committee and include the effects of reasonable temperature increases inside the concrete, the data shown in Figures 4 through 6

indicate that a significant number of studies have reported significantly more capacity loss than these limits. Several authors indicate that testing in high pH solution or saturated concrete is aggressive and results from tests that include these conditions are not representative of the long-term performance of GFRP reinforced concrete structures in the field. This argument has been somewhat quieted with the recent development of ASTM and ACI documents that require these exposures. However, care must be taken as very seldom is a designer able to control the exposure conditions after the structure has been constructed. In addition, because loss in tensile capacity of GFRP bars results in no visible indicators of degradation (e.g., corrosion surface stains) and non-destructive methods for assessing this loss in capacity are not available, care must be taken when using GFRP bars.

To better understand how GFRP bars deteriorate in a concrete environment, a description of the reported mechanisms of deterioration will be provided. It has been reported that the pore humidity in concrete seldom drops below 72% (Pyc 1998). When GFRP bars are exposed to this humid, high pH environment (pore solution exhibits a pH of ~12.5 to 13), this pore solution can migrate into the vinyl ester, polyester, or composite material that covers the glass fibers in the GFRP bar (see Figure 1). With time, the depth of migration increases. When the pore solution reaches the glass fiber-composite material interface, it is reported that the solution reacts with the glass surface and deteriorates the bond between the composite and glass. This bond is critical to the performance of the GFRP bar as this bond creates the composite action between the glass fibers and composite material. Once this bond is destroyed, the fiber continues to degrade and the bar loses capacity. Huang and Aboutaha (2010) reported that the composite matrix, the glass fiber, and the interface between these two materials can be susceptible to attack, especially by alkali attack in concrete.

Although one claim for using GFRP bars is the elimination of classic corrosion, GFRP bars do exhibit loss in tensile capacity as a result of deterioration of the glass-composite bond, which results in loss in capacity of the structure and can result in reduced service lives of GFRP-reinforced structures. Huang and Aboutaha (2010) reported that degradation of the GFRP bars begin when free hydroxyl ions (OH⁻) and water diffuse through the composite matrix of the bars towards the glass fibers. The ester group undergoes hydrolysis and several studies indicate that water can lead to swelling stresses, which leads to cracking and glass fiber-composite debonding

(Bank et al. 1995, fib 2007). The authors also reported that glass fibers are susceptible to leaching and etching and this leaching and etching cause notching and embrittlement of the glass fibers, which results in a reduction in capacity.

Katsuki and Uomoto (1995) reported that the residual tensile strength of GFRP bars after exposure to alkaline solutions can be predicted. The authors hypothesized that GFRP bars degrade due to the attack on the glass fibers at the fiber-composite material interface by the alkalis present in the concrete pore solution. These authors observed and measured the depth of penetration of the alkaline solution into GFRP bars using an electron probe microscope analyzer and using these data proposed the following expression to estimate the depth of penetration of the pore solution:

$$x = \sqrt{2Dct} \quad (\text{Eq. 2})$$

where x , D , c , and t represent the depth of pore solution penetration from the surface of the bar (cm), the diffusion coefficient for the pore solution into the FRP bar ($\text{cm}^2 \text{h}^{-1}$), the alkaline concentration of the pore solution (mol/l), and the time of exposure (h), respectively. To predict the residual tensile strength of GFRP bars the authors assumed the area where the alkalis penetrated the GFRP bars have no strength; that is once the pore solution reaches the fiber the bond is instantaneously destroyed. This general concept is shown in Figure 8 (R_0-r_1 is the depth of pore solution penetration, x , in Eq. 2). As a result of this deterioration of the bond and glass fibers, the authors proposed the following expression for the computation of the residual tensile strength:

$$\sigma_t = \left(1 - \frac{\sqrt{2Dct}}{R_0}\right)^2 \sigma_0 \quad (\text{Eq. 3})$$

where the terms are as described earlier and σ_t , σ_0 , and R_0 are the tensile strength at any given age (MPa), the tensile strength before exposure (MPa), and the bar radius (cm), respectively. The authors exposed GFRP bars to a 1.0 mol/l aqueous solution of NaOH at 104 °F. The diffusion coefficient reported

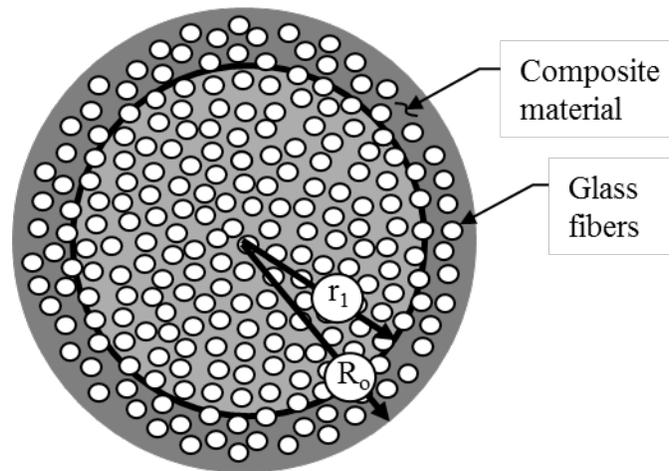


Figure 8 Graphic showing degradation area as proposed by Katsuki and Uomoto (1995)

was 2.8×10^6 cm²/h and the results from the model predicted the loss of tensile capacity of the bars. However, because the research was based on specimens exposed to high temperature, the applicability to normal exposure conditions was unknown.

Other models have been developed but the model by Katsuki and Uomoto (1995) was reported to provide a reasonable estimate of loss in capacity (Gurtin and Yatomi 1979, Carter and Kibler 1978). Aguiniga (2003) reported that the hypothesis that the glass fibers instantaneously lose all capacity overestimates the loss of strength and reported a factor, λ , that compensated for the slower rate of degradation and bond deterioration as follows:

$$\sigma_t = 1 - \left(\frac{\sqrt{2D\lambda t}}{R_o} \right)^2 \sigma_0 \quad (\text{Eq. 4})$$

Although Aguiniga (2003) reported λ as a function of pore solution concentration and time, later Aguiniga et al. (2004) reported that when λ was fit to the overall lowest observed residual tensile strength, the value of λ was 0.006 when using exposure data up to 50 weeks. Using this information, the authors concluded that an "environmental reduction factor of 0.7 for glass FRP bars given in the ACI 440 design guidelines may be unconservative beyond approximately 7 years..." Wang et al. (2011) reported that the strength reduction of GFRP bars is dependent on temperature and can be estimated as follows:

$$SR = 114.4 - 15 \times \text{Log}(t) \text{ for } T = 68 \text{ }^\circ\text{F} \quad (\text{Eq. 5})$$

$$SR = 113.5 - 19.2 \times \text{Log}(t) \text{ for } T = 140 \text{ }^\circ\text{F} \quad (\text{Eq. 6})$$

where t is time in days. The authors reported that for 100% RH and a temperature of 50 °F, the strength retention of GFRP bars would be approximately 60% (40% loss of strength) after 20 years. Chu and Karbhari (2005) reported that the percent retention, P , in tensile strength of GFRP could be determined as follows:

$$P = -7.256 \times \ln(t) + 105.65 \quad (\text{Eq. 7})$$

where t is exposure time in weeks. Using this equation, Karbhari et al. (2007) reported that "the environmental reduction factor of 0.7 recommended by the ACI 440 design guidelines (ACI 2003)

may be unconservative beyond about 9.8 years of exposure, under conditions wherein the FRP was always immersed in water..."

Trejo et al. (2011) reported that the residual capacity of GFRP bars embedded in concrete could fall below the design specified capacity between approximately 18 and 21.5 years, depending on bar size. The authors extracted GFRP bars from concrete samples exposed to the Texas environment for 7 years. Similar to the research by Aguiniga (2003), Aguiniga et al. (2004), Wang et al. (2011), Chu and Karbhari (2005), and Karbhari et al. (2007), Trejo et al. (2011) reported that the ACI exposure factors may be unconservative and may have to be reduced. In 2012 Kim et al. reported that "the probability of failure for decks with 13M (#4) and 19M (#6) GFRP bars exceeded the probability of failure values recommended by AASHTO LRFR" at temperatures between 55 and 91 °F. The authors also reported that larger diameter bars did not exhibit the same performance and these larger bars exhibited a lower probability of failure.

Some recent investigations contradict the research findings of the authors and researchers above. Gooranorimi and Nanni (2015) reported on GFRP bars extracted from a bridge built in Texas after 15 years in service. This bridge was a part of the research work performed by Trejo and Aguiniga and reported on by Aguiniga (2003) in his PhD dissertation. This research resulted in other research and reports by Aguiniga et al. (2004), Kim et al. (2009, 2010a, 2010b), Trejo et al. (2009), Trejo et al. (2011), Kim et al. (2012), and Gardoni et al. (2012). Gooranorimi and Nanni (2017) assessed concrete pH and concrete carbonation and performed scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDS), glass transition temperature (T_g), and horizontal shear strength testing of extracted GFRP samples. The original construction of the bridge included embedding additional GFRP bars, referred to as witness bars, into the bridge deck. The authors concluded that the concrete exhibited carbonation and the depth of carbonation had in some cases reached the witness bars. This increased carbonation depth would have decreased the pH of the pore solution and would likely make the pore solution less aggressive for deterioration to the GFRP bars. The authors reported that the microscopic examination did not show any GFRP degradation, EDS result did not suggest any evidence of chemical attack, that the T_g values were higher than 212 °F, and concluded that the "study provided partial confirmation that GFRP bars maintained their microstructural integrity after 15 years in a field application." However, no tensile testing of the bars was reported as part of the publication.

Mufti et al. (2005, 2007) extracted cores from structures across Canada and reported that "no deterioration of GFRP took place in any of the field structures" and concluded that "GFRP is durable in concrete." Similar to the research by Gooranorimi and Nanni (2015), Mufti et al. (2005) performed optical microscopy, SEM, EDS, infrared spectroscopy (IR), differential scanning calorimetry to assess T_g of samples extracted from the structures, but no physical testing of the GFRP mechanical properties were assessed.

In 2014, Park et al. investigated the impact of accelerated aging conditions on the long-term flexural behavior and ductility of GFRP-reinforced and steel-reinforced members. The testing program included exposing pre-cracked reinforced concrete beams to an average relative humidity of 80% and 116 °F. The authors concluded that members with steel reinforcement exhibited a higher reduction in flexural strength than members with GFRP reinforcement and concluded that for flexural members the substitution of GFRP reinforcement for steel reinforcement had a positive influence on durability.

Khatibmasjedi and Nanni (2017) reported on the use of GFRP reinforcement in concrete made with seawater and salt-contaminated aggregates and concluded that the tensile properties of the GFRP bar samples "was slightly improved after 6 months exposure to accelerated conditioning" and seawater concrete and accelerated conditioning has a positive impact on horizontal shear strength of bars embedded in concrete and a negative impact on transverse shear strength.

Much of the research indicating that GFRP reinforcing bars do not exhibit degradation have been based on localized testing of the composite or glass components of GFRP bars taken from small specimens obtained from field structures. Although this approach provides some advantages, this type of experimental testing program could be limited as investigations at localized sites may not be representative of the overall conditions of the remaining member or structure. Also, the research by Park et al. (2014) subjected GFRP- and steel-reinforced cracked concrete beams to high temperatures and an aggressive chloride environment. The cracks in the beams were significantly wide. These test conditions are well known to lead to early corrosion of steel-reinforced concrete beams. The results indicate that these same conditions result in lower deterioration rates for GFRP-reinforced concrete. However, several points should be made regarding these results: steel is not a new material and corrosion performance of steel embedded

in concrete has been extensively investigated; GFRP reinforcement is a relatively new material and a reliable, repeatable, and accurate method for assessing the performance of GFRP reinforcement embedded in concrete must be developed to ensure the safety of the system; little consensus has been reached on the long-term performance of GFRP reinforced concrete; subjecting members to an environment that is well-established to be very aggressive to steel-reinforced concrete specimens and then comparing results against this aggressive environment is likely not a fair comparison for most environmental conditions and likely is not representative of most field conditions; and lastly, embedding GFRP bars into a high pH medium (i.e., concrete) does subject the GFRP directly to that environment and testing under these conditions in an accelerated manner is reasonable to justify safety. Research on the use of GFRP bars for concretes containing salts may be promising but significantly more research is necessary to justify its safe use.

3. Standardized Durability Tests for GFRP Reinforcement

In 2012 ASTM D7705, Standard Test Method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction, was developed to quantify the alkali resistance of FRP bars used as reinforcing bars in concrete. The standard includes three test procedures and all tests are performed at elevated temperatures ($140\text{ }^{\circ}\text{F} \pm 5\text{ }^{\circ}\text{F}$). The first test (procedure A) includes immersing GFRP bars in an alkaline solution while the bars are under unloaded conditions. The second test, procedure B, immerses GFRP bars in alkaline solution while the bars are subjected to tensile forces. Procedure C includes embedding GFRP in moist concrete and assessing the tensile capacity of the bars after exposure. The alkali resistance for all procedures is quantified as the ratio of the residual tensile strength of the exposed bars with the tensile strength of the unexposed GFRP bars. All tests are evaluated at 1, 2, 3 and 6 months, or longer if specified.

In 2015 ACI published 440.9R, Guide to Accelerated Conditioning Protocols for Durability Assessment of Internal and External Fiber-Reinforced Polymer FRP Reinforcement. This document allows four tests to assess the durability of GFRP bars: modified versions of the three methods allowed in ASTM D7705 and a sustained bending stress test. The sustained bending test includes subjecting GFRP bar segments to bending by securing these bars in a curved strain jig

following ASTM D543, and immersing these bars in a heated ($140\text{ }^{\circ}\text{F} \pm 5\text{ }^{\circ}\text{F}$), high pH solution. This test subjects the bar specimens to a specified sustained flexural strain over time.

Although the requirements in the ACI 440.9R document are similar to the ASTM D7705 requirements, many critical requirements are different. The ACI document requires testing following the general procedure A in the ASTM specification but at $122\text{ }^{\circ}\text{F}$ instead of $140\text{ }^{\circ}\text{F}$. In addition, the ASTM test procedure for procedure B requires that the pH of the test solution "shall be maintained by the addition of hydroxides and tap water as necessary to maintain the required pH level" for specimens continuously immersed in alkaline solution. The ACI document only requires covering the alkaline solution before and during testing and states that this should prevent reducing the solution pH and solution evaporation. Because pH measure is on a log scale and because deterioration of GFRP is highly dependent on solution pH, not maintaining a constant pH could reduce capacity loss. The ACI document only requires that the solution pH be checked at the end of the conditioning and there are no requirements for reporting this pH value. Although seemingly minor, these changes likely provide less severe conditions than those required in the ASTM standard and could result in significantly different results than the ASTM results.

The fourth test allowed by ACI seems to be less severe than the tensile test. First, while in bending potential microcracking would likely occur at the outer edge of the surface in tension. Because the alkaline solution can penetrate these microcracks and accelerate deterioration, by forcing potential microcracking to only one side of the specimen the deterioration is likely only focused at the cracked side. Also, the duration of the sustained bending test is 3000 hours. Although no research has been published to determine the ranking of severity of these tests, the ACI test method could be considered to be less aggressive than the ASTM tests, although research is needed to determine this. Also, the ACI 440.9R document states that the test procedures "are meant to generate a database of consistent test results that can be used in the future to refine the environmental factors recommended" in the ACI documents. However, modifying standard testing protocol as defined in the ASTM standards could likely lead to more scatter of test data and less confidence in test results, and ultimately less confidence in the GFRP reinforcing materials.

The applicability of these test results to actual field structures is unknown. In fact, ACI 440.9R states that "the results of the conditioning and testing recommended in this guide are not intended

to be useful in the prediction of service life." The guide does encourage using test results in conjunction with field evaluations so that future correlation between the testing and field performance can be achieved. However, at this time, sufficient field data are likely not available to achieve this goal.

4. General Design Methodology and Challenges for GFRP-reinforced Concrete Members

In 2015 ACI published the *Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymers (FRP) Bars* (ACI 440.1R-15). The document is a comprehensive guide in the US for the design of GFRP-reinforced concrete.

Because GFRP reinforcing bars are anisotropic, the high tensile strength associated with these bars occurs only in the direction of the reinforcing fibers. The 440.1R document reports that the anisotropic nature of the bars also influences shear strength, dowel action, and bond performance. Because GFRP reinforcing bars do not yield (see Figure 3), the design procedures outlined in ACI 440.1R account for this lack of ductility by recommending design procedures that possess higher reserve strength. Reinforced concrete members containing steel reinforcement are regularly designed to ensure tension-controlled behavior; this behavior results in yielding of the steel prior to crushing of the concrete. This yielding of the steel provides member ductility and when overloaded, a warning of failure of the steel-reinforced member occurs. However, because GFRP-reinforcement exhibits no yield point and only a small percentage of the ductility of steel reinforcement, there will likely be less warning of failure when overloaded. Therefore, other considerations have to be considered for GFRP-reinforced flexural beams.

The 440.1R document reports that when FRP reinforcement ruptures, failure of the reinforced member is sudden and catastrophic with limited warning. If GFRP-reinforced concrete members are designed to experience tension-controlled failure, the ductility would be significantly less than a steel-reinforced concrete member. Reinforced members can alternatively be designed to fail via concrete crushing. The ACI 440.1R document reports that this failure mode is marginally more desirable for flexural concrete members. Although challenges exist with both methods, ACI 440.1R allows both design procedures for flexural members as long as each satisfy the strength and serviceability criteria established in the document.

The strength design philosophy outlined in ACI 440.1R states that the design flexural strength (or the nominal flexural strength multiplied by a strength reduction factor, ϕ) at a section of the member should exceed the factored moment. Values of ϕ depend on the design philosophy and reinforcement ratio as shown in Figure 9. See ACI 440.1R for full details.

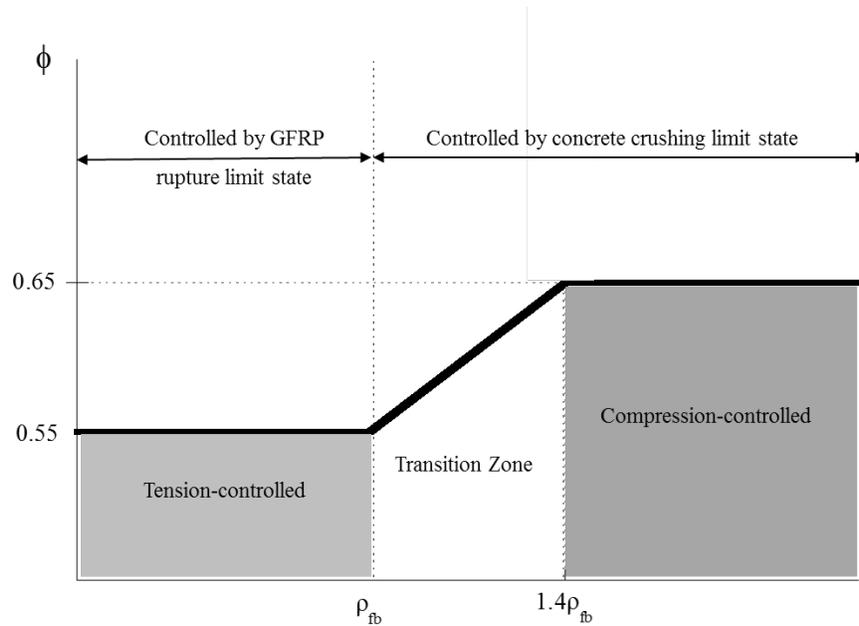


Figure 9 Strength reduction factors as a function of GFRP reinforcement ratio for flexural strength design.

It should be noted that GFRP-reinforced members have relatively small stiffness values after cracking when compared with steel-reinforced members. Because of this, deflections may control the design. ACI 440.1R provides two general methodologies to control flexural cracking and deflection for GFRP-reinforced members: calculating crack width or using an indirect procedure that limits maximum bar spacing. The document provides a comprehensive procedure for performing both methods and provides design examples in Chapter 11 of the 440.1R document. For a complete review of the design procedures for GFRP-reinforced members, the reader is encouraged to review this document.

ACI 440.1R allows both tension- and compression-controlled failures during the design process. Because of concerns with the longer-term durability of GFRP reinforcing bars, the ACI document limits the design tensile strength of the reinforcing bars. Equation 1 showed that an

environmental reduction factor, CE, is required to determine the design tensile strength, f_{fu} , of GFRP-reinforced concrete members. As already presented, the literature contains significant information on the degradation rate of GFRP bars and GFRP-reinforced concrete systems. Many papers now focus on whether the long-term tensile strength of the GFRP reinforcement will be above or below this design strength. As already noted, the maximum allowable percent loss in tensile strength for GFRP bars exposed to earth and weather would be approximately 34% and for GFRP bars not exposed to earth or weather would be approximately 24% (these could vary as these depend on the standard deviation of the tensile test results of the GFRP lot tested). However, as can be seen in Section 2.7, significant research has been performed that indicates reductions in strength that are much larger than these values. Many variables have been reported to influence the strength of GFRP bars; these include moisture content of the concrete, pH of the concrete pore solution, temperature of the concrete-bar system, GFRP reinforcing bar size, GFRP materials, bar stress in service, and others. Some researchers assume low exposure temperatures and dry concrete and report that the environmental reduction factors may be conservative. Because the designer cannot know the exposure conditions of the structure over its entire life, care must be taken when using these reduction factors. The literature clearly shows that reductions in tensile strength can exceed those published by ACI 440.1R.

In addition to design changes, and durability and long-term performance concerns associated with GFRP reinforcing bars, the bond between GFRP reinforcing bars and steel reinforcing bars is different. ACI 440.R1 uses the term k_b to quantify bond. This term is a coefficient that accounts for the degree of bond between the GFRP bar and the adjacent concrete. A k_b of 1.0 indicates the GFRP bar has similar bond to that of steel and concrete, a k_b value greater than 1.0 indicates a bond inferior to that of steel and concrete, and a k_b of less than 1.0 indicates a bond superior to that of steel and concrete. El-Nemr et al. (2013) reported that a k_b values of 1.2 for helically wrapped FRP bars and 1.0 for sand-coated GFRP bars embedded in normal and high strength concretes. The ACI 440.1R document recommends a k_b of 1.4. Mosley et al. (2008) also reported that the bond strength of GFRP reinforcement was significantly lower than that achieved by steel reinforcement and concluded that modulus of elasticity of the GFRP was a significant factor affecting the bond strength.

GFRP bars require that all bars be bent when fabricated; that is, these bars cannot be field bent. ACI 440.1R reported that although manufacturing of GFRP bars with sharp bends is possible, a minimum bend radius to bar diameter ratio (r_b/d_b) of 3 is recommended. Even with these larger bend ratios, Trejo et al. (2005) reported that GFRP bars exhibit significant reductions in strength when pre-bent, but also reported that a deck-rail system constructed with bent GFRP and epoxy-coated reinforcement performed well in actual crash testing. Imjai et al. (2017) reported that a r_b/d_b greater than 4 is required to guarantee a minimum bend capacity of only 40% of the theoretical composite strength. Ahmed et al. (2010) reported that the reduction in tensile strength at the bend zone is a result of the weakness of the fibers in the transverse direction accompanied by the kinking of the innermost fibers.

Because of the low stiffness, high strength, and low ductility of GFRP reinforcing bars, conventional design methodologies have to be modified for these systems. ACI 440.1R-15 provides a comprehensive method for the design of concrete members containing GFRP reinforcement but caution should be taken when assessing the long-term performance of these systems as the literature indicates that GFRP reinforcement can degrade and lose tensile strength. When these bars lose strength, there is no indication to the users that these bars have reduced capacities.

5. Summary

Embedding glass fibers in composites was first patented in 1936. Since this time fiber reinforced polymers have been used in many industries that require strong, lightweight materials. Although many industries have implemented the use of many of these FRP types, because of the higher costs associated with the non-GFRP products, these products have not been able to widely penetrate the engineering and construction markets. However, the lower relative cost of GFRP has stimulated much interest and since the 1990s significant research has been performed assessing the design and use of these reinforcing bars. Significant research has been performed on the design, use, and performance of GFRP reinforcing bars and significant advances have been made in the design of GFRP-reinforced concrete members. Although significant advances have been made in the design, challenges still exist with the use of GFRP reinforcing bars.

Compared to steel reinforcement, GFRP reinforcing bars exhibit low modulus of elasticity values, low ductility, and lower bar-concrete bond, and can result in structures with larger deflections and larger crack widths. Table 2 shows a summary of properties for steel reinforcing bars and GFRP bars. The GFRP reinforcing bars also exhibit higher initial strengths, are electrically non-conductive, and are non-magnetic, making GFRP reinforcing bars applicable to construction where high voltages are present (e.g., high voltage substations) or where magnetic fields can influence equipment operation (e.g., MRI rooms in hospitals).

One characteristic that has not achieved consensus in the engineering community is the durability of GFRP when embedded in concrete. Concrete is composed of portland cement, water, and aggregates and the portland cement results in a high pH pore solution. Although the composite surrounding the glass fibers in GFRP reinforcement is supposed to protect these glass fibers from potential deterioration, the pore solution can penetrate this composite. Glass is susceptible to etching and leaching when exposed to high pH environments. This etching and/or leaching results in loss of bond between the glass fibers and composite material or results in weakening of the glass fibers. Both mechanisms can result in loss of strength of the GFRP reinforcing bar. Significant research has reported this. Some current research indicates that GFRP embedded in field structures do not exhibit degradation. However, these results that indicate low or no degradation do not include a direct measure of the residual tensile strengths, a property commonly reported to decrease when exposed to high pH environments (e.g., concrete pore solution). Although indirect measures of GFRP degradation are improving, direct measurements of GFRP reinforcement degradation provide clear and unambiguous measures and these direct measures are likely more representative of actual performance.

The durability of GFRP reinforcing bars embedded in concrete depends on the amount of moisture available in the concrete, the pH of the pore solution, the temperature of the GFRP and concrete, the ability of the composite material to resist solution and ion penetration, the size of the reinforcement, the quality of the fabrication process, and others. Dry concrete will likely have limited influence on the residual tensile strength of GFRP reinforcing bars as no pore solution will be available to penetrate the GFRP reinforcing bar. However, very little concrete contains no pore solution.

Table 2—Summary of comparisons of steel reinforcement and GFRP reinforcement properties and general design values.

Material Specifications	Grade 100 Reinforcement	Grade 80 Reinforcement	Grade 60 Reinforcement	GFRP
		ASTM A1035 ASTM A615	ASTM A955 ASTM A755 ASTM A776	ASTM A955 ASTM A775 ASTM A776
Tensile Strength	125 to 150 ksi #3 through #18	~100 ksi #3 through #18	~90 ksi #3 through #18	GUTS ^[1] #2 through #10 dependent on size: ~80 to 130 ksi; GUTS #11 through #13 ^[2] ~60 to 70 ksi
Yield Strength	100 ksi	80 ksi	60 ksi	No defined yield strength; bar fracture at ultimate
Approximate Design Yield Strength	60 ksi	48 ksi	36 ksi	12 to 20 ksi
Modulus of Elasticity	29 x 10 ³ ksi	29 x 10 ³ ksi	29 x 10 ³ ksi	~6.7 x 10 ³ ksi
Ultimate Strain, %	>7	>7	>9	~0.9 to 1.9
Percent of Bar Quantity Required for Same Design Load (Deflection and Cracking)	100%	100%	100%	400%
Shear Strength Design	80 ksi	60 ksi	60 ksi	22 ksi
Bent Strength (% of straight bar)	100	100	100	~40% ^[3]

(1) Guaranteed Tensile Strength is calculated as the mean tensile strength of a given lot, which can vary from one lot to another and from one source to another, minus three times the standard deviation.

(2) Tensile properties of #11, #12, and #13 bars are reported to NOT guaranteed due to inability to achieve a valid bar break. Manufacturers report that they reserve the right to make improvements in product or/and process which may result in changes to physical or mechanical properties.

In summary, although GFRP reinforcing bars do have some advantages for specific applications (non-magnetic and electrically non-conductive) this literature review indicates that GFRP bars do exhibit the following characteristics:

- Significantly lower ductility than steel;
- Loss in capacity when exposed to moisture;

- Loss in capacity when exposed to high pH solutions;
- Loss in capacity when embedded in moist concrete, and;
- Low strengths when pre-bent.

The literature also indicates that GFRP-reinforced concrete structures:

- Could require more reinforcement when compared to steel;
- When in moist environments, could exhibit reductions in structural capacity, and;
- When in moist environments, could exhibit reduced service lives.

Because the degradation of GFRP produces no signs of deterioration and because the literature indicates that GFRP bars experience loss in capacity when embedded in concrete, engineers must use care when specifying GFRP reinforcement.

6. Appendix

Table A1.1 Changes in GFRP UTS Reported in the Literature

Authors	Pub. Year	Bar Type	Exposure Type	Exposure Duration	% Change in UTS
Katsuki and Uomoto	1995	--	1 mol/l NaOH	120 days	-60%
Tannous and Saadatmanesh	1998	E-glass/PE; $\phi=0.39$ in	Water @ 77 °F	6 mos.	-6.3%
Tannous and Saadatmanesh	1998	E-glass/PE; $\phi=0.39$ in	CA(OH) ₂ Sol. (PH=12) @ 77 °F	6 mos.	-25%
Tannous and Saadatmanesh	1998	E-glass/PE; $\phi=0.39$ in	CA(OH) ₂ Sol. (PH=12) @ 140 °F	6 mos.	-28.5%
Tannous and Saadatmanesh	1998	E-glass/VE; $\phi=0.39$ in	Water @ 77 °F	6 mos.	-2.9%
Tannous and Saadatmanesh	1998	E-glass/VE; $\phi=0.39$ in	CA(OH) ₂ Sol. (PH=12) @ 77 °F	6 mos.	-13%
Tannous and Saadatmanesh	1998	E-glass/VE; $\phi=0.39$ in	CA(OH) ₂ Sol. (PH=12) @ 140 °F	6 mos.	-20.3%
Vijay and GangaRao	1999	NR	0.2% CA(OH) ₂ +1.4% KOH+1.0% NaOH Sol. @ 71.6 °F Avg	15 mos	-32.2% max
Sekijima et al.	1999	E-glass/VE grid	Embedded in high early-strength conc. placed outdoors	7-8 yrs	~-25% max
Waldon et al.	2001	NR	Alkali solution @ 140 °F	545 days	-69%
Waldon et al.	2001	NR	Concrete @ 140 °F	545	-55%
Dejke	2001	VE/E-glass	Moist concrete @ 140 °F	1 year	-40 to - 52%
Nishizaki and Meiarashi	2002	VE	Water @ 140 °F	434 days	~-45%
Kajorncheappunngam et al.	2002		5M NaOH @ 140 °F	5 mos	-73%
Benmokrane et al.	2002	VE/E-glass	0.247 lbs Ca(OH) ₂ +0.009 lbs KOH per Qrt water	90 days @ 30% of UTS	-4%
Benmokrane et al.	2002	VE/E-Glass	Concrete	140 days @ 30% of UTS	-16%
Benmokrane et al.	2002	VE/AR- Glass	Concrete	140 days @ 30% of UTS	-1%
Aguiniga et al.	2004	various	0.035 lbs Ca(OH) ₂ per Qrt of water	50 weeks	-7%

Table A1.2 Changes in GFRP UTS Reported in the Literature (continued)

Authors	Pub. Year	Bar Type	Exposure Type	Exposure Duration	% Change in UTS
Nkurunziza et al.	2005	VE/E-glass; #3 bars	Water	417 days	-2.9%
Nkurunziza et al.	2005	VE/E-glass; #3 bars	0.247 lbs Ca(OH) ₂ +0.009 lbs KOH per Qrt water	417 days	-5.9%
Gremel et al.	2005	E-glass	0.0044-0.0066 lbs of NaOH per Qrt water @ 140 °F	30 days; 25% of σ_u	-18 to 35%
Bakis et al.	2005	VE/E-glass	Concrete exposed to freeze-thaw cycles	~12 mos	~-20%
Bakis et al.	2005	VE/E-glass	Concrete exposed to outside conditions	~36 mos	~0%
Trejo et al.	2005	VE and PE	Alkaline solution, pH=12	350 days	-7.3 to -15.2
Chen et al.	2006	VE/E-glass	0.004 lbs Ca(OH) ₂ +0.041 lbs KOH+0.005 lbs NaOH per Qrt water @ 140 °F	240 days	-62.6%
Debaiky et al.	2006	VE/E-glass; 16 mm	0.0019 lbs NaOH+0.0088 lbs KOH per Qrt water	2 mos	-16%
Karbhari et al.	2007	VE/E-glass	Water	112 wks, unstressed	-32%
Karbhari et al.	2007	VE/E-glass	Water	112 wks, 0.57 ϵ_u	-47%
Robert et al.	2009	VE/E-glass	Concrete exposed to water @ 73 °F	240 days	-9.3%
Robert et al.	2009	VE/E-glass	Concrete exposed to water @ 104 °F	240 days	-10.2
Robert et al.	2009	VE/E-glass	Concrete exposed to water @ 140 °F	240 days	-15.6
Robert et al.	2010	VE/E-glass	Mortar exposed to water @ 73 °F	240 days	-5.1%
Robert et al.	2010	VE/E-glass	Mortar exposed to water @ 104 °F	240 days	-8.1%
Robert et al.	2010	VE/E-glass	Mortar exposed to water @ 140 °F	240 days	-10.1%
Davalos et al.	2011	VE/E-glass	Concrete exposed to water @ 140 °F, unloaded	270 days	~-55%

Table A1.3 Changes in GFRP UTS Reported in the Literature (continued)

Authors	Pub. Year	Bar Type	Exposure Type	Exposure Duration	% Change in UTS
Davalos et al.	2011	VE/E-glass	Concrete exposed to water @ 140 °F and low load	270 days	~-50%
Kim et al.	2012				
Fergani et al.	2018	VE/E-CR Glass	Moist concrete, 68 °F	1 year	-41%
Fergani et al.	2018	VE/E-CR Glass	Moist concrete, 104 °F	1 year	-41%
Fergani et al.	2018	VE/E-CR Glass	Moist concrete, 140 °F	1 year	-37%

7. References

- ACI 440R-07 Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures, American Concrete Institute, Farmington Hills, MI, 2007.
- ACI 440.1R-15 Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars, American Concrete Institute, Farmington Hills, MI, 2015.
- ACI 440.3R-12 Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures, American Concrete Institute, Farmington Hills, MI, 2012.
- ACI 440.9R-15 Guide to Accelerated Conditioning Protocols for Durability Assessment of Internal and External Fiber-Reinforcement, American Concrete Institute, Farmington Hills, MI, 2015.
- Aguiniga, F., Characterization of Design Parameters for Fiber Reinforced Polymer Composite Reinforced Concrete Systems, PhD Dissertation, 2003, Texas A&M University.
- Aguiniga, F., Bradberry, T.E., and Trejo, D., "Time-dependent Mechanical Property Changes of Glass Fiber-Reinforced Polymer Exposed to High pH Environments," *Earth and Space* 2004, pp. 585-592.
- Ahmed, E. A., El-Sayed, A. K., El-Salakawy, E., and Benmokrane, B., "Bend Strength of FRP Stirrups: Comparison and Evaluation of Testing Methods," *ASCE Journal of Composites in Construction*, 2010. Pp3-10.
- Aiello, M. A., "Concrete Cover Failure in FRP Reinforced Concrete Beams under Thermal Loading," *Journal of Composites for Construction*, A.S.C.E., V. 3, No. 1, February 1999, pp. 46-52.
- Al-Salloum, Y. A. and Almusallam, T. H., "Seismic Response of Interior RC Beam-Column Joints Upgraded with FRP Sheets: I: Experimental Study," *Journal of Composite in Construction*, V. 11, No. 6, 2007, pp. 575-589.
- Bakis, C.E., Boothby, T.E., Schaut, R.A., and Pantano, C.G., "Tensile Strength of GFRP Bars Under Sustained Loading in Concrete Beams," *ACI Special Publication 230*, 7th International Symposium on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures, Eds. C.K. Shield, J.P. Busel, S.L. Walkup, and D.D. Gremel, October 2005, pp.1429-1446.
- Bank, L. C., Gentry, T. R., and Barkatt, A. (1995). Accelerated Test Methods to Determine the Long-Term Behavior of FRP Composite Structures: Environmental Effects. *Journal of Reinforced Plastics and Composites*, 14(6), 559–587.
- Benmokrane, B., Wang, P., Ton-That, T.M., Rahman, H., and Robert, J.F., "Durability of Glass Fiber-Reinforced Polymer Reinforcing Bars in Concrete Environment," *Journal of Composites for Construction*, Vol. 6, No. 3, August 1, 2002, pp. 143-153.
- Brown, V. L. and Bartholomew, C. L., "FRP Dowel Bars in Reinforced Concrete Pavements," *ACI SP 138-48*, 1993, pp. 813-830.
- Bunea, S. P., "Concrete Reinforced with GFRP (Glass-Fiber Reinforced-Plastic) in Lieu of Conventional Steel," *ACI SP 125-6*, 1991, pp. 97-124.
- Busel, J. P. "Fiber Reinforced Polymer (FRP) Composites Rebar," A. C. M. Association, FL-DOT, Tampa, FL., 2012.
- Carter, H. G., and Kibler, K., Langmuir-Type Model for Anomalous Moisture Diffusion in Composite Resins, *Journal of Composite Materials*, Vol. 12, pp.118-131, April 1978.
- Chen, Y., Davalos, J.F., and Ray, I.R., "Durability Prediction for GFRP Reinforcing Bars Using Short-Term Data of Accelerated Aging Tests," *Journal of Composites for Construction*, Vol. 10, No. 4, August 1, 2006, pp. 279-286.

- Chu, W., and Karbhari, V. M., "Effect of Water Sorption on Performance of Pultruded E-Glass/Vinylester Composites," *J. Mater. Civ. Eng.*, 17(1), pp. 63–71., 2005.
- Davalos, J.F., Chen, Y., and Ray, I., "Long-term durability prediction models for GFRP bars in concrete environment," *Journal of Composite Materials*, Vol. 46, No. 16, pp. 1899-1914.
- Debaiky, A.S., Nkurunziza, G., Benmokrane, B., and Cousin, P., "Residual Tensile Properties of GFRP Reinforcing Bars after Loading in Severe Environments," *Journal of Composites for Construction*, Vol. 10, No. 5, October 1, 2006, pp. 370-380.
- Dejke, V. and Tepfers, R., "Durability and service life prediction of GFRP for concrete reinforcement," Burgoyne C (ed.), *Proceedings of 4th International Conference on Fibre-Reinforced Plastics for Reinforced Concrete Structures FRPRCS-5*, Vol. 1, University of Cambridge, Cambridge, 2001, pp. 515–520.
- Ehsani, M. R., Saadatmanesh, H., and Tao, S.. 1993. "Bond of GFRP Rebars to Ordinary-Strength Concrete," *ACI International Symposium on Non-Metallic Continuous Reinforcement*, Vancouver, Canada, pp. 333-345.
- Fardis, M. N., and Khalili, H. H., "FRP-encased Concrete as a Structural Material," *Magazine of Concrete Research*, V. 34, No. 121, pp. 191-202, 1981.
- Fergani, H., Di Benedetti, M., Oller, C.M., Lynsdale, C., Guadagnini, M., "Durability and Degradation Mechanisms of GFRP Reinforcement Subjected to Severe Environments and Sustained Stress," *Construction and Building Materials*, Vol. 170, May 2018, pp. 637-648.
- fib Bulletin 40, *FRP Reinforcement in RC Structures*, September 2007.
- Gardoni, P., Trejo, D., and *Kim, Y. H., "Time-variant Capacity Model for GFRP Bars Embedded in Concrete," *ASCE Journal of Engineering Mechanics*, Vol. 139, No. 10, December 2012.
- Gooranorimi, O. and Nanni, A., "GFRP Reinforcement in Concrete after 15 Years of Service," *ASCE Journal of Composites for Construction*, 2017, Vol. 21, No. 5.
- Gurtin, M. E., & Yatomi, C. (1979). On a Model for Two Phase Diffusion in Composite Materials. *Journal of Composite Materials*, 13(2), 126–130.
- Gremel, D., Galati, N., and Stull, J., "Method for Screening Durability and Constituent Materials in FRP Bars," *ACI Special Publication 230*, 7th International Symposium on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures, Eds. C.K. Shield, J.P. Busel, S.L. Walkup, and D.D. Gremel, October 2005, pp. 153-164.
- Huang, S. and Aboutaha, R., "Environmental Reduction Factors for GFRP Bars Used as Concrete Reinforcement: New Scientific Approach," *ASCE Journal of Composites for Construction*, September/October 2010, Vol. 14, No. 5, pp. 479-486.
- Imjai, T., Guadagnini, M., and Pilakoutas, K., " Bend Strength of FRP Bars: Experimental Investigation and Bond Modeling," *ASCE Journal of Materials in Civil Engineering*, Vol. 29, No. 7, July 2017.
- Kajorncheappunngam, S., Gupta, R.K., and GangaRao, H.V.S., "Effect of Aging Environment on Degradation of Glass-Reinforced Epoxy," *Journal of Composites for Construction*, Vol. 6, No. 1, February 1, 2002, pp. 61-69.
- Karbhari, V.M., Stachowski, C., and Wu, L., "Durability of Pultruded E-Glass/Vinylester under Combined Hygrothermal Exposure and Sustained Bending," *Journal of Materials in Civil Engineering*, Vol. 19, No. 8, August 1, 2007, pp. 665-674.
- Khatibmasjedi, M. and Nanni, A., "Durability of GFRP Reinforcement in SEACON," *CDCC 2017 - The Fifth International Conference on Durability of Fiber Reinforced Polymer (FRP) Composites for Construction and Rehabilitation of Structures*, University of Sherbrooke, Quebec, CANADA, July 2017.

- Katsuki, F., and Uomoto, T. (1995), "Prediction of Deterioration of FRP Rods due to Alkali Attack," Proceedings of the Second International RILEM Symposium (FRPRCS-2), Non-Metallic (FRP) Reinforcement for Conc. Struct., L. Taerwe, ed., E&FN Spon, London, 83-89.
- Kim, Y.H., Gardoni, P., and Trejo, D., "GFRP-Reinforced Bridge Decks: Time-Variant Capacity and Reliability," Refereed, the First International Conference on Computational Technologies in Concrete Structures (CTCS09), Jeju, Korea, May 24-27, 2009.
- Kim, Y.H., Trejo, D., Gardoni, P. (2010), "Time-Variant Reliability Analysis and Flexural Design of GFRP-Reinforced Bridge Decks," Fifth International Conference on Bridge Maintenance, Safety and Management, Philadelphia, Pennsylvania, PA, July 11-15, 2010.
- Kim, Y.H., Gardoni, P., Trejo, D., "Time-Variant Capacity and Reliability of GFRP-Reinforced Bridge Decks," Submitted to the Second International Conference on Sustainable Construction Materials and Technologies, Ancona, Italy, June. 28-30, 2010.
- Kim, Y. H., Trejo, D., Gardoni, P., "Time-variant Reliability Analysis and Flexural Design of GFRP-reinforced Bridge Decks," ASCE Journal of Composites for Construction, Vol. 16, No. 4, August 2012, pp. 359-370.
- Mosley C. P.; Tureyen A. K.; Frosch R. J. (2008), "Bond strength of nonmetallic reinforcing bars" ACI Structural Journal, 5 (105): 634-642.
- Mufti, A.A., Onofrei, M., Benmokrane, B., Banthia, N., Boulfiza, M., Newhook, J.P., Bakht, B., Tadros, G.S., and Brett, P., "Durability of GFRP Reinforced Concrete in Field Structures," ACI Special Publication 230, 7th International Symposium on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures, Eds. C.K. Shield, J.P. Busel, S.L. Walkup, and D.D. Gremel, October 2005, pp. 1361-1378.
- Mufti, A.A., Onofrei, M., Benmokrane, B., Banthia, N., Boulfiza, M., Newhook, J.P., Bakht, B., Tadros, G.S., and Brett, P., "Field Study of glass-fibre-reinforced polymer durability in concrete," Canadian Journal of Civil Engineering, 34, 2007, pp. 355-366.
- Mufti, A., Banthia, N., Benmokrane, B., Boulfiza, M., and Newhook, J., "Durability of GFRP Composite Rods," Concrete International, February 2007, pp. 37-42.
- Mukherjee, A. and Arwika, S. J., "Performance of glass fiber-reinforced polymer reinforcing bars in tropical environments - Part 1: Structural scale tests, ACI Structural Journal, 2005, pp. 745-753.
- Nishizaki, I. and Meiarashi, S., "Long-Term Deterioration of GFRP in Water and Moist Environment," Journal of Composites for Construction, Vol. 6, No. 1, February 1, 2002, pp. 21-27.
- Nkurunziza, G., Benmokrane, B., Debaiky, A.S., and Masmoudi, R., "Effect of Sustained Load and Environment on Long-Term Tensile Properties of Glass Fiber-Reinforced Polymer Reinforcing Bars," ACI Structural Journal, V. 102, No. 4, July-August 2005, pp. 615-621.
- Park, Y., Kim, Y.H., Lee, S.H., Long-Term Flexural Behaviors of GFRP Reinforced Concrete Beams Exposed to Accelerated Aging Exposure Conditions, Polymers, 6, June 2014, pp. 1773-1793.
- Pyc, W., Field Performance of Epoxy-Coated Reinforcing Steel in Virginia Bridge Decks, PhD Dissertation, 1998, Virginia Polytechnic Institute and State University, Blacksburg, VA.
- Rahman, A.H., Taylor, D.A., and Kingsley, C.Y., (1993), "Evaluation of FRP as Reinforcement for Concrete Bridges", Proc. FRP Reinforcement for Concrete Structures, Int. Sympos., ACI SP-138, A. Nanni and C.W. Dolan, Eds., ACI, Farmington Hills, Michigan, pp. 71-82.
- Robert, M., Cousin, P., and Benmokrane, B., Journal of Composites for Construction, Vol. 13, No. 2, April 1, 2009, pp. 66-73.

- Robert, M. and Benmokrane, B., "Physical, Mechanical, and Durability Characterization of Preloaded GFRP Reinforcing Bars," *ASCE Journal of Composites for Construction*, July/August 2010, Vol. 14, No. 4, pp. 368-375.
- Robert, M. and Benmokrane, B., "Behavior of GFRP Reinforcing Bars Subjected to Extreme Temperatures," *Journal of Composites for Construction*, Vol. 14, No. 4, August 1, 2010, pp. 353-360.
- Schaefer, B., "Thermal and Environmental Effects on Fiber Reinforced Polymer Reinforcing Bars and Reinforced Concrete," M.S. Thesis, Texas A&M University, May 2002.
- Sekijima, K., Otsuka, Y., and Konno, T., "Durability of Fiber Reinforced Polymer Reinforcement Embedded in Concrete," *Fourth International Symposium on Fiber-Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, ACI Special Publication 188, Ed. by A. Nanni, C. Dolan, S. Rizkalla. Farmington Hills, MI, ACI International, August 1999, pp. 501-513.
- Sen, R. and Shahawy, M., "Accelerated Bond and Durability Testing of FRPs for Bridge Applications," SP 143, 1994, pp. 297-314.
- Sen, R., Mullins, G., and Salem, T., "Durability of E-Glass Vinylester Reinforcement in Alkaline Solution," *ACI Structural Journal*, V. 99, No. 3, May-June 2002, pp. 369-375.
- Tannous, F.E. and Saadatmanesh, H., "Environmental Effects on the Mechanical Properties of E-Glass FRP Rebars," *ACI Materials Journal*, V. 95, No.2, March-April 1998, pp. 87-100.
- Tannous, F.E. and Saadatmanesh, H., "Durability of AR Glass Fiber Reinforced Plastic Bars," *Journal of Composites for Construction*, Vol. 3, No. 1, February, 1999, pp. 12-19.
- Tottori, S., and Wakui, H. 1993. Shear capacity of RC and PC beams using FRP reinforcement. *ACI Structure Journal*, SP-138, 615-632.
- Trejo, D., Aguiñiga, F., Yuan, R.L., James, R.W., Keating, P.B., Characterization of Design Parameters for Fiber Reinforced Polymer Composite Reinforced Concrete Systems, Final Research Report FHWA/TX-03/1520-3, Texas Transportation Institute and Texas Department of Transportation, College Station, TX, September 2003, 280 pages.
- Trejo, D., Aguiñiga, F., Buth, G., Yuan, R. L., James, R. W., and Keating, P. B., Fiber Reinforced Polymer Bars for Reinforcement in Bridge Decks, FHWA/TX-05/9-1520-S, 2005.
- Trejo, D. and Reinschmidt, K., "Justifying Materials Selection for Reinforced Concrete Structures. II: – Economic Analysis," *Journal of Bridge Engineering*, January/February 2007, Vol. 12, No. 1, pp. 38-44.
- Trejo, D., Gardoni, P., Kim, J.J., and Zidek, J., Long-Term Performance of GFRP Reinforcement, Research Report 0-6069, February 2009, FHWA/TX-09/0-6069-1, 123 pages.
- Trejo, D., Gardoni, P., and Kim, J.J., "Long-Term Performance of Glass Fiber-Reinforced Polymer Reinforcement Embedded in Concrete," *ACI Materials Journal*, V. 108, No. 6, November-December 2011, pp. 605-613.
- Vijay, P.V. and GangaRao, H.V.S., "Accelerated and Natural Weathering of Glass Fiber Reinforced Plastic Bars, Fourth International Symposium on Fiber-Reinforced Polymer Reinforcement for Reinforced Concrete Structures, ACI Special Publication 188, Ed. by A. Nanni, C. Dolan, S. Rizkalla. Farmington Hills, MI, ACI International, August 1999, pp. 605-614.
- Waldron, P., Byars, E.A., and Dejke, V., "Durability of FRP in Concrete: A State of the Art," *International Workshop on Composites in Construction*, July 20-21, 2001, Capri, Italy.

- Wang, C., Xian, G., Ou, J., Durability study of GFRPP rebar in alkali, acid and salt solution, ACI Special Publication 275, 10th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures 2011, FRPRCS-10, in conjunction with the ACI Spring 2011 Convention - Tampa, FL, April 2011, pp. 1085-1094.
- Youssef, T. and Benmokrane, B., "Creep behavior and tensile properties of GFRP bars under sustained service loads," American Concrete Institute, ACI Special Publication. 2. 675-694, 2011.
- Zou, Y. and Huckelbridge, A., "Experimental Analysis of Crack Growth in GFRP Reinforced Concrete," Journal of Bridge Engineering, Vol. 12, No. 2, March 1, 2007, pp. 246-255.