Experimental Research on Material Behaviour of Glass Fiber Reinforced Polymer Bars in Tension

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Abstract

Glass Fiber Reinforced Polymer (GFRP) rebars have been widely used to solve the corrosion problem of steel bars in concrete structures. It has been produced as a lightweight and corrosion-resistant than steel reinforcement in many structural applications. They are regarded as a promising substitute for steel bars in concrete infrastructures. It is necessary to test GFRP bars to fully understand their material properties to ensure the safe and efficient use of the material. In this study, five specimens of each type of GFRP bars with a diameter of 6, 8, 10, 12, and 14 mm were tested under tension. Therefore, a total of 25 samples were examined from the same manufacturer. According to ASTM’s recommendations (D7205/D7205M-06) for tensile tests of GFRP bars, the diameter and thickness of the steel pipes for both ends were considered in the preparation of the test specimens to keep the GFRP bars consistent and aligned throughout the experiment. The experimental test results included the stress-strain curves, tensile strength, ultimate strain, and modulus of elasticity. The study showed an accurate result that indicated the tensile strength of the GFRP bars can be expressed by a linear distribution. For a bar diameter of 10mm, the length to diameter ratio $L_e/d_b=8$ showed a maximum tensile to compressive strength ratio. In the failure results of the test, there were two-mode failures of GFRP bars: fracture failure and pull-out failure of GFRP bars. Most of the specimens had GFRP bar fracture failures, only two specimens (GBT1-10-2 and GBT1-10-3) were damaged due to the pull-off of the GFRP bars which was not a typical failure mode.

Keywords: GFRP Bars, Tensile Test, Stress-Strain Curve, Fracture Failure

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1. Introduction

Structural engineers are frequently faced with repairing components of civil infrastructures. Many buildings and highways are structurally deficient, resulting from common problems such as the age of the structure, change in the use of the structure, and deterioration due to environmental exposure. A traditional method of rehabilitating deficient members is steel plate bonding. Over time it was revealed that this method suffered from several disadvantages, such as the difficulty of the installation, the complexity of handling, and the corrosion susceptibility [1]. To solve this problem, an externally bonded fiber-reinforced polymer (FRP) reinforcement is being researched and used to repair and rehabilitate damaged concrete structures as an alternative to the steel plate bonding repair process [1]. FRP bar has several advantages that aid in structural integrity. The composite material is lightweight, non-corrosive, and it is relatively easy to handle. Because FRP bar will be exposed to different types of loads and environments over long periods of service life, the durability of the material must be investigated. The majority of research to date has focused on short-term strengthening without considering the effects of sustained loading and long-term environmental conditions [1]. The durability of concrete structures has always been a great concern. The corrosion of steel reinforcement is one of the most pressing issues in managing durability. Examples of critical structures susceptible to reinforcement corrosion are coastal structures, chemical industry sites, harbors, and bridges. Using an alternate reinforcement material is one solution to this problem. GFRP bars are made of composite fibers and have various distinct characteristics, such as excellent fatigue behavior, high strength to weight ratio, high tensile strength, and non-conductivity [2].

Glass fiber reinforced polymer bars are increasingly used by engineers when designing structures because of their excellent strength properties. This material strength is characterized by its capacity to bear a load without excessive deformation or failure [3]. When a sample of GFRP bar is tested under axial force, the applied force divided by the area of the cross-section (stress) is proportional to the ratio between the change in length and its initial length (strain). GFRP bar gets back to its original shape and length when the applied load is removed. In other words, under axial forces, GFRP bars have linear elastic action [3].

The key mechanical properties governing the structural behaviour of these elements when used as reinforcement
in concrete flexural elements are their tensile strength, bond properties, and elastic modulus [2]. GFRP (glass fiber reinforced polymer) composites are now widely used in the manufacturing industries especially in the aircraft, aerospace, and automotive industries due to their outstanding mechanical and thermal properties such as more specific strength, better specific elasticity modulus, high damping factor, or damping capacity, better corrosion resistance, efficient fatigue resistance, and low thermal expansion coefficient. Hence, the machinability behavior of these composites [4] must be understood. Drilling is commonly used in the aforementioned industries to assemble the elements. Because of their isotropic nature and in-homogeneity, the machining of these composites is unlike traditional metals. Fiber pull-out, delamination, and burring of fibers are major disadvantages of these composites in machining. In the machining of GFRP composites, a sufficient set of process parameters is, therefore, an essential concern [4].

The most notable distinctions between GFRP bars and steel-reinforced structures are the significantly low elasticity modulus and the absence of any yield behavior. For a structure, ductility is inelastic energy dissipation that enables internal forces to be redistributed when the structure is near failure, which is typically provided by steel's yield behavior. The GFRP bars themselves cannot be relied upon to provide any ductility, as the bars have limited inelastic energy dissipation due to linear stress-strain behavior before rupture. This implies that to prevent catastrophic failures, failure mechanisms must be carefully considered in GFRP RC design. Ductility must be integrated into the system as a whole, which can be accomplished by introducing redundancy into the framework. In the case of localized failure, a redundant system enables the redistribution of loads. GFRP bars will stretch approximately 20 mm per meter of original length before failure giving a warning by producing large deflections and wide cracks [5].

As creep-rupture is a brittle and unexpected failure mechanism that can occur due to sustained loads exceeding a certain percentage of the ultimate strength, the long-term behavior of GFRP bars must be considered in the design. It is widely accepted that a GFRP RC section would need to be over-reinforced for most structural applications, which corresponds to a reinforcement ratio greater than about 0.5 percent (fib 2007) for GFRP bars [6]. Currently, there is no standardized procedure for GFRP bar manufacture, so there can be significant variations in the properties of 'similar' products from different manufacturers [5].

Subsequently, global output grew exponentially hitting the current development in the late 1960s [7]. The combination of low material, manufacturing costs, and developments in member manufacturing rendered polymer production to be cost-effective and disseminated to other fields. Furthermore, due to its outstanding manufacturing adaptability, high resilience, and structural performance (strength-to-weight ratio), GFRP bars offer very versatile design solutions and benefit from increasingly low production and erection costs [8,9,10,11].

The process of producing composite materials by mixing two different materials is not new. Ancient Egyptians used a straw to strengthen mud to create a stronger composite material. Only a later version of this concept is the fiber-reinforced polymer. The use of Fiber Reinforced Polymer (FRP) bars goes back to the 1950s after World War II in various fields such as the aerospace and automotive industries. Nowadays different parts of today's vehicles are made of composites. Many large parts of modern aircraft are made out of composites as they are lighter and more fatigue resistant compared to traditional materials [12].

Bennokrane et al. (2000) [13], tested four different types of FRP bars in tension using a similar test setup to ASTM D7205/7205M-06 [14]. The tested specimens they used had a length of 1600 mm and were embedded in 600 mm steel anchors that had an inner diameter of 30 mm that was grouted with high-performance resin grout. At the end of the test, they were able to achieve failure in the free length indicating that the test can be used to determine the ultimate tensile strength of the bars.

Arzewska P., Polak M.A., and Penlidis A. (2019) [15] tested the determination of tensile characteristics of GFRP bars including the tensile strength, ultimate strain, and elasticity modulus according to different test standards. Test results for tensile characterization were obtained on four types of GFRP bars from four manufacturers with six different diameters. Besides, according to seven criteria, the analysis contrasts different test procedures to describe the tensile properties of GFRP bars to analyze the proposed test procedures and to expose the key differences.

The overall objective of the study is to define and assess the overall adequacy of the use of GFRP reinforcing products as a substitute for reinforced concrete steel reinforcement. Due to a lack of information about the actions of such participants, the efficient use of GFRP reinforcement in deep members has been hindered. To date, most studies have concentrated primarily on the flexural or shear behavior of longitudinally reinforced shallow members with GFRP and most of them used small-scale research. Therefore, this study aims to provide engineers and researchers with a better understanding of the analysis and behavior of tensile GFRP reinforced members. The results obtained throughout this study characterize the tensile behavior of GFRP bars and present an experimental
study to examine the proposed test method that addresses the issues.

2.0 EXPERIMENTAL BEHAVIOR

Overall, this test method presents a GFRP bar embedded at the end using adhesive anchors and steel caps, to be tested consistently under tensile load until it fails in a mechanical testing machine. The aim of developing this test method was to assist researchers and designers in assessing tensile strength, elasticity modulus, and stress-strain curve. The gripping and alignment are performed during the test specimen preparation process. By confining the ends of GFRP bars, the steel cap and adhesive anchors act as a gripping method to prevent premature failure and allow them to obtain their maximum tensile capacity. Besides, when the adhesive anchors are mounted, the alignment can simply be carried out, which can prevent unnecessary bending and premature failure and improve the accuracy of test results. For each test condition, testing five specimens is recommended to record clear and agreed data sets.

Steel cap, plastic cover, rivet, and adhesive anchors are among the components of the test fixture. It is suggested that the diameter of the steel cap be considered twice the effective bar diameter, although its length is recommended to be the same as the effective bar diameter. The steel cap must be dense enough not to be yielded or distorted by the adhesive anchor lateral strain. To give a free length equal to twice its diameter, the steel cap should be connected to a plastic cover with a square cross-section.

The process starts with the preparation of specimens by preparing steel caps, then setting up GFRP bars for the first end of the specimen while monitoring the orientation, and ending with doing the same for the other end. Fully smooth and perpendicular to its longitudinal axis must be the ends of the GFRP bar. It is important to check the orientation of the specimen if it is positioned in the center and perpendicular to it. After positioning the GFRP bar at the center of the steel cap, insert the rivets into the steel cap and add adhesives to it. If the preparation is finished, by applying a uniform and monotonic tension force, the specimens can be examined. If no premature cap failure is detected, the test results are deemed appropriate. In other words, if the breakage of GFRP bars occurs at the free length of the specimen, the experiments are completed successfully.

![Figure 1. The physical picture of the GFRP tendon.](image)

2.1 Test Plan

The tensile properties of GFRP bars of five different diameters have been evaluated in this test and the effect of the diameter on the tensile properties of GFRP bars has been analyzed. To ensure the reliability of the test results, a total of five groups having 25 test pieces were analyzed for 5 test pieces in each group.
2.2 Test Materials

2.2.1 GFRP bars

The GFRP bar developed by Zhejiang Xinna Composite Material Co., Ltd. with diameters of 6, 8, 10, 12, and 14mm is the material used in this test. Due to the high demand for building infrastructure, these bars were chosen. Figure 2 demonstrates the physical image of the tensile test piece.

![Figure 2. The physical picture of GFRP tendons.](image)

2.2.2 Adhesives (504AB Glue)

According to GB/T 30022-2013 specification, make a GFRP tendon test piece. During the manufacturing process, first put one end of the galvanized steel pipe. Seal, then pour 504AB glue on the other end until it is about to overflow, and then insert the GFRP tendon into the tube and center it. Consider the adhesion between the steel pipe and the 504AB glue that may not be enough. Insert 4 rivets in advance at the end where the steel pipe is sealed. In this way, it improves the adhesion between the steel pipe and the glue which enables the GFRP tendons to be better centered.

![Figure 3. The physical picture of 504AB Glue.](image)

Table 1. Tensile specimen grouping.

| D (mm) | L_T (mm) | L_e (mm) | Quantity |
|--------|----------|----------|----------|
| 6      | 1000     | 400      | 5        |
| 8      | 1000     | 400      | 5        |
| 10     | 1000     | 400      | 5        |
| 12     | 1000     | 400      | 5        |
| 14     | 1000     | 400      | 5        |

D= Diameter, L_T= Total Length, L_e= Effective Length

Table 2. GFRP tendon design matrix.

| No. | Material        | Specification                  | Quantity |
|-----|-----------------|--------------------------------|----------|
| 1   | Galvanized      | thickness 2mm, length 300mm    | 50       |
| 2   | 504AB glue      |                                | 40       |
| 3   | Rivet           | length 50mm, thickness 3mm     | 200      |
2.2.3 Steel cap

The functions of the steel cap are holding the GFRP bar, alignment, gripping action, and strengthening the ends of the specimens. The ease of alignment and gripping are the advantages of using the steel cap filled with high strength and fast setting anchoring adhesive. The alignment is controlled once GFRP is inserted into the steel cap filled with adhesives to align the GFRP bar and steel cap. It is necessary to cut the ends of the GFRP bars perpendicular to the longitudinal axis of the bars and to place the bars at the center of the steel caps. Then, a level at the flat surface of the GFRP bar can give the required alignment. For the second steel cap, the process should be repeated once the adhesive is fixed. The steel caps offered a solid capping for the GFRP bar after the adhesive was set, to avoid any premature crushing at the ends. The lateral containment of the steel rings filled with an adhesive provided by the end of the GFRP bar helps to prevent localized crushing of the ends of the GFRP bar.

![Steel cap](image)

**Figure 4.** The physical picture of a steel cap.

2.2.4 Rivet

Mechanical fasteners such as rivets or bolts are also used to fasten GFRP laminates. A rivet is a mechanical fastener composed of a head on one end and a cylindrical stem on another (called the tail) which has the appearance of a metal pin. They won't loosen when subjected to vibration and can secure joints with short clamp lengths. Choosing the correct size of the rivet while mounting makes the test samples vibration-resistant and permanent.

![Rivet](image)

**Figure 5.** The Physical Picture of a Steel Cap.

2.2.5 Plastic cover

The plastic cover used during sample fabrication was a PVC material which prevented the adhesive material from pouring out of both ends of the specimens. It was placed on both the top and bottom of the specimen by using 502 super glue.

![Plastic cover](image)

(a) Plastic cover (b) 502 super glue (c) Steel cap

**Figure 6.** Placement of plastic cover on both ends of the steel cap.
2.3 Test Scheme
In this study, GFRP bars with five different diameters of 6, 8, 10, 12, and 14 mm were prepared, with a total length of 1000 mm. The length of the GFRP test piece includes the anchor length of 300 mm at both ends and the effective length of 400 mm in the middle for all specimens. The geometric dimensions and schematic diagram of GFRP bars are shown in Figure 6 below.

2.4 Test Equipment and Loading Scheme
The overall prepared specimens of GFRP bars were conducted by utilizing the 1000 kN electro-hydraulic servo universal testing machine under tension loading. The loading method adopts displacement loading and a loading rate of 5mm/min. The relation between the load and displacement was linear until an abrupt drop in the load occurred indicating the occurrence of failure without showing any plateau or any kind of ductile behavior. The test samples showed brittle behavior. As shown in Figure 8, the data was collected with effective gauge length and GFRP tendons for different diameters were used for the tensile test.
2.5 Design Guidelines for Structures Reinforced with GFRP bars
FRP reinforcement is linear elastic up to failure and in general, it can develop much greater tensile strength than steel reinforcement, but is less stiff, having an elastic modulus as low as 30,000 N/mm². As a result, FRPs can lead to RC structures with very different behavior from conventional RC. The design guidelines for the United States are based on improvements to the steel code of practice of the American Concrete Institute (ACI) and contain information collected from worldwide studies and field applications. They support both compressive (concrete crushing) and tensile (FRP bar rupture) failure modes, but depending on the intended failure mode, strength reduction factors differ (ACI Committee 440, 2006) [16]. The guideline's recommendations are meant to be conservative (Fico, 2008) [17].

2.6 Sample Preparation
The specimens for the tensile test were prepared according to the ASTM D7205 [18] guidelines. The total length (Lₜ) of the tensile specimen was 1000mm. The free length between the steel tube anchors (Lₑ) was 400mm. A steel tube with an outside diameter d of 21mm, inside diameter dᵢ of 19mm, and seamless length of 300mm. The epoxy resin and hardener were used to fill the void between the bars and the steel tubes. For proper alignment, the steel tubes and bars were mounted vertically in a wooden frame. The first anchor was turned upside down after 72 hours and the same process for the second anchor was repeated. According to the requirements given by the resin manufacturers, in standard indoor laboratory conditions, the total setting time for both sample anchors was 72 hours.

2.7 Calculation of Tensile characteristics
The tensile test was conducted using a universal testing machine with a capacity of 600kN at the strength of the materials laboratory. The loading rate was at 5mm/min until the failure of the tensile specimen.

2.7.1 Tensile strength
It varies with the cross-sectional dimensions of the bar due to the shear lag effect and therefore tensile strength should be referenced based on the bar size. To determine the tensile strength, the tensile strength of GFRP bar samples was determined according to Equation 4.1

\[ f_{t} = \frac{F_{t}}{A} = \frac{4F_{t}}{\pi d^{2}} \]

Where \( f_{t} \) is tensile strength in MPa; \( F_{t} \) is the tensile ultimate load value of the test piece in N; \( d \) is the diameter of the test piece in mm.

| No. | Specimen No. | D (mm) | A (mm²) | Lₜ (mm) | Lₑ (mm) |
|-----|--------------|--------|---------|---------|---------|
| 1   | GBT1-6-1     | 6.00   | 28.27   | 1000    | 400     |
| 2   | GBT1-6-2     | 6.00   | 28.27   | 1000    | 400     |
| 3   | GBT1-6-3     | 6.00   | 28.27   | 1000    | 400     |
| 4   | GBT1-6-4     | 6.00   | 28.27   | 1000    | 400     |
| 5   | GBT1-6-5     | 6.00   | 28.27   | 1000    | 400     |
| 6   | GBT1-8-1     | 8.00   | 50.27   | 1000    | 400     |
| 7   | GBT1-8-2     | 8.00   | 50.27   | 1000    | 400     |
| 8   | GBT1-8-3     | 8.00   | 50.27   | 1000    | 400     |
| 9   | GBT1-8-4     | 8.00   | 50.27   | 1000    | 400     |
| 10  | GBT1-8-5     | 8.00   | 50.27   | 1000    | 400     |
| 11  | GBT1-10-1    | 10.00  | 78.54   | 1000    | 400     |
| 12  | GBT1-10-2    | 10.00  | 78.54   | 1000    | 400     |
| 13  | GBT1-10-3    | 10.00  | 78.54   | 1000    | 400     |
| 14  | GBT1-10-4    | 10.00  | 78.54   | 1000    | 400     |
| 15  | GBT1-10-5    | 10.00  | 78.54   | 1000    | 400     |
| 16  | GBT1-12-1    | 12.00  | 113.10  | 1000    | 400     |
| 17  | GBT1-12-2    | 12.00  | 113.10  | 1000    | 400     |
| 18  | GBT1-12-3    | 12.00  | 113.10  | 1000    | 400     |
| 19  | GBT1-12-4    | 12.00  | 113.10  | 1000    | 400     |
| 20  | GBT1-12-5    | 12.00  | 113.10  | 1000    | 400     |
| 21  | GBT1-14-1    | 14.00  | 153.90  | 1000    | 400     |
| 22  | GBT1-14-2    | 14.00  | 153.90  | 1000    | 400     |
| 23  | GBT1-14-3    | 14.00  | 153.90  | 1000    | 400     |
| 24  | GBT1-14-4    | 14.00  | 153.90  | 1000    | 400     |
| 25  | GBT1-14-5    | 14.00  | 153.90  | 1000    | 400     |

D=Diameter; A=Area; Lₜ=Total length; Lₑ=Effective length
2.7.2 Ultimate strain

It is the strain that is corresponding to the maximum stress point on the stress-strain curve, and the material will fail after reaching this point. The ultimate strain of GFRP bar samples was determined according to Equation 4.2.

\[ \varepsilon_t = \frac{F_t}{E_{ft}A} \]  

(4.2)

Where \( F_t \) is the tensile ultimate load value of the test piece in N; \( E_{ft} \) is the tensile elastic modulus in GPa; \( A \) is the cross-sectional area of the test piece in mm\(^2\).

2.7.3 Modulus of elasticity

It is the slope of load–strain curve obtained from an extensometer or strain gauge readings. Equation 4.3 is used to calculate the value of the modulus of elasticity:

\[ E_r = \frac{\Delta \sigma_t}{\Delta \varepsilon_t} \]  

(4.3)

Where, \( \Delta \sigma_t \) is the difference in applied tensile stress between the starting and ending points in MPa; \( \Delta \varepsilon_t \) is the difference in tensile strain between the starting and ending points in %.

2.8 Failure Modes

In the failure results of this test, GFRP tendons have two failure modes: tensile failure of GFRP tendons and pull-off failure of GFRP tendons.

2.8.1 GFRP Tendons Pulled-off Failure

In this test result, only two test pieces with a diameter of 10 mm were damaged due to the pull-off of the GFRP rib ends. The samples were GBT1-10-2 and GBT1-10-3, as shown in Figure 9.

![Figure 10. GFRP tendons at the end of the pull-off failure](image)

2.8.2 GFRP Tendons Fracture Failure

Among the failure specimens obtained in this test, most specimens had GFRP tendon fracture failure, as shown in Figure 10. Most of the failure mechanisms found from the tension test were performed as defined by the fracture of the fibres in the free length of the bars. Besides, the form of failure was a brittle type of failure as predicted where the breakage of the free-length fibres occurred suddenly without any yield.

![Figure 11. GFRP tendon fracture failure diagram](image)

2.9 Test Results

The ultimate load, tensile strength, elastic modulus, and ultimate strain of GFRP bars obtained in this test are shown in Table 4. Overall, these tests showed a slightly higher modulus of elasticity in compression and tension, by comparing the results of compressive to tensile tests. However, if the guaranteed tensile characteristics of bars