A NEW APPROACH TO TENSILE TESTING OF GFRP BARS

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Keywords

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Abstract

Tensile testing is a critical procedure for evaluating the mechanical properties of Glass Fiber Reinforced Polymer (GFRP) bars, which emerged as an alternative to traditional steel reinforcement in reinforced concrete structures. While significant research has led to the development of testing standards for GFRP bars, their implementation often necessitates additional specimens and specialized equipment compared to their steel counterparts. This study proposes a new method for conducting GFRP tensile tests using standard equipment designed for conventional structural steel rebar testing. By employing existing devices, our approach offers a practical and cost-effective solution for assessing the tensile properties of GFRP reinforcement. This simplified testing method aims to enhance efficiency, facilitate wider adoption of GFRP bars in reinforced concrete structures, and contribute to the advancement of sustainable construction practices. As a result of the study, it has been observed that this testing method can be effectively used.

GFRP DONATILARIN ÇEKME TESTİ İÇİN YENİ BİR YAKLAŞIM

Anahtar Kelimeler

GFRP donatılar
Mekanik Özellik
Çekme Testi
Deneysel Analiz
Sürdürülebilir Yapı

Öz

Çekme testi, geleneksel çelik donatıya alternatif olarak kullanılan Cam Elyaf Takviyeli Polimer (GFRP) çubukların Mekanik özelliklerin değerlendirilmesinde kritik bir rol oynamaktadır. GFRP çubuklar için test standartlarının geliştirilmesi için yapılan araştırmalar önemli bir aşamaya gelmiş olmasına rağmen, çelik donatıların testlerine kıyasla, bu testlerin uygulanması genellikle daha çok sayıda numune ve özel ekipman gerektirmektedir. GFRP çekme testleri için bu çalışmada, çelik donatılar için kullanılan mevcut test ekipmanlarının kullanıldığı yeni bir yöntem önerilmektedir. Geliştirilen bu yenilikçi yaklaşım, GFRP takviye elemanlarının mekanik özelliklerinin değerlendirilmesi için pratik ve maliyet-etkin bir çözüm sunmaktadır. Bu test yöntemi, GFRP çubukların betonarme yapılarda daha yaygın olarak kullanılmasını kolaylaştırarak verimliliği artırmayı ve sürdürülebilir inşaat uygulamalarının ilerlemesine katkıda bulunmayı hedeflemektedir. Yapılan deneyler sonucunda bu test yönteminin etkili olarak kullanılabileceği görülmüştür.

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1. Introduction

Fiber Reinforced Polymer (FRP) bars have gained significant attention as an alternative to traditional steel reinforcement in reinforced concrete structures due to their excellent corrosion resistance, high strength-to-weight ratio, and potential for improving the durability and sustainability of constructions (Bakis et al., 2002; Balendran, Rana, Maqsood and Tang, 2002; Benmokrane, Chaallal and Masmaudi, 1995; Gudonis et al., 2014; Nanni, 1993). Although a great amount of research promotes the application of FRP bars in structures, the widespread use of FRP bars is limited due to the anisotropic nature and some mechanical drawbacks, such as lower elasticity modulus and different mechanical behavior under tension and compression compared to steel rebars (Kodur, Venkatachari, Matsagar and Singh, 2022; Liu et al., 2021). Tensile testing of GFRP bars is a fundamental requirement for evaluating their mechanical properties and ensuring their safe and efficient utilization in a wide range of structural applications. Mechanical properties and performance of FRP bars have been investigated through tensile testing by recent studies (Al-Salloum, El-Gamal, Almusallam, Alsayed and Aqel, 2012; D'Antino and Pisani, 2023; Feng et al., 2022; Hitesh Kumar, Mohandoss and Anjana, 2023; Kocaoz, Samaranayake and Nanni, 2005; Lu, Yang and He, 2021; Spagnuolo, Rinaldi, Donnini and Nanni, 2021; Wiater and Siwowski, 2020; You, Kim, Park, Seo and Lee, 2017). These studies have focused on various parameters, such as ultimate tensile strength, modulus of elasticity, strain capacity, and failure modes.

Several codes and standards have been implemented different methods to assess the tensile characteristics of FRP bars (ASTM D7205/D7205M-21, 2021; CNR-DT 203/2006, 2007; CSA S806-12, 2012; JSCE-E 531, 1995). Table 1 lists different standards for tensile testing of FRP bars and compares their specifications. In the table, ϕ represents the nominal diameter, f_u is the ultimate strength, and A is the cross-section area of the FRP rebar. These standards specify specimen dimensions, loading rates, and testing conditions to ensure reliable and consistent results. However, adherence to these standards often requires specialized equipment and increased specimen quantities, making the testing process complex and costly. Furthermore, individual standards also vary in their tensile test requirements, such as the length of the test specimen, gage length of extensometer, test duration, and speed of the test. Another issue is the length of the specimen. As given in Table 1, free length of the specimen should be at least 100 mm or 40 times of the nominal diameter. If anchorage length is added to the required free length, the total length of the specimen exceeds the allowable length of the most of the conventional tensile testing machines widely available at laboratories globally.

Wiater and Siwowski (2020) investigated tensile properties of glass fiber reinforced polymer (GFRP) bars under different testing methods suggested by various standards. The authors imply the difficulties in comparing the results gathered from each standard due to differences in calculating elasticity modulus and determination of nominal and effective diameter of the bars, which affects the tensile strength values.

Table 1. Different standards for tensile testing of FRP bars

Test Standard	Length of Free Specimen (mm)	Number of Test Pieces	Anchorage, L_g (mm)	Gauge Length (mm)	Test Duration (minutes)	Speed of the Test
ASTM D7205 (2021)	≥380 or ≥40ϕ	At least 5	$\phi<13 \rightarrow L_g\geq300$ $13\leq\phi<19\rightarrow L_g\geq380$ $19\leq\phi<32\rightarrow L_g\geq460$ $\phi\geq32\rightarrow L_g\geq800$	≥8ϕ	1-10	-
ISO 1046-1 (2015)	≥300 or ≥40ϕ	At least 5	The anchorage must be capable of transmitting solely the tensile force along the longitudinal axis of the test specimens.	≥100 ≥8ϕ	-	0.5% - 1.5% per minute (Strain rate)
CSA S806 (2012)	≥40ϕ	At least 5	$L_g\geq250$ or $L_g\geq f_uA/350$	≥5ϕ	-	250-500 MPa/min (Stress rate)
CNR-DT 206 (2007)	≥100 or ≥40ϕ	At least 5	The anchorage must be capable of transmitting solely the tensile force along the longitudinal axis of the test specimens and to cause the test piece to fail at the test section	≥8ϕ	1-10	-
JSCE-E 531 (1995)	≥100 or ≥40ϕ	At least 5	The anchorage must be capable of transmitting solely the tensile force along the longitudinal axis of the test specimens and to cause the test piece to fail at the test section	≥8ϕ	-	100-500 MPa/min (Stress rate)

The differences between test methods and not having a universal testing for FRP rebars limits their implementation in the field. Understanding the tensile characteristics of FRP rebars is essential for design purposes and it needs to be easy and accessible for both manufacturers and end users to get their materials to be tested reliably. To compare different factors that affects tensile behavior of GFRP rebars, Kumar et al. (2023) conducted a literature review on the tensile and creep behavior of FRP bars. The authors investigated surface treatments, bar diameter and temperature effects on tensile behavior of GFRP bars. They highlighted the need for the development of universal tensile testing method for the wider adaptation of GFRP rebars in construction.

Kocaoz et al. (2005) conducted tests using anchorage method proposed by Micelli and Nanni (2001). The anchorage system consists expansive cementitious grout filled steel pipes. They investigated four groups of GFRP bars with different surface coating. The bar diameter of the GFRP bars in all groups were 12.5 mm (#4 bars) and they all had the same materials, shape and fiber-volume ratio. The anchorage length was 305 mm and they used a threaded end for the better bond to prevent the separation of coating in the anchorage. The total length of the specimens was $40\phi+2L_g$ chosen according to ACI test specifications for FRP rods, which equals to 1110 mm for #4 GFRP bars.

D'Antino and Pisani (2023) investigated tensile and compressive characteristics of thermoset and thermoplastic GFRP bars. The authors used ISO 1046-1 for tensile testing procedures. They used epoxy bonded steel pipes for the anchorage. The length of the pipes was modified based on the anticipated peak applied load for each diameter, resulting in varying overall lengths of the specimens and the utilization of different testing machines. The authors emphasized that the selection of the testing machine took into consideration not only its maximum capacity but also factors such as the maximum distance between the heads and the head gripping system. Similar challenges and complexities arise when conducting other testing methods as specified in different test standards for performing tensile tests on FRP bars. A universally accepted and easy-to-use testing method is essential for accurately evaluating the tensile properties of FRP bars to facilitate widespread adoption of consistent characterization procedures.

The main aim of this study is to offer a solution to this problem with proposing a new test method suitable for readily available standard testing devices. This novel approach provides easy and effective solution to determining tensile properties of GFRP bars, enabling the wider application of these advance materials. This study introduces an innovative approach to GFRP tensile testing, utilizing the devices and procedures commonly used for standard tensile testing of reinforced concrete steel. By employing the existing infrastructure, proposed method offers a cost-effective and practical solution for evaluating the mechanical properties of GFRP reinforcement without compromising the accuracy of results. This study aims to provide construction professionals and researchers with an efficient and accessible method for GFRP tensile testing, promoting the broader utilization of GFRP reinforcement in the construction industry.

2. Materials and Method

2.1. Materials

The GFRP bars used in this research were manufactured by pultrusion by using E-glass and vinyl-ester resin. Helically wrapped GFRP reinforcement bars with diameters of 12, 14, 16, and 18 mm were used in testing. Figure 1 shows the test specimens with different diameters. Each thick in the ruler represents one millimeter. At least 3 specimens were used for each test. The structural properties of the GFRP bars used in the experimental study are presented in Table 2.

Figure 1. GFRP rebars

Table 2. Properties of GFRP

Fiber type	Resin type	Fiber content by weight, %	Fiber content by volume, %	Density g/cm^3
E-Glass	Vinyl Epoxy	> 75	>65	>1.80

2.1. Method

In this study, research and publication ethics were compiled with. Five different test procedures were tested as an alternative to the method specified in the ASTM D7205 standard. In the first method, the reinforcement was subjected to direct tensile testing without any treatment. In the second method, a rubber membrane was wrapped around on the both ends of the specimens and anchored to the grips through these. In the third method, the GFRP rebars were anchored using epoxy bonded steel pipes, the difference from the test standard was the length of the anchorage, which was kept shorter to fit the specimen's length to the maximum allowed distance between the heads of the conventional testing machine readily available at Eskisehir Osmangazi University Materials testing laboratory. In the fourth method, a turned section with a length of $10 \times d_0$ was created in the middle of the test specimens and a dog bone shape was provided. In the fifth method, similar to the fourth method, the middle part was tapered, and a special cylindrical apparatus made of steel material was used to hold only this apparatus in the jaws. Tensile tests were performed with a 'Kalite' brand universal tensile-compression device with a capacity of 250 kN at room temperature and a testing speed of 10 mm/min. Strain rate (ε) varied between 1.2-2×10^{-3} s^{-1}.

3. Results and Discussion

In the first method, the GFRP rebar was subjected to direct tensile testing without any treatment. However, as seen in Figure 2, first crushing and then slippage occurred in the gripping part of the heads during the test.

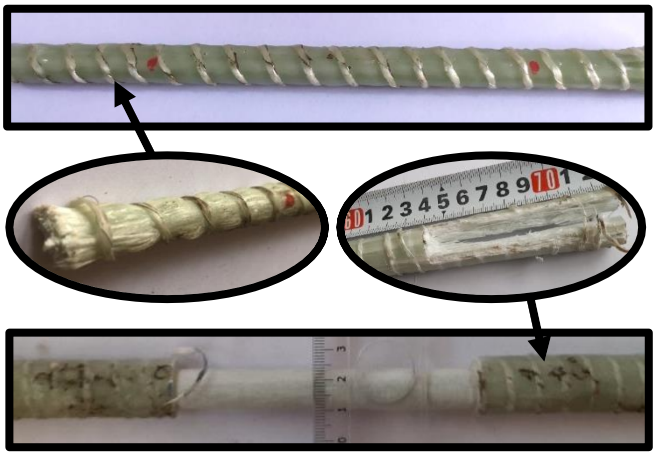

Figure 2. Samples with and without treatment

In the second method, as seen in Figure 3, a rubber membrane was wrapped around and adhered to the part where the jaws are located. During the tensile testing, slippage occurred at the beginning of the loading, and the specimen could not tested to the maximum capacity due to the slippage of the rubber band. In the third method, as recommended by ASTM D7205, the GFRP reinforcement was placed inside a steel tube concentrically and adhered with epoxy.

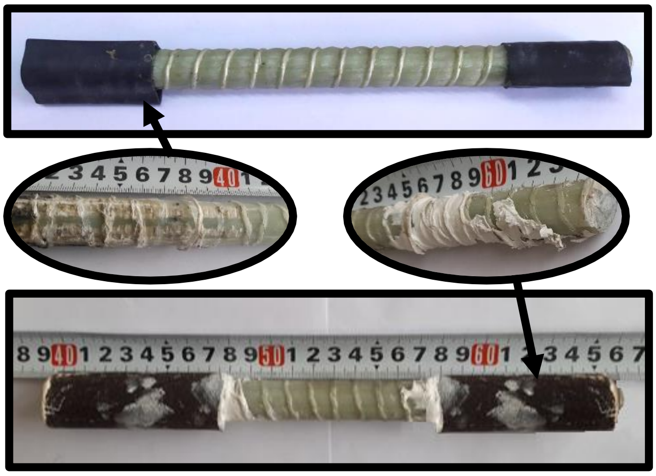

Figure 3. Rubber membrane and steel cap applications

According to the ASTM D7205, the length of the caps is longer to maintain the adherence bond and to prevent the caps from slipping off the ends of the samples during the tensile test. This requires longer GFRP bar samples and a longer stroke length (distance between the jaws) in the machine compared to standard steel reinforcement. However, this stroke distance cannot be provided in many universal testing machines. Therefore, a shorter sample was preferred considering the stroke length according to the recommended method. During the experiment, the steel cap held by the jaws was not long enough, inevitably slipping occurred.

As the fifth method, the middle of the sample was first turned to a length of $10 \times d_0$, and a 2 mm indentation was provided on the surface. Special half-cylinder-shaped apparatuses, with the diameter of the end of the sample thinned according to the sample diameter, the upper diameter being the unprocessed diameter of the sample, and the length being determined considering the grip length, were placed on the area where the jaws hold the sample to grasp the indentation part of the samples, as shown in Figure 4. The test results showed that the fracture did not occur at the jaws or at the narrowed section of the cross-section but in the form of fiber rupture in the middle of the sample, indicating the success of the method.

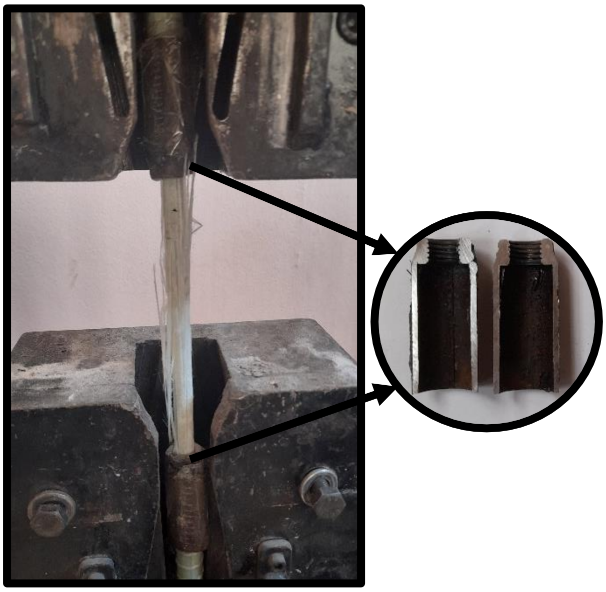

Figure 4. Suggested method for the tensile testing

The stress-strain diagram obtained from the tensile test performed on samples with different diameters is given in Figure 5. As seen from Figure 5, stress changes proportionally to strain. GFRP bars, which are an anisotropic material due to their brittle nature and glass fibers, did not exhibit a linear elastic behavior as expected. Since GFRP is a composite material, a homogeneous structure is not obtained in either the fibers or resin phase during the bonding of glass fibers with epoxy resin. Therefore, discontinuities occurring due to defects during tensile effects have partially affected the linear behavior negatively. During the tensile test, poorly wrapped with resin compared to others, the rupture of fibers reaching their ultimate tensile strength has caused sudden stress drops and small zigzags as the load is redistributed to other fibers. However, since the resin and fibers move together, no curvilinear behavior has been observed.

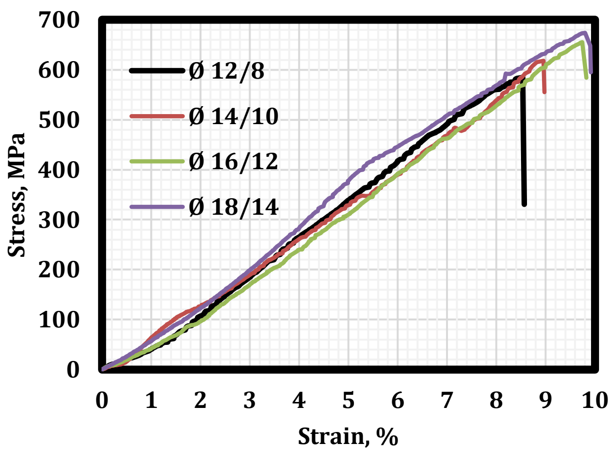

Figure 5. Stress-strain relationships of GFRP rebars

The tensile strengths of GFRP bar specimens with different diameters are shown in Figure 6. The tensile strengths increased by up to 15% as the specimen diameter increased. The increase in diameter and consequently, the increase in the number of fibers led to an increase in strength. It was expected that the force per unit area would remain constant as in the steel specimen. However, since the specimens are composite materials and fibers are effective in tension, the force per unit area has changed.

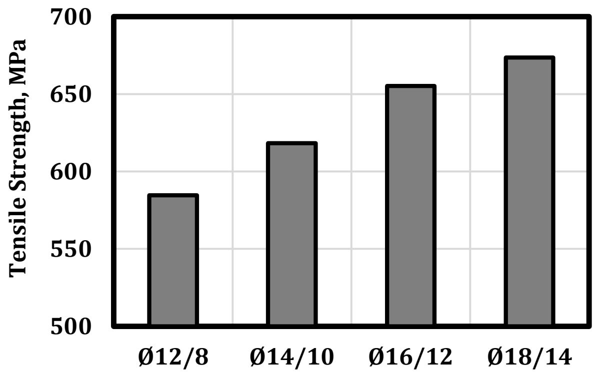

Figure 6. Tensile strength of tested GFRP rebars

The maximum elongation values at the fracture under tensile stress are given in Figure 7. It can be seen that the elongation values vary between 8.5% and 10%. The elongation increases become prominent especially when the diameter increases from 14/10 mm to 16/12 mm, reaching up to 10%. It can be said that the fibers, apart from the binding resin, are particularly effective in this elongation increase. Although glass is a brittle material with a limited non-linear deformation, the resin and other coatings used in the production of the glass fibers used in GFRP have an effect on this elongation.

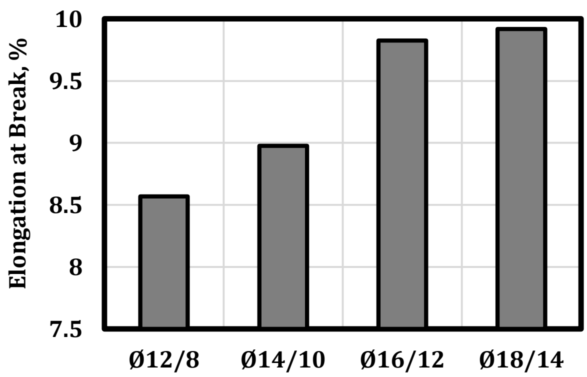

Figure 7. Total elongation changes with reinforcement diameter

The elastic modulus values calculated based on the strains of GFRP bars with different diameters under the tensile forces are given in Figure 8. The elastic modulus of GFRP rebars varied between 68-73 GPa. The change was below 8%, however it was irregular. The anisotropic and composite nature of GFRP, the combination of binding resin-glass fibers, and the defects arising from the material and production of glass fibers could be effective in this variation.

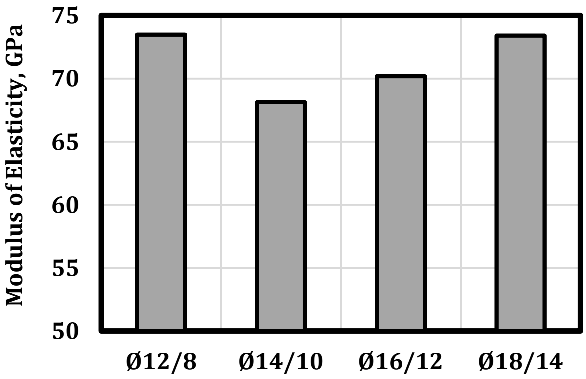

Figure 8. Elasticity modulus of GFRP bars under tension

The toughness values calculated using the stress-strain graphs drawn in Figure 9 are given. It is seen that the static toughness values of GFRP specimens with different diameters vary between 0.024-0.034 joule/mm^3. As the reinforcement diameter increases, static toughness values have increased up to 40%. Although the stress increase and strain increase are not linear, and there is no increasing or decreasing curve, taking into account the areas below the stress strain curves, the increase in maximum stress value and the increase in maximum strain value are proportional, increasing the areas, thus increasing the static toughness values.

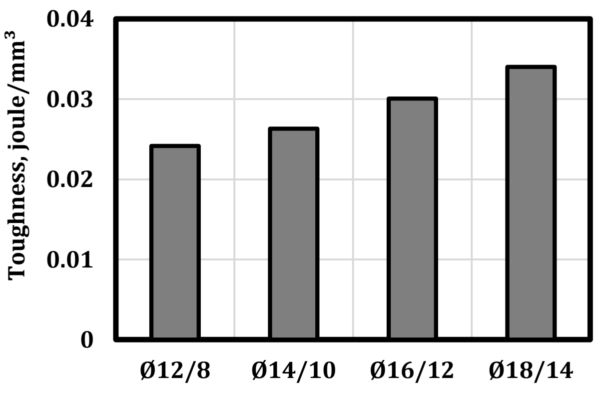

Figure 9. Toughness of GFRP bars

4. Conclusions

The results are concluded as below:

- Stress-strain values obtained under the tensile effect of GFRP reinforcements increase approximately proportionally, but they also occur in discontinuities as well as deviations from linearity. Since the fracture of the relatively weak fibers bonded with resin as the load increases, the deformations and stresses are affected limitedly, it is reflected in the graph as small changes.
- It has been observed that the tensile strengths of GFRP bars reach values of up to 670 MPa. In structural design, the area calculated based on load-bearing capacity is considered, and the number of bars that provide this area is selected according to the reinforcement diameters. However, diameter changes in GFRP reinforcements should be taken into account as they can cause changes in strength.
- In structural design of reinforced concrete structures, the yield strength of reinforcement is considered. A total elongation value of more than 12% is desired for conventional steel reinforcement. However, while reinforced steel undergoes limited deformation until yielding, a significant portion of deformation occurs during strain hardening and necking. In the design conditions of the structure, deformation of the reinforcement is limited. However, it has been observed that these deformation values are quite high in GFRP reinforcements.
- It has been observed that the elastic modulus of GFRP reinforcements reaches 7.3 MPa. Since these values are significantly lower than the elastic moduli of concrete and steel that make up reinforced concrete, the behavior of GFRP reinforced concrete structures differs from conventional steel reinforced counterparts. And therefore, GFRP material tests are important and should be more easily done to specify the mechanical properties of the GFRP bars for each application.
- The static toughness values of the specimens have been observed increase with increasing diameter, reaching a value of 0.034 joules/mm^3.

Average test results of GFRP bars are given in Table 3.

Table 3. Summary of test results

	Test results (average)
Tensile strength, MPa	633
Total elongation, %	9.3
Modulus of Elasticity, GPa	71
Toughness, Joule/mm^3	0,028

This study aimed to determine the mechanical properties of GFRP reinforcements under tensile forces using different methods, without damaging the specimen during processing or testing with the apparatus. It has been demonstrated that the mechanical properties can be determined in all devices where standard steel tensile tests can be performed. Increasing research on determining the mechanical properties of GFRP bars and their use in design is important for reducing uncertainties in this field and increasing their practical applications. It is recommended to test this experimental method for different types of FRP reinforcements in future studies.

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Contribution of Researchers

K. Aybar contributed to the experimental study, methodology, writing - original draft, writing – reviewing and editing of the study.
M. Eryılmaz Yıldırım contributed to the literature review, methodology, experimental study, writing – reviewing and editing, writing – English translation of the study.
M. Canbaz contributed to the conceptualization, methodology, evaluation of the results, visualization, writing – reviewing and editing of the study.

Conflict of Interest

No conflicts of interest have been declared by the authors.

References

Al-Salloum, Y. A., El-Gamal, S., Almusallam, T. H., Alsayed, S. H., & Aqel, M. (2013). Effect of harsh environmental conditions on the tensile properties of GFRP bars. *Composites Part B: Engineering*, *45*(1), 835–844. https://doi.org/10.1016/j.compositesb.2012.05.004

ASTM D7205/D7205M-21. (2021). *Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars*.

Bakis, C. E., Bank, L. C., Brown, V. L., Cosenza, E., Davalos, J. F., Lesko, J. J., Machida, A., Rizkalla, S. H., & Triantafillou, T. C. (2002). Fiber-reinforced polymer composites for construction - State-of-the-art review. *Journal of Composites for Construction*, *6*(2), 73–87. https://doi.org/10.1061/(ASCE)1090-0268(2002)6:2(73)

Balendran, R. V., Rana, T. M., Maqsood, T., & Tang, W. C. (2002). Application of FRP bars as reinforcement in civil engineering structures. *Structural Survey*, *20*(2), 62–72. https://doi.org/10.1108/02630800210433837

Benmokrane, B., Chaallal, O., & Masmoudi, R. (1995). Glass fibre reinforced plastic (GFRP) rebars for concrete structures. *Construction and Building Materials*, *9*(6), 353–364. https://doi.org/10.1016/0950-0618(95)00048-8

CNR-DT 203/2006. (2007). *Guide for the Design and Construction of Concrete Structures Reinforced with Fiber-Reinforced Polymer Bars* (Issue June).

CSA S806-12. (2012). *Design and Construction of Building Structures with Fibre-Reinforced Polymers*. Canadian Standards Association.

D'Antino, T., & Pisani, M. A. (2023). Tensile and compressive behavior of thermoset and thermoplastic GFRP bars. *Construction and Building Materials*, *366*(December 2022), 130104. https://doi.org/10.1016/j.conbuildmat.2022.130104

Feng, G., Zhu, D., Guo, S., Rahman, M. Z., Jin, Z., & Shi, C. (2022). A review on mechanical properties and deterioration mechanisms of FRP bars under severe environmental and loading conditions. *Cement and Concrete Composites*, *134*, 104758. https://doi.org/10.1016/j.cemconcomp.2022.104758

Gudonis, E., Timinskas, E., Gribniak, V., Kaklauskas, G., Arnautov, A. K., & Tamulėnas, V. (2014). Frp Reinforcement for Concrete Structures: State-of-the-Art Review of Application and Design. *Engineering Structures and Technologies*, *5*(4), 147–158. https://doi.org/10.3846/2029882x.2014.889274

JSCE-E 531. (1995). *Test Method for Tensile Properties of Continuous Fiber Reinforcing Materials*.

Kocaoz, S., Samaranayake, V. A., & Nanni, A. (2005). Tensile characterization of glass FRP bars. *Composites Part B: Engineering*, *36*(2), 127–134. https://doi.org/10.1016/j.compositesb.2004.05.004

Kodur, V., Venkatachari, S., Matsagar, V. A., & Singh, S. B. (2022). Test Methods for Characterizing the Properties of Fiber-Reinforced Polymer Composites at Elevated Temperatures. *Polymers*, *14*(9), 1734. https://doi.org/10.3390/polym14091734

Kumar, M. H., Mohandoss, P., & Anjana, L. (2023). Investigation on tensile and creep behaviour of glass fiber reinforced polymer (GFRP) bars: A review. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.04.656

Liu, Y., Zhang, H.-T., Zhao, H.-H., Lu, L., Han, M.-Y., Wang, J.-C., & Guan, S. (2021). Experimental Study on Mechanical Properties of Novel FRP Bars with Hoop Winding Layer. *Advances in Materials Science and Engineering*, *2021*, 1–18. https://doi.org/10.1155/2021/9554687

Lu, C., Yang, Y., & He, L. (2021). Mechanical and durability properties of GFRP bars exposed to aggressive solution environments. *Science and Engineering of Composite Materials*, *28*(1), 11–23. https://doi.org/10.1515/secm-2021-0002

Micelli, F., & Nanni, A. (2001). Mechanical properties and durability of FRP rods. In *CIES Report 00-22* (Issue March). Taylor & Francis. http://www.crcnetbase.com/doi/10.1201/9780203883440.ch65

Nanni, A. (1993). Fiber-Reinforced-Plastic (FRP) Reinforcement for Concrete Structures. In A. Nanni (Ed.), *Canadian Journal of Civil Engineering*. Elsevier. https://doi.org/10.1016/C2009-0-09136-3

Spagnuolo, S., Meda, A., Rinaldi, Z., & Nanni, A. (2018). Residual behaviour of glass FRP bars subjected to high temperatures. *Composite Structures*, *203*, 886–893. https://doi.org/10.1016/j.compstruct.2018.07.077

Spagnuolo, S., Rinaldi, Z., Donnini, J., & Nanni, A. (2021). Physical, mechanical and durability properties of GFRP bars with modified acrylic resin (modar) matrix. *Composite Structures*, *262*, 113557. https://doi.org/10.1016/j.compstruct.2021.113557

Wiater, A., & Siwowski, T. (2020). Comparison of Tensile Properties of Glass Fibre Reinforced Polymer Rebars by Testing According to Various Standards. *Materials*, *13*(18), 4110. https://doi.org/10.3390/ma13184110

You, Y. J., Kim, J. H. J., Park, K. T., Seo, D. W., & Lee, T. H. (2017). Modification of rule of mixtures for tensile strength estimation of circular GFRP rebars. *Polymers*, *9*(12). https://doi.org/10.3390/polym9120682