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RESEARCH ARTICLE

Investigation of the bending strength of glass fiber-reinforced polymer (GFRP) bars exposed to thermal stress

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Abstract

Nowadays, the utilization of composite reinforcement instead of steel rebars in construction is considered as an alternative and many methods are being intensively studied on composite bars. The superior tensile strength, lightness, corrosion resistance, and long service life of GFRP composite reinforcements have made them a strong competitor to steel rebars. Reinforced concrete structures constitute a large part of the existing building stock in Turkey and around the world. Therefore, composite bars have the potential to be widely utilized. This study investigates the flexural strength of GFRP composite bars after exposure to distinct thermal stress. In the study conducted, 47 GFRP bar bending specimens with a length of 150 mm and a diameter of ϕ10 mm were tested with a 3-point bending test after the thermal process was completed until GFRP bars reached the ultimate load-carrying capacities. During the experiments, GFRP bars were exposed to 9 distinct temperature loads: 22°C, 100°C, 150°C, 175°C, 200°C, 225°C, 250°C, 300°C, and 500°C, respectively. As a result of the tests performed, GFRP bars reached the highest bending load value at 200°C, which is 13% higher than the average of the reference specimens tested at 22°C room temperatures. It is seen that in possible situations such as fire, the load-carrying capacity of GFRP bars will start to decrease after 200°C, and at 500°C, the resin completely melts, and the GFRP bars lose their rigidity and strength. When the average deflection values of the GFRP bar specimens are compared for 22°C and 300°C, a 35% reduction was calculated at 300°C.

1. Introduction

Composite materials have begun to be widely used in the construction sector in recent years. GFRP bars are used in many different areas, especially in reinforced concrete structural elements, in situations where sea salt, humidity, contact with water (in structural column beam elements), etc. will cause corrosion, and in lightweight, high-strength, pre-stressed concrete. Thermal damage detection in FRP-reinforced concrete structures using ultrasonic-guided waves was investigated experimentally [1]. The effect of temperature increase in the early stage was examined with time domain signals and signals with different frequencies and the distortion was explained. The effect of high temperature on the tensile properties of thermoplastic FRP bars and thermoplastic FRP-concrete bond behavior was explored [2]. The study, which was carried out

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between room temperature and 120 degrees, revealed that thermoplastic FRP bars retained 84.1% of their tensile strength at 120 ˚C. Research has been carried out to detect thermally generated microcracks in FRP [3]. Thermal microcracks in FRP decreased with increasing fiber size, which forms the interphase between fiber and matrix. In CFRP and GFRP composites, measurements were carried out in increments up to 800 ˚C with a heat treatment time of 4 hours to continuously observe the degree of thermal decomposition of the resin [4]. Thermal decomposition of unsaturated polyester occurred at the melting point of 350°C, independent of the type of fiber reinforcement used. Thermal insulation and fire protection plaster for FRP systems aerogel nanoparticles and phyllosilicates have been experimentally investigated for their contribution to fire resistance [5]. The outcomes demonstrate that the incorporation of aerogel into the mineral (gypsum) matrix was accomplished using various types of surfactants. The 3-point bending behavior of glass/Kevlar/carbon fiber composites was investigated experimentally [6]. Extensive testing demonstrated that the incorporation of graphene nanoparticles significantly improved the overall strength of the composites, effectively reducing the risk of failure under various mechanical loading conditions. The flexural behavior of lightweight ultra-high-performance fiber-reinforced concrete beams reinforced with GFRP and steel bars with various reinforcement ratios was investigated [7]. The structural behavior of precast concrete beams with joints reinforced with GFRP bars was explored [8]. An experimental study on the structural performance of concrete beams reinforced with prestressed GFRP and steel bars was carried out [9]. A parametric study, finite element analysis, and load capacity calculation were carried out for the flexural behavior of seawater and sea sand concrete beams reinforced with GFRP bars [10]. The fatigue life and behavior of ribbed GFRP-reinforced concrete beams were investigated [11]. The shear behavior of regularly oriented steel fiber-reinforced concrete beams reinforced with glass fiber polymer (GFRP) bars was studied [12]. Out-of-plane impact behavior and post-impact damage of GFRP bar-reinforced concrete shear walls in fire conditions were evaluated [13]. Post-fire performance of hybrid GFRP bars and steel-reinforced concrete columns was investigated [14]. Thermal evaluation of GFRP-reinforced concrete bridge decks was carried out in fire scenarios [15].

Thermal analysis of GFRP-reinforced continuous concrete slabs exposed to top fire was investigated and the effect of concrete cover was discussed [16]. Thermal effects on GFRP reinforcement were investigated by experimental study and analytical analysis [17]. The investigation of the bending strength of Glass Fiber fiber-reinforced polymer (GFRP) bars exposed to thermal load has been studied very limitedly in literature, therefore this subject needs to be investigated. Within the scope of this study, 3-point bending tests were performed on 41 GFRP bar specimens after they were exposed to thermal load at different levels but for equal periods. In this way, the temperature level of the flexural strength of the GFRP bar specimens was investigated experimentally. Flexural strength and weight fluctuation were recorded at temperatures in the range from 22 to 500 °C, these temperature values are suggested in the literature [18].

2. Methods and materials

The experimental investigation of the GFRP bar specimens was conducted using a three-point bending test setup to evaluate their flexural behavior under static loading using the Yüksel Kaya Makina 3-point bending device. The GFRP bar specimens were simply supported with a span length of 100 mm, and a hydraulic testing machine applied controlled incremental loads at the midpoint of the span. A precision displacement transducer was installed at midspan to record deflection, while a load cell accurately measured the applied forces. Each GFRP bar specimen, with dimensions of 10 mm diameter and, 150 mm length, was carefully positioned on the test apparatus, ensuring proper alignment with the supports. The test commenced with the gradual application of the load, and the corresponding deflections were recorded. The test was terminated once the GFRP bar specimen reached its ultimate load-carrying capacity and exhibited visible failure. Critical data, including load-deflection responses, ultimate load, maximum deflection, and failure modes, were documented for each GFRP bar. The mechanical properties of the FRP components fiber and epoxy are presented in Table 1.

Detailed information such as tensile strength, tensile modulus of elasticity, flexural strength, and flexural modulus of elasticity of epoxy is also presented in Table 1.

Fig. 1 illustrates the setup of the three-point bending test conducted on a cylindrical GFRP (Glass Fiber Reinforced Polymer) bar specimen, along with its corresponding dimensions. In this test, the cylindrical specimen is supported at two points while a load is applied at the midpoint to evaluate its bending behavior. The dimensions of the specimen, including its length, diameter, and other relevant parameters, are also provided to help understand the test configuration and its results.

Key parameters, including bending moment, stress, deflection, and geometric details for a circular cross-section GFRP bar specimen beam, were analyzed. The bending strength was defined as the maximum stress experienced at the moment of rupture.

Deflection (Δ) is dependent upon not only the material but also the configuration of cross-section and unsupported length. Max bending stress (σ_{max}), max bending moment (M_{max}), moment of inertia (I), elastic modulus (E) formulas are presented in equations (1)-(4). y is the distance from the center of the specimen to the convex surface.

Table 1. Mechanical properties of the FRP components

Epoxy	Unit	Value	Glass Fiber	Properties	Value
Tensile Strength	MPa	60 ± 6	Glass Type	E	
Tensile Elastic Modulus	GPa	4.0 ± 0.4	Product detail	single-ended	
Strain at Fracture	%	3.0 ± 0.3	Humidity amount (%)	maximum	0.1
Elongation at Break	%	1.5 ± 0.1	Coupling agent	silane	
Flexural Strength	MPa	110 ± 10	Coupling amount (%)	average	0.55±0.15
Flexual Elastic Modulus	GPa	3.6 ± 0.3	Resin Compatibility	Unsaturated Polyester, Vinylester, Epoxy	
Heat Deflection Temperature	°C	127 ± 5	Usage	Pultrusion	

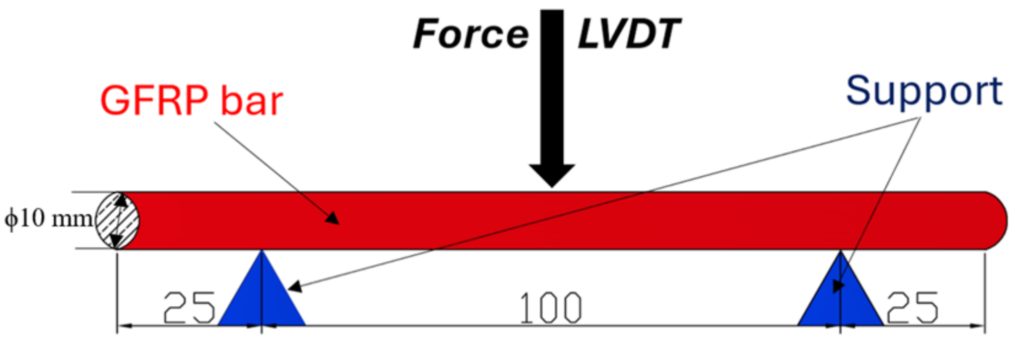

Fig. 1. Schematic Three Point Bending test of cylindrical GFRP bar specimen and dimensions

$$\sigma_{max} = \frac{My}{I} \tag{1}$$

$$M_{max} = \frac{FL}{4} \tag{2}$$

$$I_{circular} = \frac{\pi r^4}{4} \tag{3}$$

$$E = \frac{FL^3}{48\Delta I} \tag{4}$$

3. Thermal analysis

In the tests conducted on GFRP bar specimens, samples exposed to 9 distinct temperatures were used. Among the temperatures used, 22 degrees - room temperature is accepted as the reference sample. Cylindrical GFRP bar specimens were exposed to temperature values of 22 °C, 100 °C, 150 °C, 175 °C, 200 °C, 225 °C, 250 °C, 300°C and 500 °C degrees, respectively, for equal periods of 4 hours. Thermal tests were carried out after the specified temperature was reached and kept constant for 4 hours. Beforehand, the heating rate was kept constant and unchanged. In this way, the effect of temperature level on the bending behavior of cylindrical GFRP bar specimens was obtained more accurately. In addition, the weights of the specimens exposed to thermal effects were recorded by weighing them with the help of a precision scale. Fig. 2 presents the experimental three-point bending test setup of the cylindrical GFRP bar specimen. Table 2 presents the geometric properties, weights, and test details of a total of 47 GFRP bar test specimens. Each cylindrical GFRP bar specimen tested at different temperatures was weighed before exposure to temperature and testing.

The loading rate used in the experiments was fixed and 30.5 Hz was used. In all bending tests, the distance between supports is set as 100 mm. All GFRP bar specimens have a length of 150 mm and a diameter of 10 mm. However, their weights varied between 21 g and 22.5 g. The glass transition temperature of the epoxy resin will remain for approximately 6 days at an operating temperature of 18° C - 20° C. For optimum heat resistance properties, the composite should be cured for one hour at 80° C - 100° C. GFRP bars have glass fiber, and polyester resin content and consist of 4800 tex. The material details of glass fiber and resin are presented in Table 1.

Fig. 2. Experimental Three Point Bending test setup of cylindrical GFRP bar specimen

Table 2. Test matrix

Temperature series (°C)	Specimen No	Diameter ϕ (mm)	Length (mm)	Weight (gr)	Support Span (mm)	Test speed (Hz)
22	N1			22.5		
	N2			22		
	N3			22		
100	N1			22		
	N2			22		
	N3			21.5		
	N4			22		
	N5			21.5		
	N6			21.5		
150	N1			22		
	N2			21.5		
	N3			22		
	N4			22		
	N5			22.5		
	N6			22		
175	N1			21.5		
	N2			22		
	N3			22		
	N4			22.5		
200	N1			21.5		
	N2			22		
	N3			22		
	N4			22.5		
	N5	10	150	21.5	100	30.5
	N6			22		
225	N1			22		
	N2			22		
	N3			22.5		
	N4			21.5		
250	N1			22.5		
	N2			21.5		
	N3			22		
	N4			22		
	N5			22		
	N6			22.5		
300	N1			21.5		
	N2			22		
	N3			22		
	N4			22		
	N5			22.5		
	N6			21.5		
500	N1			22		
	N2			21		
	N3			22		
	N4			22.5		
	N5			21.5		
	N6			22		

Fig. 3 presents the GFRP bar specimens before and after exposure to thermal load for 200-300 and 500 degrees. The color changes are from red to orange, red to black, and red to gray for 200, 300, and 500 degrees, respectively.

Fig. 3. GFRP bar specimens before and after exposure to thermal load for 200-300 and 500 degrees

A total of 47 GFRP bar samples were first exposed to thermal load for 4 hours and then 3-point bending test analysis was completed. Fig. 4. Shows cylindrical GFRP bar specimens subjected to thermal load in the range of 22-500 degrees and whose bending tests were completed. The color of the GFRP bars that were kept at 500 degrees for 4 hours turned from red to gray. However, in the process of taking them out of the oven cabin, it is seen in Fig. 4 that the resin of the GFRP bars completely lost its strength and no longer had any strength, and only the glass fibers turned yellow. While it is observed that the color change begins seriously at 200 degrees, it is noteworthy that the color reaches completely black at 300 degrees. At 225 and 250 degrees, GFRP bar specimens turning light and dark brown are observed. There was no serious color change in the cylindrical GFRP bar specimens at thermal loads of 100 and 150 degrees.

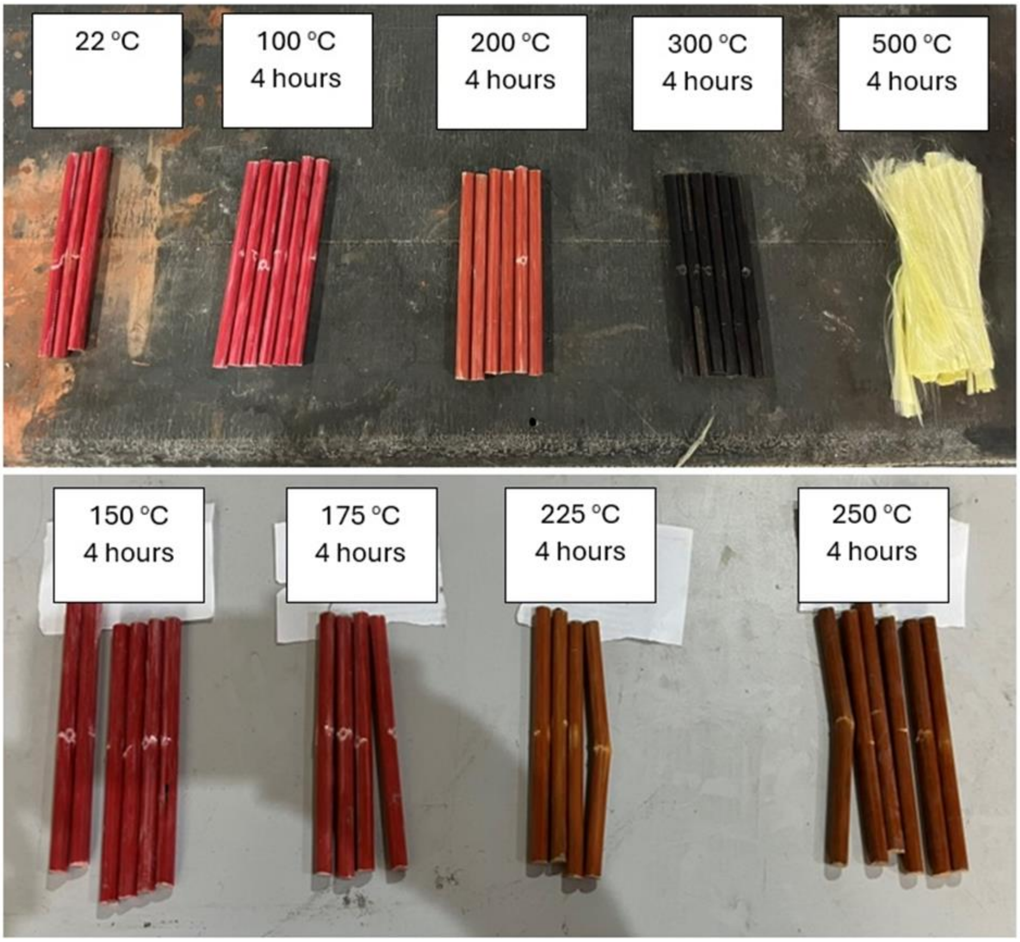

Fig. 4. GFRP bar specimens after thermal load and bending tests between 22-500 degrees

4. Results

After the thermal load application stages were completed for the GFRP bar specimens, 3-point bending tests were performed. In this way, the bending strength of the reference samples at 22 degrees was compared with those exposed to thermal load, and the thermal effect was presented. After thermal analysis, load carrying capacity, deflection, and weight change in GFRP bar specimens were investigated and presented in this section. Fig. 5 presents the ultimate load values and averages carried by GFRP bar specimens at all temperatures.

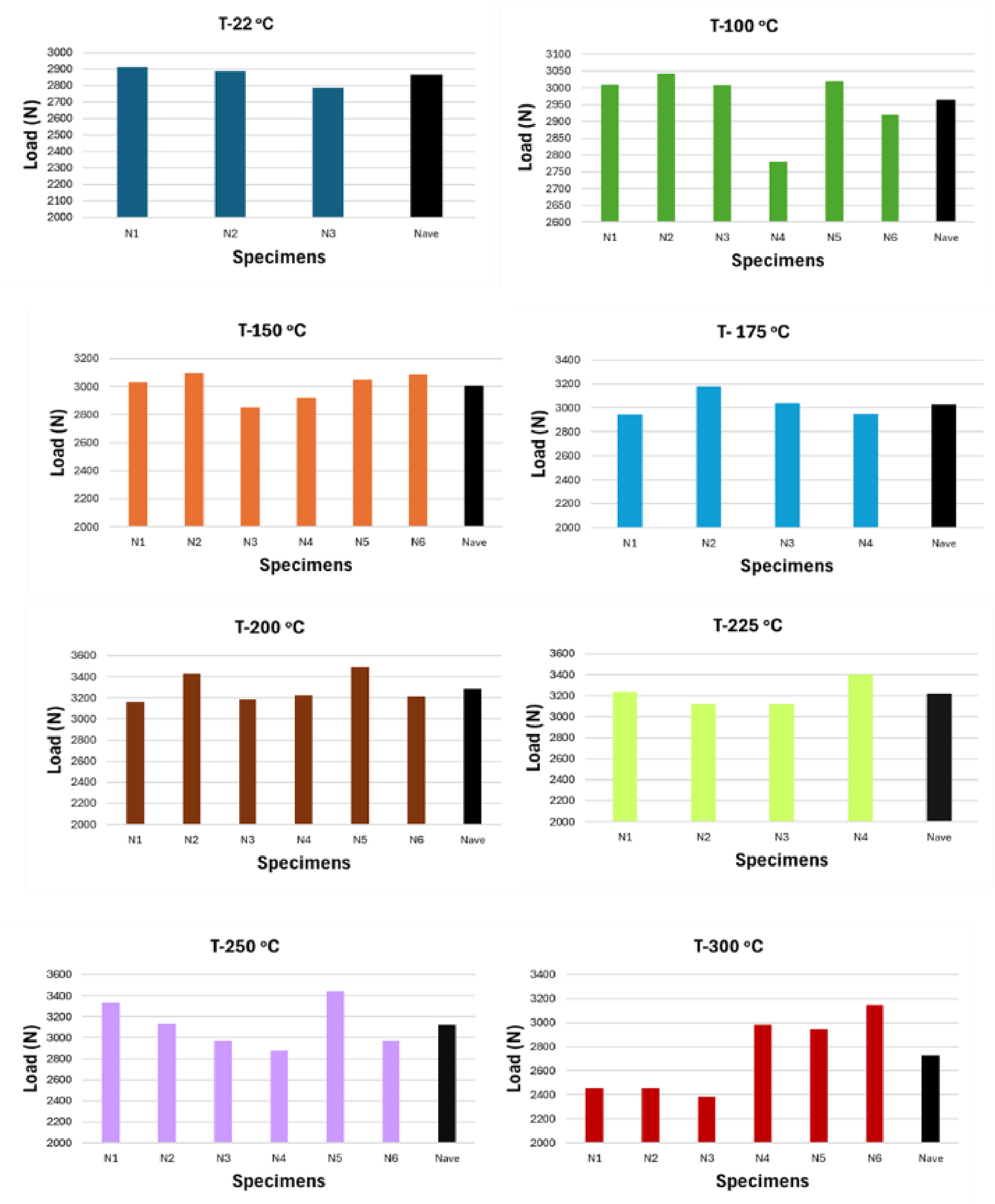

Fig. 5. Average ultimate load carrying capacities of GFRP bar samples after the bending test and thermal load effect

As a result of the analysis, the average maximum ultimate load-carrying capacity of the GFRP bar specimens was obtained at 200 degrees. A decrease in the ultimate load-carrying capacity averages was detected after 200 degrees up to 300 degrees. Fig. 6 gives the average ultimate load-carrying capacities of GFRP bar specimens in all temperature groups. Since the resin of the GFRP bar samples burned at 500 degrees and the bar property was lost, a 3-point bending test could not be performed and the bending strength value at this temperature was accepted as 0.

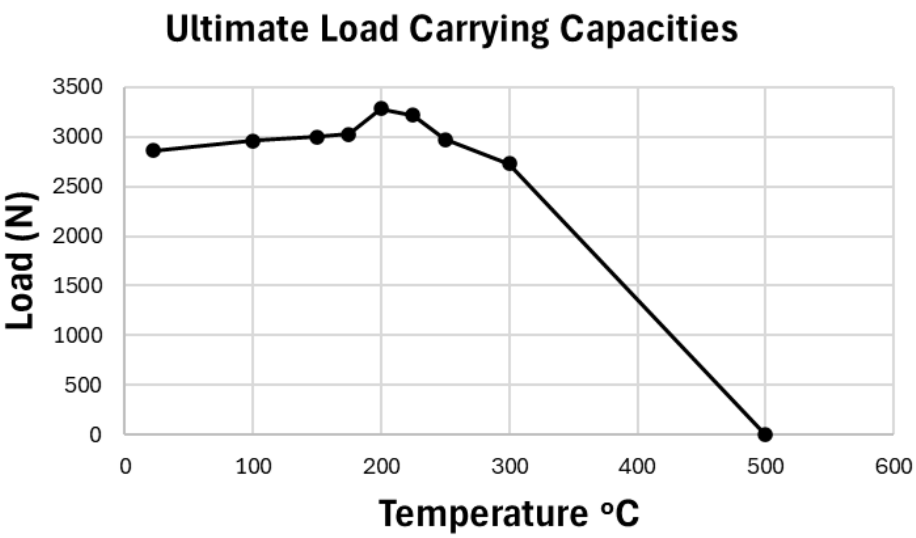

Fig. 6. Average ultimate load carrying capacities of GFRP bar samples after the thermal load and bending test results

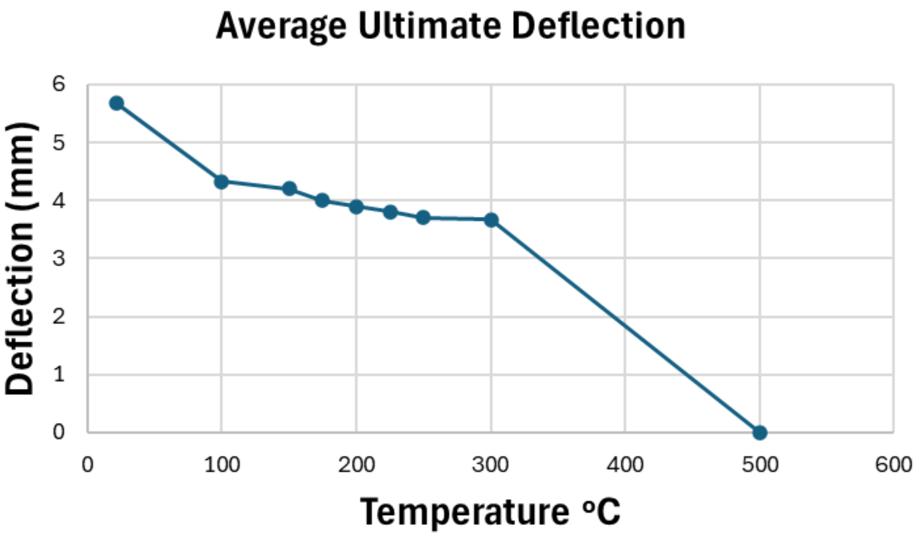

Fig. 7. Average ultimate deflection capacities of GFRP bar samples after the thermal load and bending test

Fig. 7 presents the average of the ultimate deflection values of the GFRP bar specimens for each temperature group. When Fig. 7 is examined, it is seen that the highest deflection value is reached in the samples at normal room temperature (22 ºC).

A decrease of around 35% was achieved between the deflection at 22 degrees and 300 degrees. This situation should be evaluated as a negative effect of the increase in temperature in terms of energy absorption capacity. Fig. 8 shows the weighing stages of cylindrical GFRP bar specimens exposed to different temperatures using a precision balance. A decrease of approximately 4.5% was detected in the mass of GFRP bar samples from 22 degrees to 300 degrees.

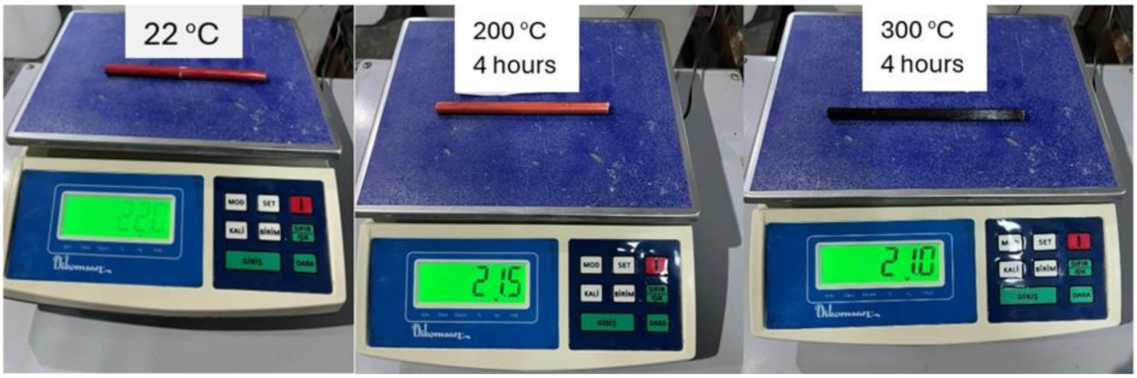

Fig. 8. Examples of weighing GFRP bar samples with precision scales from 22 degrees to 300 degrees

Table 3. Mass reduction of specimens

Temperature, °C	Reduction for the specimen no (g)						
	N1	N2	N3	N4	N5	N6	**Nave**
22	22.5	22	22	-	-	-	**22.17**
100	22	22	21.5	22	21.5	21.5	**21.75**
200	21.5	21.5	21.5	22	21.5	21.5	**21.58**
300	21	20	20.5	20.5	21	21	**20.67**

Table 3 presents the change in mass decrease of the samples according to the temperature increase. The average GFRP bar mass was obtained as 22.17 g at 22 degrees normal room temperature. However, this value was determined to drop to 20.67 g at 300 degrees, the highest temperature measured. It is understood from Table 2 that the average mass reduction of GFRP bar specimens increases as the temperature increases and the average mass of 6 samples is 21.75 g at 100 degrees. The average mass of 6 specimens weighed 21.58 g at 200 degrees.

The reason for examining the weight change of the samples was to understand the effect of the GFRP bar samples on the ultimate load-carrying capacity. A serious relationship between mass loss and mechanical behavior is striking after 200 degrees, especially after 300 degrees, the sudden decrease in the bending load carrying capacity of the GFRP bar samples is seen directly with the melting of the resin.

5. Conclusions

In this study, the bending strength of GFRP composite bar reinforcements, which are used in the construction sector, when exposed to temperature increase was experimentally investigated with 47 cylindrical GFRP bar samples. Important outcomes and recommendations obtained from the research are presented below.

- It was determined that the resin of the specimens completely melted at the highest applied temperature of 500 degrees and the GFRP bars turned into glass fiber filaments at these temperatures.
- Although the strength increases up to 200°C, a reduction in deflection capacity is observed. This matter is attributed to the enhanced initial stiffness of the GFRP bar specimens.
- If GFRP bar reinforcement is to be used in structural elements exposed to thermal loads such as factories, industrial buildings, cooling towers, etc. in case of fire, it is concluded that there will be a serious loss of strength in GFRP bar reinforcement if the temperature exceeds 200 degrees.

- As the temperature increase continued, a decrease in the deflection value was detected, which gives us the result that the GFRP samples exposed to the temperature fractured more brittle.
- The average mass reduction in GFRP bar specimens due to temperature increase was obtained as 6.8% from the comparison of 300 degrees and 22 degrees temperature.
- It is recommended to further develop these studies by including different environmental conditions such as seawater effects.
- At this point, temperature resistances of different composite materials such as carbon (CFRP), basalt (BFRP), and aramid (AFRP) should be tested and comparisons in terms of temperature are recommended.
- Resin, as well as GFRP filaments, plays an important role in the strength of GFRP bar specimens. At this point, it is recommended in the literature to repeat these studies by changing the resin material.

The bending behavior of samples of a specific length under increasing temperature was analyzed at a constant loading rate. Future studies should repeat this analysis with samples of varying lengths and loading rates, while also investigating the impact of support spacing and loading rate on the results.

Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Data availability statement

Data generated during the current study are available from the corresponding author upon reasonable request.

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