Research on the residual tensile strength of composite reinforcing bars exposed to elevated temperatures

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Abstract. Paper describes a testing procedure for the determination of tensile strength of the composite reinforcing bars subjected to elevated temperatures. Experimentally obtained results on GFRP bars with different diameter are presented and discussed. Moreover, a brief comparison with an analytical approach was included. Almost identical temperature reduction rate of tensile strength was observed for all tested specimens, regardless diameter of the bar. Therefore, it can be expected, that different bar diameter should not significantly affect the results especially if steady state conditions were assumed.

1. Introduction

New materials and methods for improving energy performance and long-life of constructions are the main topics of the present building industry. Over the last decade, increasing attention is paid to the fiber-reinforced polymers (FRP) as a durable and corrosion resistant alternative to the traditional steel rebar.

Elevated temperatures are known to significantly affect the properties of FRP reinforcement. Still, those effects have not yet been thoroughly investigated. For that reason, this topic is the research subject of many recent experimental studies. For example, Blontrock et al. [1], presented extensive experimental results including FRP reinforcement with glass, aramid and carbon fibers. Furthermore, based on abovementioned experimental study, Saafi [2] defined temperature reduction factors of both tensile strength and modulus of elasticity.

A similar study was carried out by Hamad et al [3], showing that the FRP bars suffered significant reductions in their mechanical properties upon exposure to high temperatures up to 450°C. The percentage decrease of mechanical properties under elevated temperatures was more pronounced in specimens with FRP bars, comparing to the commonly used steel reinforcement. Also, Hajiloo et al [4] presented a comprehensive study on characteristics of glass fiber-reinforced polymers (GFRP) bars in both steady state and transient state temperature conditions. The temperature ranged from 25–500°C, while the applied tensile load varied between 20 and 70%. All tested bars exhibited loss of strength and stiffness at high temperatures. Somewhat different approach was presented by Ellis et al. [5]. Properties of GFRP bars were investigated after exposure to elevated temperatures up to 400°C and subsequent cooling to an ambient temperature. As can be expected, tensile strength generally decreases with increasing temperature exposure. However, for specimens preheated to 400°C, as much as 83% of the original tensile strength was retained.
Recently, Ashrafi et al. [6] presented the study that included effects of different bar diameters, type of fiber, type of resin, and fiber to matrix ratio on thermal properties of the FRP rebars. Authors also presented comparison between experimentally obtained tensile strength retention and analytical predictions available in the literature, like for ex. [2]. Within the scope of the experimental study presented in this paper, effects of exposure to elevated temperatures on tensile properties of GFRP reinforcement were assessed assuming steady state temperature conditions. The study included bars with three different diameters, exposed to five temperature levels. Finally, obtained results were compared with the analytical approach presented in [2].

2. Experimental analysis

The main aim of the experimental program was to evaluate the effects of elevated temperature on tensile properties of GFRP reinforcement. The analysis consisted of 3 distinctive phases, namely: preheating, soak-time and mechanical loading.

Firstly, specimens were preheated to desired temperature, in the range of 60 to 280°C, followed by so called “soak-time”, as described in Section 2.2.1. Finally, heated specimens were continuously loaded in tension until failure (see Section 2.2.2.).

2.1. Material properties

GFRP composite reinforcing bars with various diameters were used (8, 10 and 14 mm). GFRP bars are composed of approximately E-CR glass fibers (80% by weight), and epoxide matrix. Glass transition temperature $T_g$ of the resin is 110–120°C [7]. During a pultrusion process, surface of the reinforcing bars was sand-coated to ensure sufficient bond with concrete. The assessed bars have developed and produced in the Czech Republic, by Prefa Kompozity a.s. and further labelled as “Prefa ReBar”.

Referential tensile properties were obtained experimentally at room temperature (approx. 20°C), namely tensile strength $f_{tu}$ and modulus of elasticity $E_f$. Tests were performed according to the standardized test method, described in ASTM D7205 / D7205M - 06(2016) [8] or ISO 10406-1:2015 [9]. The specimens 1,000 mm in length have been loaded using displacement control at a rate of 4 mm/min, corresponding to approximately 200 MPa/min. Modulus of elasticity was determined for a load range between 15–80%, to ensure that results are not affected by the slight movement between anchors and testing grips at the beginning of loading. Obtained results were summarized in table 1.

| Bar Type                                | Prefa ReBar       |
|-----------------------------------------|-------------------|
|                                        | G8    | G10   | G14   |
| Fiber type 1)                           | [-]   | E-CR Glass |
| Matrix type 1)                          | [-]   | epoxy  |
| Fiber content by weight 1)              | [%]   | 80    |
| Nominal diameter 1)                     | [mm]  | 8     | 10    | 14    |
| Actual diameter (with surface treatment)| [mm]  | 9.0   | 11.0  | 15.1  |
| Tensile strength $f_{tu}$               | [MPa] | 1,042 | 1,019 | 871   |
| Modulus of Elasticity $E_f$             | [GPa] | 55.0  | 52.5  | 43.3  |

1) According to manufacturer specifications [7]

2) The G14 reinforcement was produced in a different batch (with a different ratio of the matrix components).

As defined by [8, 9], steel anchors were used, due to the low transverse strength of the FRP reinforcement. Oppose to mentioned standardized tests, the total length of the specimen was 1,600 mm, while only the middle part of 580 mm was subjected to elevated temperatures.
2.2. Methods

2.2.1. Heating. The test specimens were subjected to successive heating in the electric temperature chamber TH2700 Grip-Engineering to required temperatures of 60, 100, 200, or 280°C, referred to as preheating. The heating rate of 6°C/min on average was kept, following other similar studies. For example, [10] reported an approximate rate of 7.5°C/min, while [4] reported temperature increase rate of 5.0°C/min, simulating average conditions of the bars embedded in concrete.

After preheating phase, the temperature was maintained for an additional 10 minutes to ensure a uniform temperature throughout the rebar cross section, i.e., soak-time (see figure 2). One set of specimens was left untreated, to serve as referential.

During testing, the temperature was measured on the surface of the specimens by thermocouples, in the middle (denoted as TC2-C) and 100 mm from chamber surfaces (TC1-B at the bottom and TC3-T at the top). The temperature was also measured by a built-in sensor TC0-F near the inner surface of the chamber at one half its height to ensure required time-temperature curves.

2.2.2. Mechanical testing. Once the heating phase was completed, mechanical testing was performed while maintaining the required temperatures. Thus, the tensile stress was mechanically induced to the heated specimens. The loading test was performed using the LabTech 250 mechanical universal testing machine with hydraulic jaws.

Figure 1. Steady state testing of elevated temperature effects to GFRP rebar tensile properties.

Pure tensile stress was induced by increasing deformation at a constant displacement rate of 6 mm/min until failure. Testing the specimen using the universal tensile testing machine equipped with a temperature chamber is shown in figure 1.
3. Results and discussion
The failure of all specimens could be characterized as brittle, as it can be seen in figure 2. Besides the load-time curve (red line), temperature-time curves for four different temperatures measured using thermocouples, as described in Section 2.2.1, were also presented.

The typical failure mode of specimens after the exposure to elevated temperature and mechanical loading can be observed in figure 3.

![Figure 2](image1.png)

**Figure 2.** Dependence of load and temperature on time during a test of GFRP tensile properties – test example of specimen G14_4 ($F_{\text{max}}=100.88$ kN, $T_{\text{max}}=212.9^\circ$C).

![Figure 3](image2.png)

**Figure 3.** Typical tensile failure of the specimens subjected to moderate temperature $60^\circ$C (left) and elevated temperature $200^\circ$C (right).
Relative tensile strength was used for comparison between presented experimental results and other research studies available in literature. It was defined as the ratio between the tensile strength of the bars obtained at ambient temperature of 20°C (labeled as $f_{t,20}$) and tensile strength of the specimen subjected to elevated temperatures $f_{t,T}$ (Figure 4). The obtained results, which are summarized in Table 2, include nominal temperature $T_{nom}$, maximum temperature $T_{max}$ and ultimate applied load $F_{max}$.

Maximum temperature corresponds to the ultimate applied load $F_{max}$ at the time of the specimen failure. It is defined as a maximum value measured by the thermocouples at the surface of the specimen. Nominal temperature $T_{nom}$ was measured inside the high-temperature chamber using built-in thermocouple probe.

Saafi [2] defined reduction of GFRP reinforcement tensile strength, based on the experimental results presented by [1] using temperature reduction factor $k_f$,

$$\frac{f_{t,T}}{f_{t,20}} = k_f$$

$$k_f = 1 - 0.0025T \quad \text{for} \quad 0 \leq T \leq 400°C$$

$$k_f = 0 \quad \text{for} \quad T \geq 400°C$$

where $f_{t,20}$ and $f_{t,T}$ are the ultimate tensile strength of FRP rebars at 20°C and $T°C$ respectively.

| Type of rebar | Specimen | $D$ [mm] | $T_{nom}$ [°C] | $T_{max}$ [°C] | $F_{max}$ [kN] | $f_{t,T}$ [MPa] | $f_{t,T}/f_{t,20}$ [%] |
|---------------|----------|----------|----------------|----------------|----------------|------------------|---------------------|
| G8            | G8_1     | 8        | 20             | 20.0           | 52.38          | 1042.07          | 100.0              |
|               | G8_2     | 8        | 60             | 67.4           | 44.89          | 893.06           | 85.7               |
|               | G8_3     | 8        | 100            | 109.1          | 40.19          | 799.55           | 76.7               |
|               | G8_4     | 8        | 280            | 298.1          | 38.55          | 766.93           | 73.6               |
| G10           | G10_1    | 10       | 20             | 20.0           | 80.01          | 1018.76          | 100.0              |
|               | G10_2    | 10       | 60             | 66.8           | 64.09          | 816.02           | 80.1               |
|               | G10_3    | 10       | 100            | 110.1          | 60.13          | 765.60           | 75.2               |
|               | G10_4    | 10       | 200            | 211.6          | 57.53          | 732.49           | 71.9               |
|               | G10_5    | 10       | 280            | 296.3          | 62.40          | 794.50           | 78.0               |
| G14           | G14_1    | 14       | 20             | 20.0           | 134.10         | 871.16           | 100.0              |
|               | G14_2    | 14       | 60             | 66.9           | 116.57         | 757.25           | 86.9               |
|               | G14_3    | 14       | 100            | 110.6          | 97.96          | 636.36           | 73.0               |
|               | G14_4    | 14       | 200            | 212.9          | 100.88         | 655.33           | 75.2               |
|               | G14_5    | 14       | 280            | 288.9          | 103.45         | 672.02           | 77.1               |
**Figure 4.** Residual tensile strength $f_{t,T}$ of GFRP bars exposed to elevated temperatures.

**Figure 5.** Comparison between relative tensile strength of GFRP bars and predicted values [2].
As it can be observed in figure 5, a good correlation between proposed analytical expression [2], defined using equations (1–3), was obtained for the temperatures up to the approximately 110°C. Due to the effects of elevated temperatures, the tensile strength of GFRP bars was reduced to about 70%. The abovementioned temperature of 110°C roughly corresponds to the glass transition temperature \( T_g \) of the used epoxy matrix of assessed GFRP bars.

On the other hand, for higher temperatures ranging up to 300°C, proposed values of the temperature reduction factor \( k \) seems rather conservative. Almost no further decrease in tensile strength was experimentally observed for the temperatures in this range. Similar results have been presented by Wang et al. [11], based on experimental results obtained on CFRP pultruded plates. Good correlation between experimental data and the analytical model presented by Gibson [12] was observed. Chowdhury et al [13] calibrated Gibson’s [12] equations based on the tests on GFRP coupon, showing even degradation rate, comparing to the CFRP plate coupons presented in [11, 12]. This is also in accordance with CAN/CSA S806 [14], since critical temperature of 325°C was permitted for GFRP bars adequately anchored in so called “cold-zone”, i.e., in the area which is not affected by elevated temperatures.

The almost identical temperature reduction rate of tensile strength was observed for all tested specimens, regardless diameter of the bar. Therefore, it can be expected that different bar diameter should not significantly affect the results, especially if steady state conditions were assumed. On the other hand, Wang et al. [11] concluded that bars with larger diameter shown higher resistance under elevated temperatures. Hence, considering the effect of a bar’s diameter in further research is highly recommended.

4. Conclusion

Based on presented experimental analysis it can be concluded that:

- Most of the tensile strength of GFRP bars with epoxy matrix can be expected to be retained for temperatures up to the glass transition temperature \( T_g \). Reaching the \( T_g \), the tensile strength of GFRP bars was reduced only to about 70% of the reference (unheated) sample value.

- For higher temperature range, i.e., between \( T_g \) and 300°C, only slight loss of tensile strength is likely to be observed. This is also in accordance with, for example, CAN/CSA S806, since a critical temperature of 325°C was permitted for GFRP bars adequately anchored in the so-called “cold-zone”, i.e., in the area that is not affected by elevated temperatures. Hence, for the temperature ranging up to 300°C, reduction of the tensile strength caused by elevated temperatures is governed mainly by the properties of the matrix, not the fibers.

- The GFRP bars can be used as reinforcement of concrete for the temperature of use below \( T_g \). In the event of a fire or other unexpected events, the GFRP reinforcement will ensure sufficient stability of the concrete element if the bars are adequately anchored in so-called “cold-zone”.

Still, further research is needed to prove the abovementioned hypothesis, including the assessment of different bar diameters, matrix types and fibers.

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References

[1] Blontrock H, Taerwe L and Matthys S 1999 Properties of fiber reinforced plastics at elevated temperatures with regards to fire resistance of reinforced concrete members in Fourth International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures 188 pp 43–54

[2] Saafi M 2002 Effect of fire on FRP reinforced concrete members Composite Structures 58 pp 11–20
[3] Hamad R, Megat J, Megat A and Haddad R 2017 Mechanical properties and bond characteristics of different fiber reinforced polymer rebars at elevated temperatures Construction and Building Materials 142 pp 521–535 DOI: 10.1016/j.conbuildmat.2017.03.113.

[4] Hajiloo H, Green M F and Gales J 2018 Mechanical properties of GFRP reinforcing bars at high temperatures Construction and Building Materials 162 pp 142–154 DOI: 10.1016/j.conbuildmat.2017.12.025.

[5] Ellis D, Tabatabai H and Nabizadeh A 2018 Residual Tensile Strength and Bond Properties of GFRP Bars after Exposure to Elevated Temperatures Materials 11(3) DOI: 10.3390/ma11030346.

[6] Ashrafi H, Bazli M, Najafabadi E P and Oskouei A V 2017 The effect of mechanical and thermal properties of FRP bars on their tensile performance under elevated temperatures Construction and Building Materials 157 pp 1001–1010 ISSN 09500618 DOI:10.1016/j.conbuildmat.2017.09.160.

[7] Prefa Kompozity, a.s.: Datasheet KOMPOZITNÍ VÝZTUŽE PREFA Rebar 2017 (available from: https://www.prefa-kompozity.cz/wp-content/uploads/2015/09/katalog_kompozitni_vyztuze_cze_m.pdf)

[8] ASTM D7205/D7205M-06: 2016 Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars (West Conshohocken, USA: ASTM International)

[9] ISO 10406-1:2015 Fibre-reinforced polymer (FRP) reinforcement of concrete — Test methods — Part 1: FRP bars and grids. 2. (Geneva: International Organization for Standardization)

[10] Correia J, Gomes M, Pires J and Branco F 2013 Mechanical behaviour of pultruded glass fibre reinforced polymer composites at elevated temperature: Experiments and model assessment Composite Structures pp 303–313 DOI:10.1016/j.compstruct.2012.10.051.

[11] Wang K, Young B and Smith S T 2011 Mechanical properties of pultruded carbon fibre-reinforced polymer (CFRP) plates at elevated temperatures Engineering Structures 33(7) pp 2154–2161 ISSN 01410296. DOI:10.1016/j.engstruct.2011.03.006.

[12] Gibson AG, Wu Y S, Evans J T and Mouritz A P 2006 Laminate theory analysis of composites under load in fire Journal of Composite Materials 40(7) pp 639–657

[13] Chowdhury E U, Eedson R, Green M F, Bisby L A and Benichou N 2009 Mechanical characterization of fibre reinforced polymers materials at high temperature Fire Technology 45(4) pp 1–18

[14] CAN/CSA S806-12: 2012 Design and Construction of Building Structures with Fibre-reinforced Polymers (Toronto, Canada: CSA Group)