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Size effect on compressive behavior of GFRP bars

Meltem Eryilmaz Yildirim [a,*], Kerem Aybar [b], Mehmet Canbaz [a]

[a] *Department of Civil Engineering, Eskişehir Osmangazi University, 26480 Eskişehir, Türkiye*
[b] *Department of Metallurgical and Materials Engineering, Eskişehir Osmangazi University, 26480 Eskişehir, Türkiye*

ABSTRACT

In the last three decades, studies investigating the use of Glass Fiber Reinforced Polymer (GFRP) bars as an alternative to conventional steel rebars have increased due to their corrosive resistance. In addition to corrosion resistance, GFRP bars utilize high specific tensile strength, which makes them highly desirable in civil engineering applications. However, major design guidelines for GFRP-reinforced concrete structures currently do not consider their compressive contribution. Nevertheless, there is a growing trend in utilizing GFRP bars as compressive elements, driven by various studies demonstrating their ability to bear compressive loads effectively. This increasing demand underscores the need to comprehend the mechanical properties of GFRP bars, particularly in terms of their compressive behavior. Furthermore, a standardized test method to evaluate their compressive properties has not yet been developed. Addressing these gaps, this research paper focuses on investigating the influence of specimen size on the compressive strength of GFRP bars, specifically emphasizing on the compressive properties of GFRP bars. Compressive tests were conducted on GFRP specimens with varying diameters while maintaining a constant slenderness ratio. The findings from these compression tests shed light on the critical role of size in the compressive behavior of GFRP. This research emphasizes the importance of considering size as a significant parameter in designing mechanical properties for GFRP reinforcements.

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1. Introduction

Fiber reinforced polymer (FRP) bars have been a compelling alternative to conventional steel rebars thanks to their non-corrosive and high specific tensile strength (Benmokrane et al. 1995; Nanni 1993). However, their implementation has been limited due to a primary consideration of their behavior under compression. FRP bars are composites made from fibers that are embedded in a polymeric resin matrix binder. They feature exceptional properties such as high tensile strength, non-corrosiveness, high chemical resistance, lightweight, and non-conductivity (Balendran et al. 2002; Micelli and Nanni 2001; Saadatmanesh and Ehsani 1991). On the other hand, due to these composites' anisotropic and non-homogeneous nature, their behavior under compression is different from tension and is controlled by microstructural configuration. Tensile behavior and bond properties of GFRP bars have been investigated by several researchers (Al-Salloum et al. 2013; D'Antino and Pisani 2023; Galati et al. 2004; Özkal et al. 2018; Wiater and Siwowski 2020). However, compressive load carrying capacity of FRP bars has been neglected by codes and guidelines due to insufficient research (Al-Najmi and Abed 2020). GFRP bars exhibit high tensile strength but lower compressive strength. As a result, research efforts are predominantly directed towards understanding the mechanical behavior of GFRP under tensile loading; thus, studies on compressive behavior of GFRP rebars are limited (Zhou et al. 2023).

FRP materials have different application areas and can be manufactured in different geometries. FRP laminates have various application areas from industry to

* *Corresponding author.* Tel.: +90-222-239-3750 ; E-mail address: meryilmaz@ogu.edu.tr (M. Eryilmaz Yildirim)
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construction. Lagoudas and Saleh (1993) investigated loading and geometry effects on the compressive strength of fibrous composites. Schultheisz and Waas (1996) investigated compressive testing methods and the micromechanical theories in compressive failure for fibrous composites. Berbinau et al. (1999) studied various unidirectional failure parameters for carbon-FRP (CFRP) laminates subjected to compressive forces. Soutis et al. (2002) explored the impact of specimen gauge section dimensions (length × width) on the compressive behavior of carbon/epoxy composites, examining the size-related factors. González and LLorca (2007) examined the mechanical response of unidirectional polymer composites subjected to transverse compressive loading. Zhou et al. (2013) the mechanisms leading to compressive damage in GFRP composites when subjected to off-axis loading. The authors conducted both experimental and computational investigations to analyze the microscale damage phenomena in GFRP composites at various angles between the loading direction and the fiber orientation.

Kobayashi and Fujisaki (1995) conducted compressive tests on FRP reinforcement. The researchers embedded FRP bars within a concrete prism, leaving a small space in the core. The experimental outcomes indicated that the compressive strength of the GFRP bars amounted to 30-40% of their tensile strength. Deitz et al. (2003) studied GFRP rebars under compression to investigate their ultimate capacity and Young's modulus. The authors developed a test method that consists of two steel rods, designed to thread into the heads of the testing machine. The holes in the steel rods were designed a bit greater than the diameter of the GFRP bars which effected the determination of actual slenderness ratios. Test findings show that, the maximum compression strength for non-slender specimens (unbraced length < 110 mm, diameter 15 mm) was almost 50% of their ultimate tensile strength. Bruun (2014) tested 25M (25mm diameter) GFRP bars under direct compression to investigate the relationship between compressive strength and the curve representing unbraced length interaction. According to the findings, the author demonstrated that 25 mm diameter GFRP bars with an elasticity modulus of 60 GPa experience crushing under monotonic loads when unbraced lengths are less than 230 mm (with an l/d ratio of approximately 9.0). Conversely, when the lengths are extended beyond 230 mm (resulting in an l/d ratio exceeding 9.2), may lead to random transition failure or weaker buckling failure. Khan et al. (2015) conducted compression tests on ∅15 mm GFRP bars and ∅15.9 mm CFRP bars using a modified version of the testing procedure outlined in ASTM D695-10. The longitudinal fibers of both GFRP and CFRP bars separated under compression, resulting a failure. The test findings indicated that the compressive strengths of GFRP and CFRP bars were 35% and 6% of their respective tensile strengths. Thiyagarajan et al. (2018) tested Basalt Fiber Reinforced Polymer (BFRP) bars by placing the specimens axially between the loading plates of the testing machine. Test results revealed that compressive strength of the BFRP bars were 50% of their tensile strength.

AlAjarmeh et al. (2019) proposed a new testing approach for assessing and characterizing the compressive behavior of GFRP bars. The authors employed cementitious grout-filled hollow steel caps to confine the top and bottom ends of the GFRP bars. The test findings indicated that as the unbraced bar length increased, the ratio of compressive strength to tensile strength decreased, resulting in a shift in the failure mode from crushing to fiber buckling. Zhang and Deng (2019) examined the compressive behavior of GFRP bars under sustained stress conditions in both a simulated marine environment and an alkaline solution simulating concrete conditions. In all tests, specimens of 10 mm diameter GFRP bars with a free length of 25 mm were employed. For the compressive tests, the authors used steel tubes grouted with epoxy resin matrix as enclosures at the bottom and top of the bars to avoid early failure of the GFRP bars. Abed et al. (2020) conducted dynamic and quasi-static tests to investigate the compressive strength and failure modes of GFRP and BFRP specimens. AlNajmi and Abed (2020) conducted compression tests on GFRP and BFRP samples with various diameters using steel caps in the ends of the specimens to decrease the effect of the samples tilting. The holes in the steel caps were also slightly bigger than the diameter of the specimen causing a decrease in the applied moment by the testing machine. Khorramian and Sadeghian (2021) suggested a test method for characterization of GFRP specimens under compressive forces, which includes rectangular steel plates, steel rings and anchorage adhesives. The unbraced specimen length is twice the diameter of the bars while the total length of the specimen is four times the diameter of the bars. The authors reported no buckling failure in the specimens. The failure modes included crushing in the unbraced length, crushing inside the casing and crushing of both in the unbraced length and in the casing. D'Antino and Pisani (2023) investigated tensile and compressive behavior of thermosetting and thermoplastic GFRP bars. The authors employed the compression test procedure given by Deitz et al. (2003).

Determining the compressive strength of composite bars is affected not only by the slenderness of the specimen but also by its size. This research investigates the influence of specimen size on the compressive strength of GFRP reinforcements. Compressive tests were conducted on specimens with varying diameters, while keeping the slenderness ratio constant. The obtained sigma-epsilon curves were analyzed to determine the compressive strengths, strain rates, toughness, and elastic moduli corresponding to each specimen size. This comprehensive analysis provides insights into the effect of specimen size on the mechanical properties of GFRP reinforcements under compression.

2. Experimental Study

The widespread usage of GFRP bars in structural elements guided the selection of reinforcement diameters. Recently, 10 mm diameter GFRP bars have increasingly been utilized as vertical reinforcements, commonly used for shear reinforcement or stirrups. Additionally, 12 mm diameter GFRP bars are widely employed as longitudinal reinforcements in reinforced concrete beams. According to CSA S806-12 guidelines, GFRP bars with a diameter exceeding 15 mm are recommended for longitudinal reinforcement in columns. Consequently, to ensure representation of various scenarios, specimens with 10-, 12-, 18-, and 20-mm diameter GFRP bars were chosen for this study. The physical properties of the GFRP bars used in the experimental study are provided in Table 1.

Table 1. Properties of GFRP.

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

The GFRP specimens were selected to have a slenderness ratio of 1.5, meaning that their length was 1.5 times their cross-section diameter. The slenderness ratio recommended by ASTM D695-15 (2002), ranging from 11 to 16, was not chosen due to the potential increase in local and global buckling.

Moreover, due to the heterogeneous and anisotropic nature of glass fiber reinforcements, there is currently no universally accepted standard test method for determining compressive strength. For each experiment, a minimum of 3 specimens were tested and average value of the test results are given in the graphs. The dimensions and images of the specimens are provided in Fig. 1.

Fig. 1. Test specimens.

The compressive test was conducted using the Shimadzu AG-IS 250kN Universal testing machine, as shown in Fig. 2. The crosshead speed was set at 0.5 mm/min, and the strain rate was determined to be 5x10^{-4} (s^{-1}).

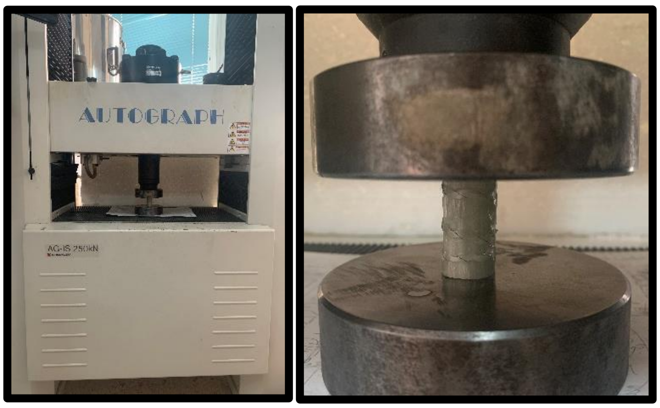

Fig. 2. Compression test apparatus and GFRP specimen.

3. Discussion

Fig. 3 shows the GFRP specimens after the compression tests. It is observed that the 10 mm diameter specimens, subjected to compressive force along the fibers, experienced fiber separation and loss of integrity. On the other hand, the other specimens maintained their integrity under the same effect, although parallel cracks were observed along the fibers. These cracks occurred in the binder resin phase and not leading to fiber detachment. Analysis of the fracture patterns in these specimens revealed a brittle fracture mode without significant plastic deformation.

The stress-strain graph drawn under the effect of the axial compression force applied in the fiber direction is given in Fig. 4. Upon examining Fig. 4, it is evident that as the specimen diameter increases, indicating a size effect, the strength increases while deformations decrease. However, when the specimen diameter reaches 20 mm, a decrease in strength and an increase in deformations are observed. As the specimen diameter increases, the fiber content also increases. In an anisotropic material, the increase in fibers plays a significant role in enhancing the strength of materials against forces applied along the fibers. Nevertheless, when the fiber content increases excessively, it becomes challenging for the resin to bond homogeneously. This leads to an increase in defects in the reinforcement cross-sectional area and a decrease in form stability, resulting in a decrease in strength. Upon closer examination of the stress-strain curve, initially a behavior close to linear elasticity is observed. As the load increases, localized fractures occur within the fiber-resin interface, causing a decrease in material resistance. Nevertheless, it can be observed that the stress continues to increase as the load is transferred to other fibers.

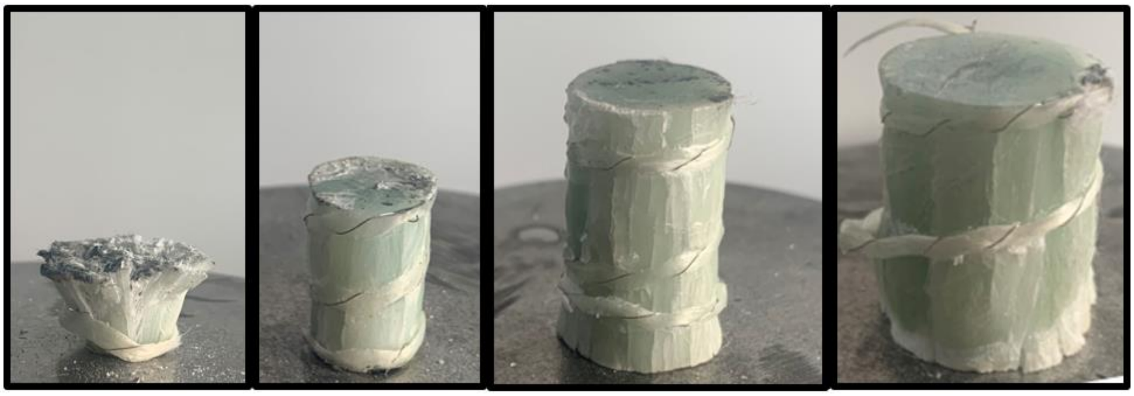

Fig. 3. Specimen images after compression test.

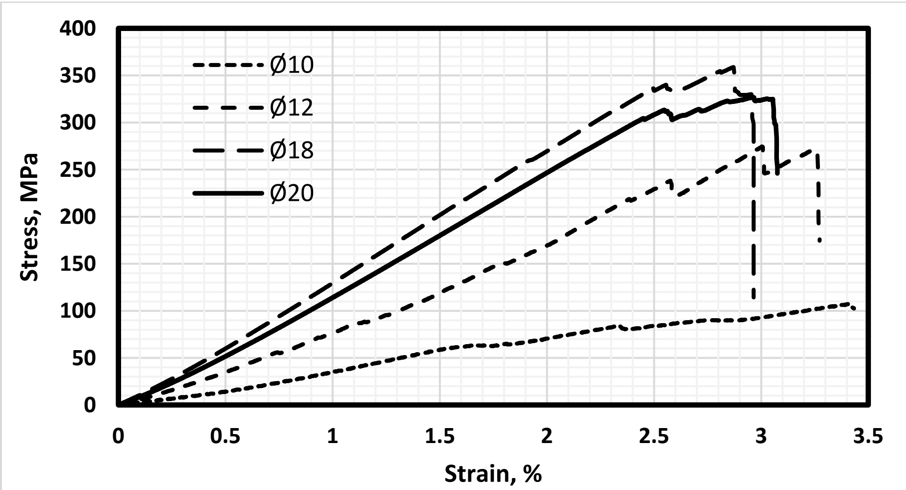

Fig. 4. Stress-strain graph of specimens under axial compressive force.

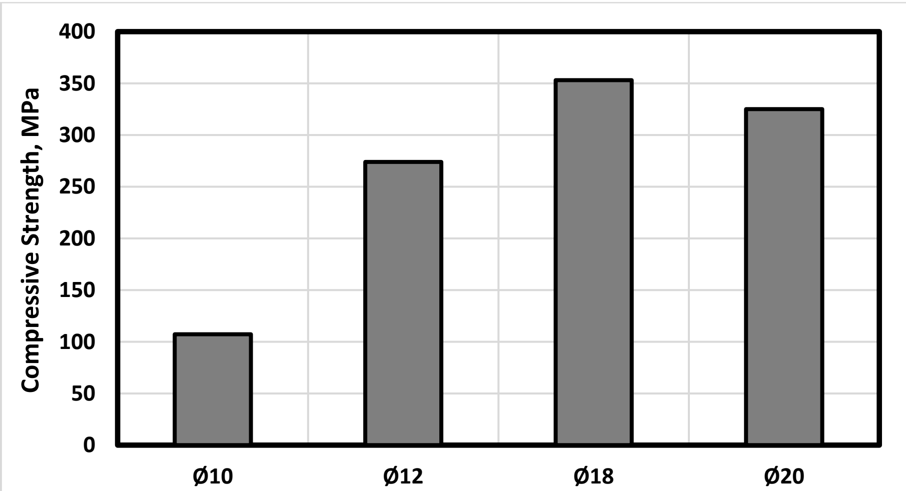

Fig. 5. Variation of compressive strength with size effect.

The variation of compressive strength in GFRP rebars concerning size effect is illustrated in Fig. 5. Experimental results show that the highest strength is observed in the 18 mm diameter GFRP specimen. As the diameter and fiber content decrease, a significant decrease in compressive strength is observed, reaching up to 70%.

However, when the diameter reaches 20 mm, the expected increase in compressive strength is not observed; instead, an approximate 8% decrease is observed between 18 mm and 20 mm diameter specimens. This decrease can be attributed to the increase in defects typically observed in brittle materials under the influence of size effect.

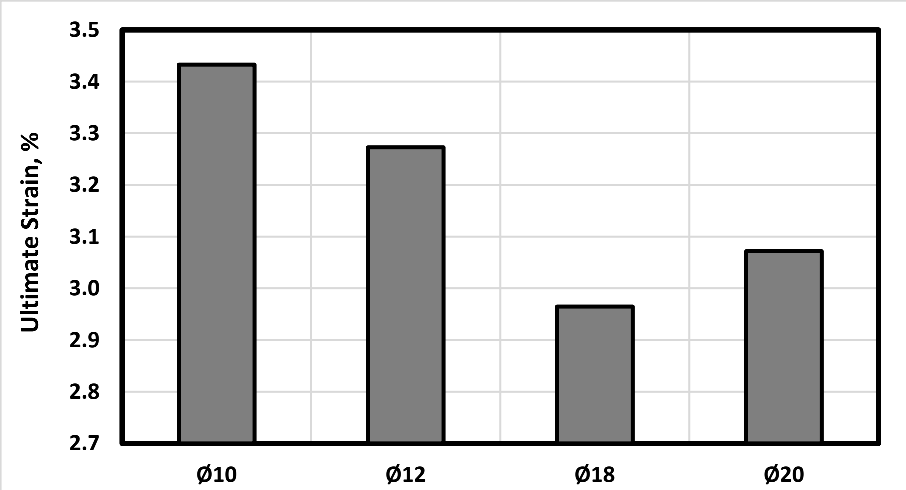

Fig. 6. Ultimate strain variation based on GFRP rebars diameter.

The size effect on the ultimate strain of GFRP rebars is given in Fig. 6. As the specimen diameter increases, along with an increase in fiber content, the resistance of the specimen to deformation increases. This leads to a decrease in strain ratios by approximately 13.6% when the diameter increases from 10 mm to 18 mm. Furthermore, when the specimen diameter reaches 20 mm, this decrease amounts to approximately 10.5%. The increase in specimen diameter results in an increase in defects originating from the binder resin, glass fiber, and their distribution. Consequently, it reduces the material strength of 20 mm specimen and leads to greater deformations compared to the 18 mm diameter specimen. These findings align with the changes observed in the compressive strength of the tested specimens.

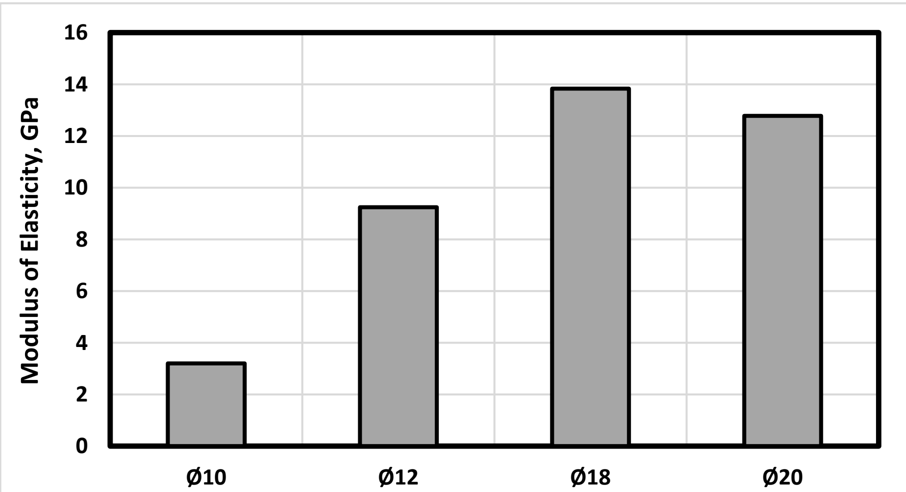

Fig. 7. Modulus of elasticity of GFRP specimens.

The relationship of the modulus of elasticity with the diameter in GFRP rebars is given in Fig. 7. The highest elastic modulus value is observed in the 18 mm diameter specimens, measuring 13.83 GPa. As the diameter decreases below 18 mm, a significant decrease of approximately 74% in the elastic modulus is observed, while an increase in diameter results in a decrease of approximately 7.6% for 20 mm specimen. The fibrous structure of GFRP, along with its anisotropic behavior and similarities to brittle materials, causes GFRP to undergo proportional deformation in response to stress until it reaches maximum stress, thereby influencing changes in elastic moduli. The increase in binder resin content within the specimens hinders their deformation under the influence of external forces and enhances their rigidity, consequently elevating their elastic moduli. However, as previously mentioned, defects and voids become more prominent beyond the 18 mm diameter, facilitating deformation, and resulting in a decrease in the elastic modulus.

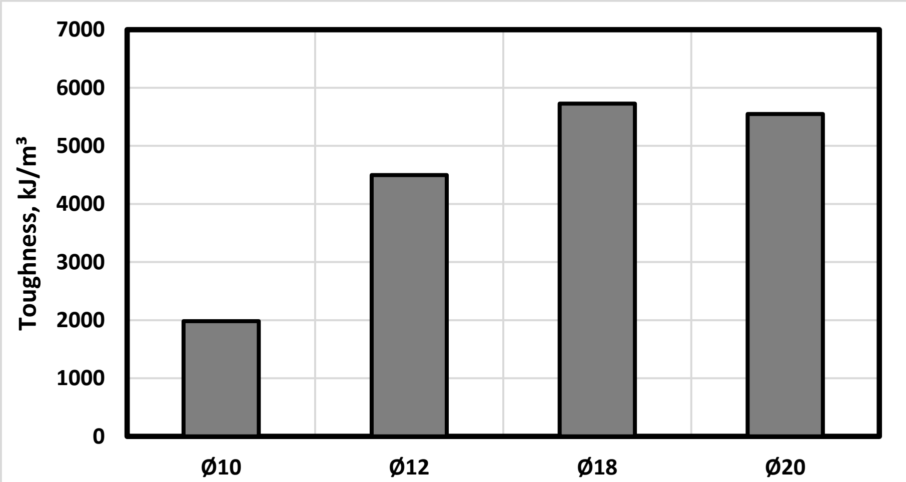

Fig. 8. Static toughness of GFRP rebars.

The static toughness values, calculated by considering the area below the stress-strain curve obtained from the compression tests on GFRP rebars, are presented in Fig. 8. It can be observed that the toughness value varies within the range of 1982-5727 kJ/mm^3. The toughness value increases by 2.26 times when the diameter increases from 10 mm to 12 mm, and it further increases by 2.88 times when it reaches 18 mm. However, when the diameter reaches 20 mm, the rate of increase decreases to 2.79 times. Based on these results, it can be concluded that in the size range up to 18 mm, the increase in fiber content and the lower amount of binder resin mitigates the effect of defects and contribute to an increase in toughness value. However, as the diameter exceeds 18 mm, the increased resin and fiber content gradually expose the influence of defects, resulting in a decrease in toughness values.

4. Conclusions

The following conclusions were reached as a result of the experimental study.

- It has been determined that under the effect of axial compressive forces, deformations and stresses increase proportionally until reaching the maximum value, and before the stresses reach their maximum, the brittle fractures in the glass fibers caused by longitudinal cracks between the fibers lead to a sudden decrease in stress. However, it has been observed that the stress continues to increase as the load is transferred to other fibers.
- The influence of size effect on the compressive strength of GFRP has indicated an increase in compressive strengths up to a diameter of 18 mm, exceeding 350 MPa, followed by a decrease beyond 18 mm.
- The study reveals that the deformation of GFRP specimens under axial compressive forces decreases as the specimen size increases. However, when the diameter exceeds 18 mm, the presence of defects becomes more prominent, leading to a decrease in the resistance to deformation.
- It has been observed that size effect is a significant factor affecting the modulus of elasticity in GFRP rebars, characterized by brittle and anisotropic fibers. Increasing the size results in an increase in the elastic modulus up to 13.8 GPa. However, beyond 18 mm, the presence of internal structural defects leads to a decrease in the elastic modulus, dropping down to 12.8 GPa.
- Size effect has been identified as an important parameter in the variation of toughness values of GFRP specimens. The highest toughness value of 0.00577 J/mm^3 was observed in the 18 mm diameter specimens.
- In structural engineering, while the size effect is not a significant factor influencing the strength of traditional steel rebars, which are isotropic, homogeneous, and ductile materials, under compressive forces, it has a detrimental effect on the strength of brittle, heterogeneous materials, especially due to internal structural defects that increase with size. GFRP, being a brittle and anisotropic material, exhibits high tensile strength but low compressive strength. In this study, it has been determined that the size of GFRP specimens affects not only the strength but also other mechanical properties under compressive forces. It is recommended to take the size effect into account when considering parameters related to mechanical properties in design. This study is primarily a preliminary work for the investigation of size effect. Conducting further experiments on different diameter size, and the other experimental and analytical studies in this area will improve the related standards, enabling the utilization of the GFRP bars for a wider application. Furthermore, it is suggested that the size effect be examined by increasing the specimen diameter at different slenderness ratios and supported by microstructure analysis for future studies.

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Conflict of Interest

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Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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