Response of GFRP bars at different temperatures

Farid Abed[1,a,*], Zeinah Elnassar[2,b], Wael Abuzaid[3,c], and Yazan Alhoubi[1,d]

[1]Civil Engineering Department, American University of Sharjah, Sharjah, United Arab Emirates

[2]Materials Science and Engineering Department, American University of Sharjah, Sharjah, United Arab Emirates

[3]Mechanical Engineering Department, American University of Sharjah, Sharjah, United Arab Emirates

[a]fabed@aus.edu, [b]g00062755@aus.edu, [c]wabuzaid@aus.edu, [d]b00052990@aus.edu

Keywords: GFRP, DIC, Compression, Elevated Temperature

Abstract. Owing to their numerous advantages, industries have been adopting fiber-reinforced polymer (FRP) bars as reinforcement in concrete members due to their superior mechanical properties and high durability. More specifically, glass FRP (GFRP) bars have been increasingly adopted for use in harsh environmental conditions due to their excellent corrosion resistance. However, the compressive response of the GFRP bars at high temperatures has yet to be studied. This paper presents the results of an experimental study that aims to investigate the mechanical behavior of glass fiber reinforced polymers (GFRP) bars subjected to compressive loads at various elevated temperatures and deformation rates. Four different temperatures, ranging between ambient and 150°C, and two deformation rates were considered. The compressive strength and the modulus of elasticity for each bar sample are measured and the failure modes are demonstrated. It was observed that the compressive strength of GFRP bars is similar under both loading rates for all temperature conditions. However, the elastic modulus of the bars showed a slight discrepancy between the different load rates, especially at an elevated temperature of 150°C. The test results indicate a linear degradation in the mechanical properties as the temperature is raised. In addition, the observed failure mode for the tested samples is splitting of the bars.

Introduction

Over recent years, polymers have been replacing metals and ceramics in engineering applications. This is primarily attributed to some of the polymers' impressive properties which include being lightweight, easily fabricated, and their ability to be processed at low temperatures [1]. An important characteristic of polymers which makes them attractive in the construction industry, is their resistance against corrosion. The deterioration of the infrastructure owing to the corrosion of steel reinforcement has been one of the major concerns in the construction industry [2]. To avoid infrastructure deterioration and loss of durability caused by corrosion of steel rebars in concrete structures, FRP bars have been used as an alternative to steel reinforcement in reinforced concrete structures due to their many advantages which include being corrosion-resistant and non-conductive. The noncorrosive FRP bars have shown promise as a way to further improve and protect concrete structures like bridges, that are directly affected by the damaging outcomes of corrosion. In addition, GFRP possesses the advantage of being more economical than other types of FRP, including aramid and carbon, thus, making this specific FRP bar type more attractive to be used for infrastructure applications [2].

Although several research studies have been conducted to characterize GFRP as longitudinal reinforcement, little information have been provided about their compressive strength, in particular, as a function of temperature and deformation rate. Extensive research studies have been conducted on the behavior of FRP bars under tension [3,4] and the performance of FRP-reinforced beams under shear [5-7]. As a general design practice, the compressive strength of GFRP bars is neglected during the design stage, according to ACI 440.11-22 [8]. This is due to the gap in literature regarding the response of such bars under compressive loading and due to the GFRP's elastic modulus, that is as low as that of concrete.

Alnajmi and Abed [9] investigated the performance of FRP bars under compression and examined the behavior of the bars as main reinforcement in columns. The experimental study consisted of a series of compression tests conducted on GFRP and BFRP bars. The results showed an increase of up to 35% of the failure loading in columns reinforced with FRP bars.

Khan et al. [10] investigated the behavior of GFRP bars under compression and tension with bar specimens having 12 mm diameter and 48 mm length. All the specimens failed prematurely due to splitting at the bar ends. The results showed that the compressive average maximum load of the specimens was 60% less than that of the average maximum load recorded under tensile loading. Abed et al. [11] conducted a series of quasi-static and dynamic load tests on GFRP and basalt FRP (BFRP) bars having different diameters (12, 17, 21, and 27 mm) with different loading rates (0.1, 1.0, and 10.0 mm/min) in order to investigate the compressive strength of such bars. The results showed that the compressive strength of GFRP and BFRP increased as the loading rate was increased. Also, the compressive strength increases as the bar diameter increases, for all FRP specimens. Similar to the results obtained from [10], the failure mode of the specimens was a premature failure at the bar ends. Thiyagarajan et al. [12] conducted an experimental study on the characteristics of basalt FRPs (BFRP) bars with different diameters of 8, 10, and 12 mm. The study revealed that the compressive strength of the BFRP bars was about 50% of the tensile strength. In addition, the ultimate compressive strength of the BFRP bars showed a slight increase as the diameter of the bar increases.

Despite the scarcity of available experimental studies investigating the compression response of FRP bars, many researchers have already accepted the use of FRP bars as a reinforcement in concrete structural members.

This paper aims to investigate the compressive properties of GFRP bars at high temperatures ranging from 25°C to 150°C. The recent ACI 440.11-22 code [8] disregards the compressive strength of GFRP reinforcement at high temperatures due to the loss of stiffness of the polymer which occurs at elevated temperature and results in buckling of the fibers. The motivation behind this work is to fill the gap in the literature regarding the compressive strength of GFRP bars at up to 150°C temperatures and provide experimental results that can be used to study the thermal response of FRP-reinforced concrete structures.

Test Set-Up and Procedure

In this research, GFRP bars of 12 mm diameter were tested under compression at four distinct temperatures of room-temperature (RT), 50, 100, and 150°C. The length of the specimens was taken to be twice the diameter of the GFRP bars (i.e., around 24 mm) in order to prevent buckling.

All tests were conducted using the universal screw-driven INSTRON test machine equipped with an environmental chamber. A high-temperature black paint was used to generate a suitable speckle pattern for full-field deformation measurements using Digital Image Correlation (DIC). Compression displacement-controlled loading was applied at two constant rates (i.e., crosshead speeds) of 0.5 and 1000 mm/min until failure. Prior to loading, the environmental chamber was used to heat the specimen to the desired deformation temperature followed by a 30-minute soaking time to ensure a homogenous temperature distribution for the entire GFRP specimens. During the tests, images of the specimens' surface were captured, and a commercial DIC software (Vic-2D 6, Correlated solutions, USA) was used the measure the displacement fields and calculate the resulting strains.

The test setup is shown in Fig. 1 and a representative specimen installed between the compression grips is shown in Fig. 2.

Figure 1: Test set-up using the DIC machine.

Figure 2: GFRP bar subjected to compressive loading.

Results and Discussion

As mentioned in the previous sections, this paper focuses on evaluating the temperature-dependent mechanical properties (compressive strength and elastic modulus) of GFRP bars subjected to compressive loading at various temperatures. Fig. 3 and Fig. 4 depict the compressive strength and elastic modulus for the 12 mm GFRP bars under various temperatures, ranging from room temperature (RT) to 150°C, and for the slow and fast rates, respectively. It is important to note that the values of the compressive strength and elastic modulus represent the average values obtained from about 4 different specimens for each testing condition.

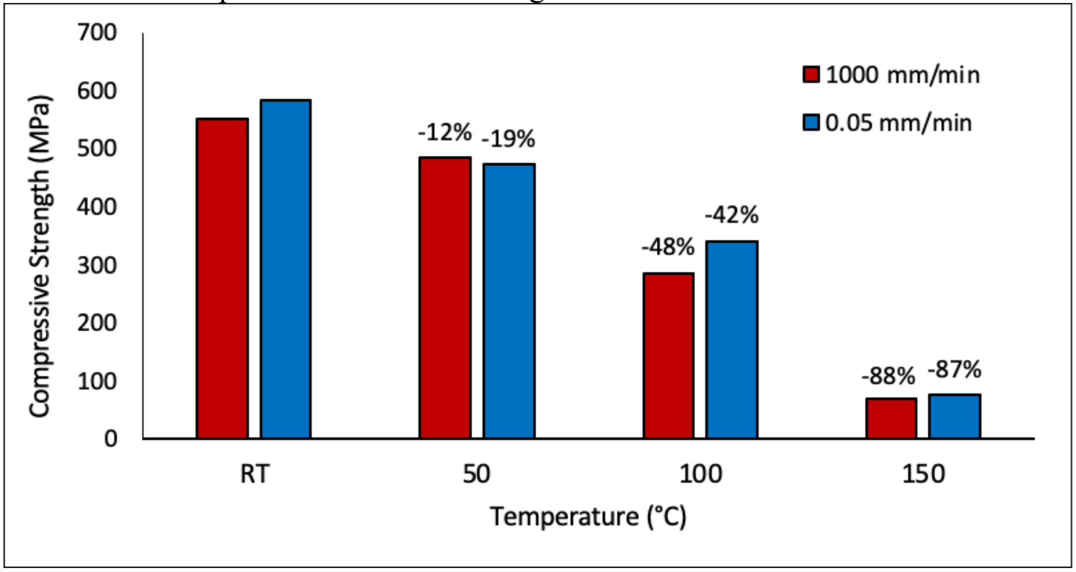

Figure 3: Average compressive strength for 12 mm GFRP bar.

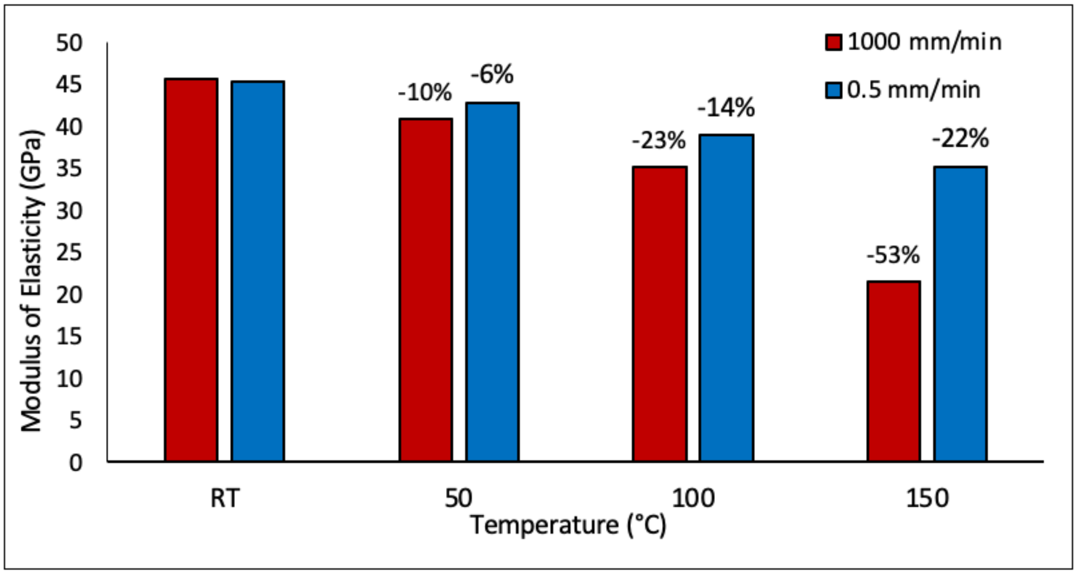

Figure 4: Average elastic modulus for 12 mm GFRP bar.

At room temperature, the compressive strength of GFRP at a loading rate of 0.5 mm/min is around 550 MPa, and it degrades by 19% and 42% at elevated temperatures of 50°C and 100°C, respectively. At 150°C temperature, the strength significantly decreases by up to 87%, as this temperature exceeds the glass transition temperature (T_g) of GFRP. The modulus of elasticity of the GFRP bars at ambient temperature for the 0.5 mm/min loading rate is recorded as 45 GPa and it decreased by 6%, 14%, and 22% as the temperature reached 50°C, 100°C, and 150°C, respectively. By comparing the rates shown in Figure 3, one can observe that the loading rate does not play a significant role in the performance of the bars, considering the strength perspective. In other words, the compressive strength of GFRP bars under a loading rate of 1000 mm/min depicted a great agreement to that of the slow rate (0.5 mm/min), in which the strength was reduced by 12%, 48%, and 88% when subjected to 50°C, 100°C, and 150°C, respectively. However, the modulus of elasticity of GFRP (shown in Figure 4) subjected to a loading rate of 1000 mm/min displayed a greater reduction of 53% at a temperature of 150°C, when compared to the 22%

reduction for the 0.5 mm/min rate. The observed failure modes of some tested specimens are shown in Fig. 5. It is evident from the figure that the governing failure mode of the specimens is splitting of the bar in half. Splitting occurred after the crushing load exceeds the strength of the bar. In addition, buckling was not observed as the length-to-diameter ratio was kept as 2.0.

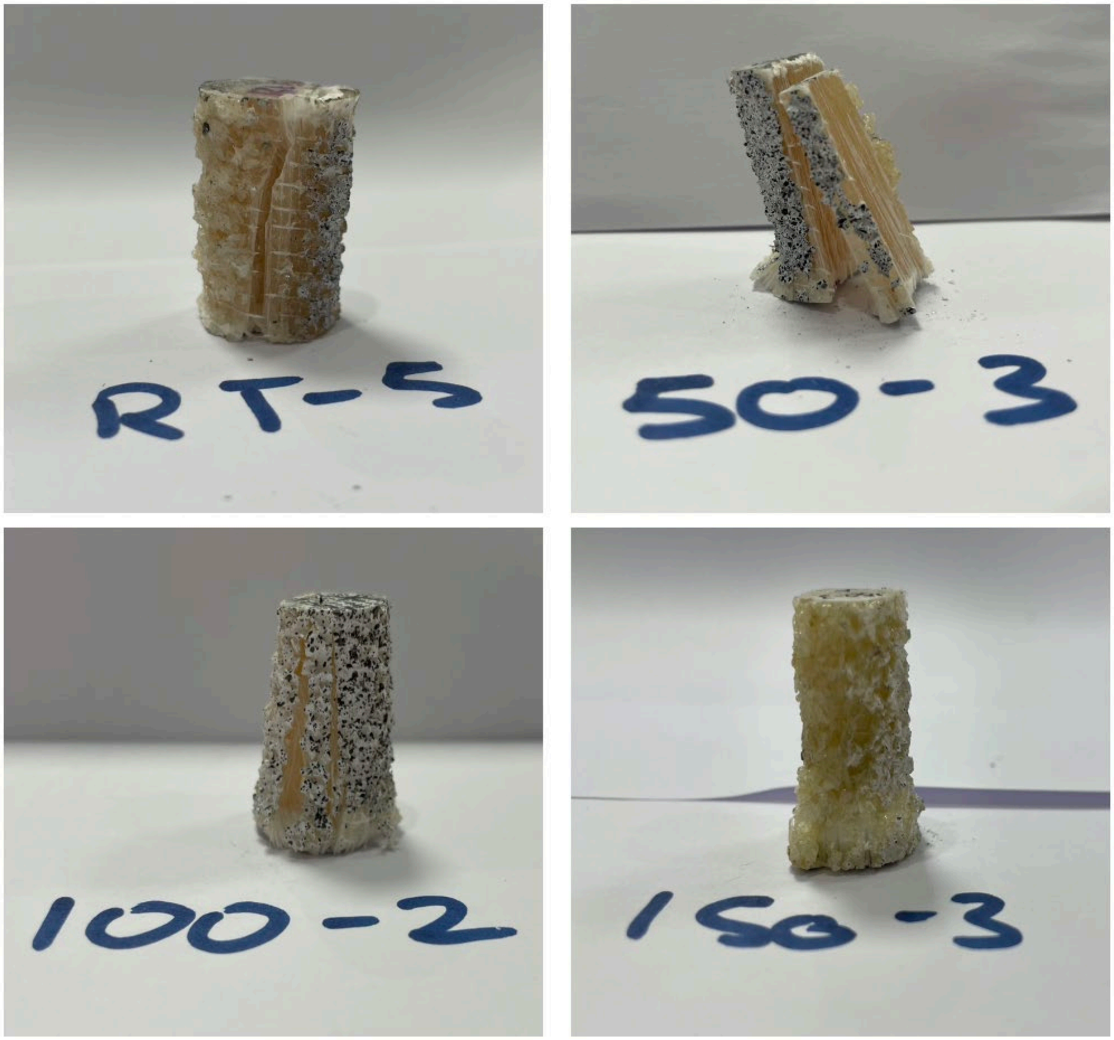

Figure 5: Failure modes of the tested specimens subjected to different temperatures.

Summary and Conclusions

GFRP bars were tested at different temperatures ranging from ambient (25°C) to 150°C in order to investigate the degradation in the mechanical properties (compressive strength and modulus) of the bars at elevated temperature, while simultaneously being subjected to compressive loads. The different parameters examined in this paper are the temperature and rate of loading.

The following observations and conclusions were drawn after the test results:

1. Generally, the modulus of elasticity and the compressive strength of GFRP bars degrade linearly as the temperature is raised from 25°C to 150°C.
2. For the compressive strength, the experimental results reported similar average stress values as the rate of loading increased from 0.5 mm/min to 1000 mm/min.
3. The average compressive strength at 150°C for the 0.5 mm/min and 1000 mm/min rates are 75.4 MPa and 68.4 MPa, respectively. However, the elastic modulus at 150°C with the 0.5 mm/min rate is 35.2 GPa and 21.53 GPa with the 1000 mm/min for the fast rate. This

further proves a discrepancy between the elastic modulus at different loading rates, as opposed to the compressive strength.

4. Splitting of the bars without premature crushing or buckling was the governing observed failure mode for the tested specimens.

References

[1] T.E. Glodek, S.E. Boyd, I.M. Mcaninch, J.J. Lascala, Properties and Performance of Fire Resistant Eco-Composites Using Polyhedral Oligomeric Silsesquioxane (POSS) Fire Retardants, J. Compos. Sci. Technol. (2008) 2994-3001. https://doi.org/10.1016/j.compscitech.2008.06.019

[2] B. Benmokrane, E. El-Salakawy, A. El-Ragaby, and T. Lackey, Designing and testing of concrete bridge decks reinforced with Glass Frp Bars, J. of Bridge Eng. (2006) 217-229. https://doi.org/10.1061/(ASCE)1084-0702(2006)11:2(217)

[3] A. Serbescu, M. Guadagnini, K. Pilakoutas, Mechanical Characterization of basalt FRP rebars and Long-Term strength Predictive model, J. Compos. Constr. 12 (2014) 1-13. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000497

[4] M. Al Rifai, H. El-Hassan, T. El-Maaddawy, F. Abed, Durability of basalt FRP reinforcing bars in alkaline solution and moist concrete environments. J. Constr. and Build. Materials. (2020). https://doi.org/10.1016/j.conbuildmat.2020.118258

[5] F. Abed, A. El Refai, S. Abdalla, Experimental and finite element investigation of the shear performance of BFRP-RC short beams, J. Struct. 20 (2019) 689-701. https://doi.org/10.1016/j.istruc.2019.06.019

[6] F. Abed, H. El-Chabib, M. AlHamaydeh, Shear characteristics of GFRP-reinforced concrete deep beams without web reinforcement, J. Reinf. Plast. Compos. 31 (16) (2012) 1063-1073. https://doi.org/10.1177/0731684412450350

[7] A. Al-Tamimi, F. Abed, A. Al-Rahmani, Effects of harsh environmental exposures on the bond capacity between concrete and GFRP reinforcing bars. Advances in concrete construction (2014). https://doi.org/10.12989/acc2014.2.1.001

[8] American Concrete Institute, "Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars," ACI 440.11-22, ACI Committee 440, Farmington Hills, MI, USA, 2022.

[9] L. AlNajmi, F. Abed, Evaluation of FRP bars under compression and their performance in RC columns, J. Materials (2020). https://doi.org/10.3390/ma13204541

[10] Q.S. Khan, M.N. Sheikh, M.N. Hadi, Tension and compression testing of fibre reinforced polymer (FRP) bars, 12th Int. Symp. Fiber Reinf. Polym. Reinf. Concr. Struct. FRPRCS-12 5th Asia-Pac. Conf. Fiber Reinf. Polym. Struct. APFIS-2015 Jt. Conf., Nanjing, China: Z. Wu, G. Wu & X. Wang; (2015).

[11] F. Abed, Z. Mehaini, C. Oucif, A. Abdul-Latif, R. Baleh, Quasi-static and dynamic response of GFRP and BFRP bars under compression, J. Compos. Part C Open Access 2 (2020) 100034. https://doi.org/10.1016/j.jcomc.2020.100034

[12] P. Thiyagarajan, V. Pavalan, R. Sivagamasundari, Mechanical characterization of basalt fiber reinforced polymer bars for reinforced concrete structures, Int. J. Appl. Eng. Res. 13 (8) (2018) 5858-5862.