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16. Abstract Fiber-reinforced polymers (FRP) are being increasingly used in the construction industry. One application is to use FRP bars as reinforcement in concrete. Glass fiber-reinforced polymer (GFRP) bars have been the focus of recent research because in corrosive environments they do not produce expansive corrosion products and the resulting concrete cracking and spalling associated with conventional steel reinforcement. Also, the initial cost of GFRP bars is lower than carbon FRP bars. During this research project, one challenge encountered with the use of GFRP bars was that limited guidance was available on what quality control and quality assurance parameters should be inspected. Also during this research project, standard testing procedures to assess key characteristics were only available in the Japanese literature. Thus, one objective of this research project was to provide guidance for the user on the following issues: 1) how to assess and test GFRP bars characteristics; and 2) how to assure that certain minimum quality levels have been achieved. This report provides this information.					
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**PRELIMINARY QUALITY CONTROL/QUALITY ASSURANCE STANDARDS
(CRITERIA) FOR INSPECTION AND TESTING OF FRP BARS**

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The researcher in charge of the project was Dr. David Trejo.

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I. INTRODUCTION

Although serious concerns still exist with the use of glass fiber-reinforced polymer (GFRP) reinforcing bars for concrete reinforcement, many researchers are continuing to investigate their performance with the objective of improving their performance. In past cases where GFRP bars have been used as reinforcement, limited guidance has been available on how to assess the mechanical and physical characteristics of these materials to ensure some minimum performance. At the start of this research limited guidance on test procedures was available. The research team reviewed the literature and in cases followed methods from the literature. In some cases the research team used test methods from the *Japanese Society of Civil Engineering's (JSCE) Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials* (1997). However, significant progress on testing of GFRP products has occurred over the last several years, especially within the American Concrete Institutes (ACI) Committee 440, Fiber Reinforced Polymer Reinforcement.

This report is presented so that important characteristics of GFRP reinforcement can be assessed to achieve some minimum level of quality. When test methods from ACI or JSCE are recommended, the reader will be directed to these corresponding documents for test information. It should be noted that in this document quality assurance is defined as a set of activities designed to ensure that the development and/or manufacturing process is adequate to ensure a material will meet their objectives (durability and serviceability). Of course, quality assurance is also performed in the manufacturing process but this report will not address quality assurance techniques used by the manufacturers. However, GFRP bars should be manufactured to assure some minimal serviceability and life expectancy. These qualities should be at least the minimum qualities of steel reinforcement. Quality control is defined here as a set of activities designed to evaluate a product, in this case, GFRP bars, for minimum levels of quality. This is accomplished with testing.

A quality control program is dependent on many factors. A quality control program for one agency may include evaluating all characteristics using the test procedures reported herein. Quality control programs for other agencies may include only select tests. It is the responsibility of the user to select a proper quality control program.

This report includes information on testing and minimum values (when available) for tensile strength, tensile modulus of elasticity, bond properties, shear strength, bent bar capacity, time-dependent characteristics, coefficient of thermal expansion, and residual strength and absorption of GFRP bars exposed to high pH environments. Methods for visually assessing GFRP bars and determining the cross-sectional characteristics of GFRP bars are also included. The bent bar capacity, some time-dependent characteristics, and the coefficient of thermal expansion tests were not performed as part of this project. However, a brief explanation of these tests is included for completeness.

II. TEST METHODS AND MINIMUM MATERIAL CHARACTERISTICS

Using GFRP reinforcing bars in infrastructure systems is relatively new. Challenges with implementing the use of this material has included the lack of standardized test procedures, quality control programs, and quality assurance. The following tests can be used to implement a quality control program. However, it should be noted that GFRP products continually change with the hopes of improving the properties and characteristics. As GFRP products are produced with different materials, the engineering properties and performance of these materials will change. As such, the following presentations are guidelines. The user must use good engineering judgment in implementing a quality control program.

As noted in [ACI 440.1R-03 \(2003\)](#), *Guide for the Design and Construction of Concrete Reinforced with FRP Bars*, quality control of GFRP bars should be performed by lot testing, either by the manufacturer or an independent, qualified third party. Manufacturers should provide the user with production run traceability. The [ACI 440 \(2003\)](#) document recommends evaluating the tensile strength, tensile modulus of elasticity, ultimate strain, fatigue strength, bond strength, coefficient of thermal expansion, and durability in alkaline environments. Additional testing should include static fatigue, a comprehensive visual assessment before placing the surrounding concrete, determining the cross-sectional characteristics of the bar, and when bent bars are used, evaluating the strength of these bent GFRP bars. Although [ACI 440 \(2003\)](#) recommends testing product “before or after any change in manufacturing process, procedure, or materials,” unless the manufacturer has shown that the product characteristics do not change with time within a defined manufacturing process, procedure, or set of materials, product testing should be performed at shorter intervals.

Visual Assessment

Results from this research project indicate that damage to the surface of GFRP bars can lead to significant reductions in durability and longer-term strength. However, limited guidelines are available for visually assessing GFRP bars. The objective of this section is to provide the user with general information on visually inspecting GFRP reinforcing bars. Because it is imperative that these bars be properly handled, transported, stored, and placed to minimize damage and maximize performance, a brief overview of handling, storing, and placing GFRP reinforcing bars is provided.

Improper handling of GFRP reinforcing bars can lead to surface damage, which can reduce the tensile capacity and durability of the bar. Results from this research project indicate that up to a 12% reduction in strength can occur after 50 weeks of exposure to simulated concrete pore solution (Trejo et al. 2003). Because of this, handling of the bars should be done in such a manner that surface damage is prevented. Deforming, heating, exposure to ultraviolet light, and other environmental exposure conditions (water, salt water, etc.) can change the material properties. As such, storage of the bars should be done to prevent exposure to these conditions. GFRP bars should be transported and stored in containers that protect the bars from property changing environmental exposure conditions. Figure 1 shows two scenarios where proper care was taken to transport the bars in wooden boxes, however, the storage conditions at the



Figure 1. Improper storage of GFRP bars at construction site.

construction site were not appropriate. Storage of GFRP bars at the construction site should be such that exposure conditions do not change the properties of the bars.

The surface of GFRP bars should not be damaged at any time. GFRP bars can be damaged during placement, prior to concrete placement, and during concrete placement. Because damaged surfaces can exhibit significant reductions in strength and durability of the bars, care must be taken to prevent surface damage during these times. [Figure 2](#) shows where a GFRP bar was burnt near an area where steel was flame cut. The integrity of this bar was likely significantly reduced. [Figure 3](#) shows workers vibrating the concrete on a deck reinforced with GFRP bars. Care must be taken to prevent surface damage to the GFRP when consolidating the concrete.



Figure 2. Burnt GFRP bar.



Figure 3. Consolidating concrete around GFRP bars.

Proper handling, transportation, site storage, and protection of GFRP bars should be practiced to prevent damage to the surface of GFRP bars. Such damage could result in reductions in strength and longer-term durability. When the surface of GFRP bars is visibly damaged replace these damaged bars with undamaged bars that are long enough to provide lap or development of the undamaged bars past the damage section.

Cross-section Characteristics

The amount of longitudinal fiber in a GFRP reinforcing bar is critical for determining the bar's engineering properties. Because the fibers are embedded in a

polymer filled matrix (60-70% fiber volume fraction) it is convenient to use actual or nominal area of the bar cross-section when determining such properties. Because some GFRP bars have non-circular cross sections, a methodology is needed to

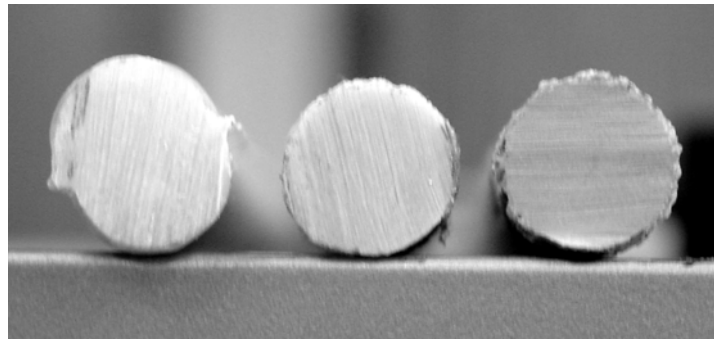


Figure 4. Cross-sections of different GFRP bars (Trejo et al. 2003).

determine area and equivalent diameter and circumference values. Figure 4 shows typical cross-sections of GFRP bars from different manufacturers. ACI 440.3R-04 (2004), *Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures*, provides guidance on how to determine these values. The reader is encouraged to review this document. Limited work has been performed on how non-circular cross-sections influence the performance of reinforced concrete systems and no guidance is provided on limits for non-circular bars.

Tensile Strength

GFRP reinforcing bars are anisotropic due to the aligned glass fiber orientation. The critical property of these reinforcing bars is the longitudinal tensile strength. The research in this project found that the tensile strength is a function of exposure time (where exposure time is defined as the time the bar is exposed to humid, moist, or wet conditions), with lower tensile strengths observed at longer exposure times. It is well known that the tensile strength is a critical design parameter and as a result of this the tensile properties should be evaluated under most conditions. Because GFRP bars deteriorate and lose strength as a function of exposure time, tests should also be performed on exposed bars to predict the later age tensile characteristics.

ACI Committee 440 (2004) and JSCE provide test guidelines for evaluating the tensile strength of GFRP bars. ACI 440 (2004) test method B.12, *Test Method for*

Longitudinal Properties of FRP Bars, provide detailed procedures for evaluating the tensile strength of unexposed GFRP bars. [ACI 440 \(2004\)](#) test method B.6, *Accelerated Test Method for Alkali Resistance of FRP Bars*, and [JSCE \(1997\)](#) E 538-1995, *Test Method for Alkali Resistance of Continuous Fiber Reinforcing Materials*, provide guidelines for evaluating the change in tensile strength as a function of exposure time. The reader is encouraged to review these documents for specifics on these tests.

[ACI 440 \(2003\)](#) recommends that tensile properties of FRP bars should be obtained from the manufacturer and recommends that this value be a guaranteed tensile strength, f_{fu}^* . This guaranteed tensile strength, f_{fu}^* , is defined as being the mean value of the tensile strength of a set of bars minus three times the standard deviation. The manufacturer must be careful that the sample size (typically greater than 25 to 30 samples) is sufficiently large and representative of the entire production run. If this is not the case, more detailed analyses should be performed. In any case, the manufacturer should report the number of samples tested and the sampling method used to select test samples.

Because the tensile strength of GFRP bars in concrete deteriorate with exposure time it is necessary to determine the rate of deterioration of these bars. As already noted, ACI and JSCE provide test methods for exposing the bars. The reader is encouraged to review these standards. The bars can be exposed to simulated concrete pore solution or directly to the concrete. Much debate exists on the applicability of exposing GFRP to simulated concrete pore solution. Exposing GFRP bars to simulated concrete pore solution likely better represents the deterioration rate of saturated concrete. The rate of loss of tensile strength is likely lower for unsaturated conditions. However, more research is needed to determine this. Testing under stressed conditions will likely better represent the actual rate of strength loss. As such, at this time, it is recommended that the lower values of tensile strengths of stressed samples be used to estimate the strength reduction of GFRP bars. It is also recommended that testing of these bars be performed well beyond the 6 months recommended in the [ACI 440 \(2004\)](#) document.

Once these data are obtained the service life of the structure can be determined by fitting a best fit line through the lower data points and determining the time in which the tensile strength of the deteriorating bars is equivalent to an environmental reduction factor, C_E (0.8 for GFRP reinforced concrete not exposed to earth and weather and 0.7 for GFRP reinforced concrete exposed to earth and weather), multiplied by the guaranteed tensile strength. Results from testing in this project indicate that the residual tensile strength of unstressed GFRP bars exposed to simulated solution will be lower than the product of the environmental reduction factor for weather exposure and the guaranteed tensile strength after approximately 7 years. It is believed that had testing been performed in stressed conditions this time would have been significantly shorter. Of course, stressed samples embedded in unsaturated concrete conditions would likely be longer than the stressed conditions in simulated concrete pore solution.

Tensile Modulus of Elasticity

One of the challenges associated with the use of GFRP bars is the low modulus of elasticity of this product. Lower modulus of elasticity values present challenges in the design process and can lead to more and/or larger cracks in a GFRP reinforced structure. However, significant work has been performed to develop design guidelines with GFRP reinforcement. For information on testing GFRP reinforcing bars for tensile modulus of elasticity the reader is directed to [ACI 440 \(2004\)](#) test method B.2, *Test Method for Longitudinal Tensile Properties of FRP Bars*, and [JSCE-E 531-1995 \(JSCE 1997\)](#), *Test Method for Tensile Properties of Continuous Fiber Reinforcing Materials*. Information on design using GFRP reinforcement that exhibits low modulus of elasticity values (compared to steel) can be found in [ACI 440 \(2003\)](#) and [JSCE \(1997\)](#) documents.

[ACI 440 \(2003\)](#) reports a range of modulus of elasticity values for GFRP bars from 5.1×10^6 to 7.4×10^6 psi. All mean values of modulus of elasticity for the unexposed reinforcement tested in this research project fell within this range. After exposure, several mean values were closer to the minimum value of this range and below the 5.8×10^6 psi minimum specified by the TxDOT's special specification for GFRP bar

reinforced concrete slab. Several results were also lower than the ACI minimum. Further research is needed to investigate the change in modulus of elasticity as a function of time exposed to a concrete environment.

Bond and Development Length

The bond characteristics of GFRP bars are influenced by the following: the manufacturing process for the bar, the surface conditions of the bar, the environmental exposure conditions and time of exposure, the test method, and other factors. [ACI 440 \(2003\)](#) states that the bond capacity of GFRP bars is independent of concrete strength when adequate cover is provided. The reader is directed to [ACI 440 \(2004\)](#) test B.3, *Test Method for Bond Strength of FRP Bars by Pullout Testing*, and [JSCE-E 540-1995 \(1997\)](#), *Test Method for Bond Strength of Continuous Fiber Reinforcing Materials by Pullout Testing*, for test procedures to evaluate the bond of GFRP. [ACI 440 \(2003\)](#) recommends that bond values be obtained from the manufacturer but also provides a conservative estimate of the basic development length of FRP bars controlled by pullout failure as follows:

$$l_{bf} = \frac{d_b \cdot C_E \cdot f_{fu}^*}{2700} \quad (1)$$

where d_b is the bar diameter in inches and C_E and f_{fu}^* have already been defined. The results of this research indicate that the ACI 440 equation is adequate. [JSCE \(1997\)](#) proposes an alternative and more complex equation for development length. However, because the [ACI 440 \(2003\)](#) equation seems to be adequate, discussions on the JSCE method for determining development length will not be discussed here. If the reader would like more information on the JSCE method for determining development length the reader is directed to section 10.5.3 of the [JSCE \(1997\)](#) document.

Shear Strength

The shear strength of GFRP reinforcement could be used for determining the contribution of longitudinal bars in terms of dowel action. However, because limited

work has been performed for this application, neither [ACI \(2003\)](#) nor [JSCE \(1997\)](#) provide recommendations for this. Results from the research in this project indicated that all bar types had mean shear strength values that exceeded 21,000 psi. In most cases, the shear strength decreased with exposure time. More research is needed to determine the contribution of longitudinal GFRP reinforcement in terms of dowel action.

Bent Bar Capacity

This research project did not evaluate the capacity of bent GFRP bars. All GFRP bars tested in this research project were made of thermoset resins and bending of these bars was not possible due to the nature of thermoset resins used of these bars. However, it is well established that bars bent prior to curing of the thermoset resin exhibit significant reductions in capacity. [JSCE \(1997\)](#) provides no guidance on testing bent GFRP bars. [ACI 440 \(2004\)](#) test method B.5, *Test Method for Bars Strength of FRP Bent Bars and Stirrups at Bent Locations*, provides guidelines for testing bent bars. Because no research was performed in the research project on this topic the reader is encouraged to review the ACI 440 documents ([2003](#), [2004](#)) to determine testing methods and minimum strength requirements.

Time-Dependent Characteristics

Two types of fatigue characteristics will be described here: static fatigue (also known as creep rupture) and conventional fatigue due to cyclic loading. When fiber-reinforced polymer bars are subjected to constant load over time these bars can suddenly fail due to static fatigue. [ACI 440 \(2003\)](#) states that glass fibers, and thus GFRP bars, are most susceptible to static fatigue. This ACI document also notes that little work has been performed on GFRP reinforcing bars. However, this document references an investigation by [Seki et al. \(1997\)](#) that show an extrapolated 45% reduction in tensile strength after 50 years. More research is needed in this area and users must consider this reduction in property during design.

[ACI 440 \(2003\)](#) also notes that cyclic tensile fatigue can reduce the static tensile capacity of GFRP bars by 10% per decade of logarithmic time. This indicates that a 60% reduction in the static tensile strength of GFRP bars could occur after 1 million cycles. Although this research did not investigate the fatigue characteristics of the GFRP bars evaluated in this project, GFRP-reinforced concrete sections were evaluated under cyclic loading conditions. With the exception of one test, the reduction in beam capacity for most beams was less than 13% after at least 1.9 million cycles. However, the deflection of the beams under cyclic loading did increase with increased cyclic loading.

[ACI 440 \(ACI 2004\)](#) method B.7, *Test Method for Tensile Fatigue of FRP Bars*, and JSCE-E 535-1995 ([JSCE 1997](#)), *Test Method for Tensile Fatigue of Continuous Fiber Reinforcing Materials*, may be used to assess the fatigue characteristics of GFRP bars. However, because only limited research has been performed in the area of fatigue of GFRP reinforcement bars, no recommendations can be provided at this time on minimum quality control values. The user should be aware that significant reductions in GFRP reinforcement strength could occur under static and cyclic loading conditions. [ACI 440 \(2003\)](#) limits the creep rupture stress for GFRP bars to 20% of the guaranteed tensile strength. According to TxDOT design notes the GFRP bars of the deck of the Sierrita de la Cruz Creek Bridge have a calculated maximum service stress of less than 15 percent and a sustained service stress of less than 5 percent of the specified guaranteed tensile strength of the bars.

Coefficient of Thermal Expansion

One advantage of GFRP reinforcing bars is that these bars do not exhibit the classical cracking and spalling caused by the corrosion of metallic materials. Although glass fibers do corrode and lose strength (see [ACI 440 \[2003\]](#) section 3.3.2), the corrosion products are non-expansive. Although these corrosion products are non-expansive, volume changes in GFRP bars can occur. Gentry (1999) reported that the transverse coefficient of thermal expansion of FRP bars ranged from 4 to 9 times that of

concrete. For GFRP-reinforced structures directly exposed to the environment, this thermal expansion could result in cracking of the concrete cover. JSCE (1997) E 536-1995, *Test Method for Coefficient of Thermal Expansion of Continuous Fiber Reinforcing Materials by Thermo-mechanical Analysis*, provides guidelines on how to evaluate this material characteristic. ACI 440 (2004) provides no guidance on evaluating this parameter.

Testing performed as part of this project did not include standardized test procedures. However, the research indicated that cracking did not occur when the temperature of GFRP reinforced samples was raised to greater than 50 °F above the temperature of the concrete samples when fabricated. Also, field observations of the Sierrita de la Cruz Bridge, which was partially constructed with GFRP bars, did not show signs of thermal cracking above the GFRP bars. Although low concrete covers and low concrete strengths could lead to thermal mismatch cracking of the concrete cover under extreme conditions, cracking caused by thermal mismatch of GFRP reinforcing bars with adequate concrete cover (> 1 inch) and strength (> 5900 psi) should not be an issue. Other conditions not evaluated in this research need further evaluation.

III. SUMMARY

Although GFRP bars for concrete reinforcement have been manufactured from some time, they have recently been experiencing more frequent use in infrastructure systems. This report identified some key characteristics of GFRP bars that should be evaluated prior to their use in reinforced concrete infrastructure systems. The reader should be aware that limited long-term information is available on the use of GFRP bars for reinforcement in concrete and the reader should be cautious in developing and implementing a quality control program. The suite of tests and proposed quality control program described above should provide the minimum needed to evaluate the characteristics of GFRP reinforcing bars.

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