Material Characteristics of Glass Fibre Reinforced Polymer (GFRP) Bars at High Temperature

Hamzeh Hajiloo[1], John Gales[2], Martin Noël[1], Mark F. Green[1]

[1] Civil Engineering, Queen's University, 58 University Avenue, Kingston ON Canada K7L 3N6
[2] Civil and Environmental Engineering, Carleton University, 3432 Mackenzie, 1125 Colonel By Drive, Ottawa ON Canada K1S 5B6

(FIRST PAGE OF ARTI CLE)

ABSTRACT

The lack of adequate information on glass fibre reinforced polymer (GFRP) material characteristics at high temperatures lowers the accuracy of analytical and design models developed to predict the behaviour of GFRP reinforced concrete members. This paper presents experimental results of a series of tensile tests on GFRP bars at elevated temperatures. These results are a part of ongoing comprehensive material tests on various GFRP products from different manufacturers. Up until now, material tests conducted on GFRP bars have been limited to bars of up to 12 mm in diameter. To represent real fire situations in typical FRP reinforced concrete structures, two novel features have been implemented in the experimental program: large and commonly used GFRP reinforcements (#5 with nominal diameter of 16 mm), and tensile tests under transient temperature. Temperature ranges from 25 to 400 ˚C have been considered for steady state temperature tests. In transient condition tests, specimens are loaded before heat exposure. For the transient temperature tests, bars loaded to service levels (75 kN) failed at temperatures above 500˚C.

INTRODUCTION

The fire resistance of glass fibre reinforced polymer (GFRP) reinforced concrete depends on the change in mechanical properties of GFRP and concrete due to fire exposure. The effect of fire on the mechanical properties of concrete is well documented [1].

Embedded in concrete, GFRP bars do not burn due to a lack of oxygen although the polymer matrix will soften [2]. Thermal and mechanical properties of a matrix depend on the composition and properties of the constituents. The glass transition temperature (T_g) is a critical characteristic of polymers around which the polymer's properties can change abruptly [1]. Typically for various FRP manufacturers, T_g is between 90 to 200 ° for the matrix. For the GFRP bars used in the current study, the average T_g is 110 ˚C. In a composite material, the fibres, which exhibit better thermal properties than the resin, can continue to support some load in the longitudinal direction. However, the tensile properties of the overall composite are reduced due to a reduction in load transfer mechanism between adjacent fibres.

BACKGROUND

Sayed-Ahmed and Shrive [3] showed that exposing carbon FRP tendons for 24 hours at 200 and 300 ˚C made the surface of the tendons dark, showing some resin loss. After 24 hours of exposure at 400 ˚C some of the fibres on the surface of bar were loose. Combustion of the matrix occurred during exposure to 500˚C within the first hour of exposure, and the tendon became a bundle of loose glass fibres.

Experiments done by Wang et al. [4] showed the stress–strain curve of FRP bars remains almost linear at higher temperatures leading to failure. Their specimens included GFRP, CFRP, as well as steel rebars for comparison purposes. There was an almost linear gradual degradation of tensile strength of FRP bars up to 500 ˚C losing almost 90% of its original strength. They noted that the reduction of tensile modulus (E_{FRP}) of GFRP is almost negligible up to 400 ˚C. They observed that GFRP holds 90% of its tensile modulus at this range. A sharp drop in the elastic modulus of specimens was observed after 400 ˚C. They have also observed a large variability in specimens' strength at temperatures higher than 350 ˚C although FRP bars still have a high level of tensile strength and elastic modulus. However, they doubted whether FRP bars should be used at such high temperatures. They found considerable differences between the high temperature performance of 9.5 mm bars and 12.7 mm ones. They postulated that the higher degradation of strength in the 12.7 mm diameter bars could be due to higher resin content in larger bars because at high temperatures the resin gets damaged first.

Recent material tests have been conducted on two types of FRP reinforcement [5, 6]; however, additional material testing is still required to fully characterize the performance of FRP reinforcement at high temperature including both tensile and bond tests. As a part of a comprehensive GFRP material test program at high temperature, three different products from different manufacturers are being tested at Queen's university, Canada including bond and tensile strength. In this paper, results for one of the widely used GFRP bars in Canada are presented. In the most recent study [7], GFRP bars of 10 mm in diameter have been tested. However, #5 GFRP bars with a nominal diameter of 16 mm are a more widely used size of GFRP bars in construction. Since all the previous experiments have focused on small bar sizes #4 and #3 with 12 and 10 mm diameter, respectively [4, 7], in the current study #5 GFRP bars, have been investigated. In a recent numerical study on GFRP reinforced concrete members in fire, Adelzadeh et.al [8] stated the need for more quantification the properties of GFRP bars in elevated temperatures.

EXPERIMENTAL PROGRAM

The objective of this material testing is to assess the strength of GFRP bars at elevated temperature to understand the fire performance of GFRP reinforced concrete members. Most of the tensile tests of FRP bars at elevated temperatures are conducted in steady state temperature conditions (heat then load) [4, 6, 9]. In a real fire scenario, service loads consisting of permanent dead loads, and a portion of the live loads are present while temperature increases during the fire exposure. It is anticipated that the presence of stress in FRP bars accelerates degradation of FRP bars at elevated temperatures. The behaviour of an FRP bar under stress during exposure to fire may be different from the behaviour of unloaded FRP exposed to high temperature. To study the effect of sustained load during heat exposure, tensile strength tests of GFRP bars have been conducted in both transient temperature and steady state temperature conditions.

To simulate fire conditions, the rate of increasing temperature was set at 5 °C/min based upon the expected rate of heat increase of FRP bars embedded in concrete. For the transient tests, specified loads were applied to the bars and the loaded bars were exposed to increasing temperatures until failure occurred under constant applied load but increasing temperature. Since the common service stress level of GFRP bars is lower than 30% of its rupture strength [5], the specimens are loaded for stress levels between 22 and 59% of their ultimate tensile strength at room temperature. Allowable service stresses are limited to 25% in CSA-S806 [10] for GFRP and 65% for CFRP bars.

Specimen Preparation

Anchorage systems for FRP bars are a challenging issue in conducting tensile tests. It is necessary to prevent FRP failure at the ends of the test specimens. Since the transverse strength of FRP bars is low, both ends of the specimen must be anchored in such a way as to ensure that the radial confining pressure on the FRP bar will not cause failure inside the grips. Some researchers [4, 6, 11] have used expansive grout to confine the FRP bar inside of a circular steel tube while in some experiments [6] epoxy was used to hold the bars in the steel sleeve. It was observed that epoxy resin is not strong enough to provide the required gripping action up to bar rupture [12]. In this study, in order to come up with the most reliable and cost-effective method of anchoring GFRP bars, several methods have been tried. These include wedge anchors, steel tubes with non-shrinkage Sika-212 grout, and steel tubes filled with RockFrac® expansive grout. For this study, the latter method was selected for the majority of the test specimens. The steel tubes were cut from 6 m long Schedule-80 1 ¼ inch pipes with 42 mm outer diameter and 4.9 mm thickness. Because of the limiting height of the testing machine, the maximum length of the steel tubes was 350 mm. In Figure 1, sleeves filled with expansive grout are shown at both ends of a tested specimen. Chemical reactions taking place in the expansive cement during curing exerted sufficient lateral pressure on the FRP bar to keep it anchored in the steel tubes.

Figure 1 Steel tubes at the ends of specimen after tests

Test Setup

Two identical specially-built fixtures were installed in an Instron 600LX loading actuator to hold the steel sleeves (Figure 2). A heating chamber is located between the two top and bottom fixtures and the GFRP samples extended through the chamber. The test samples were 1500 mm long, from which a length of 240 mm was exposed to heat inside the chamber. The steel sleeves were 350 mm long which can be used to apply tensile loads up to 230 kN on the samples. Both steel plates have a slot to facilitate the bars' placement in the fixtures.

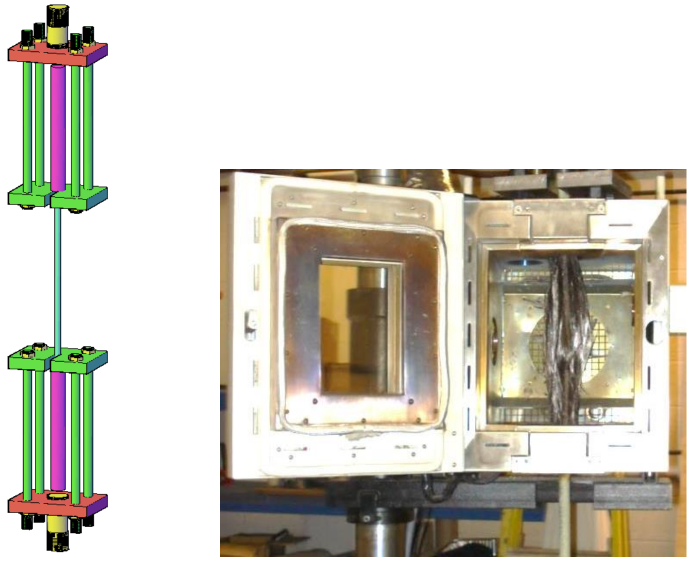

Figure 2 Test setup: (Left) Fixture; (Right) Heating chamber

Several thermal evaluation tests have been done in the furnace to understand the thermal lag and differences between the thermocouples touching the surface of the bars and the built-in thermocouples of the furnace (see Figure 3). The average temperature of the bars was calculated from readings of three thermocouples touching the surface of the bars and compared to the furnace temperature.

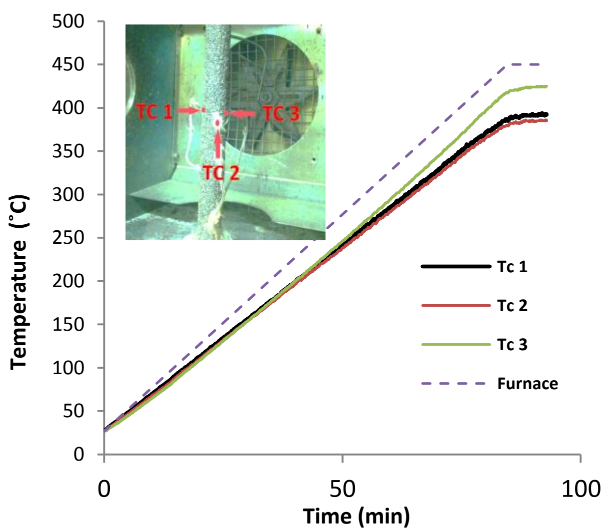

Figure 3. Thermal evaluation of the furnace

TEST RESULTS

Tensile tests have been performed on the same bars at different temperatures to study the influence of temperature changes on the tensile strength of GFRP bars.

Tensile tests have been conducted in two methods, namely steady state and transient tests.

Steady state tests

Table I summarizes the results of the steady state tests. Under steady state conditions, the machine's stroke continuously adjusts the position of the actuator to counter the longitudinal expansion of the bar as the temperature increases to maintain a constant negligible load of 2 kN. Since every specimen has to be aligned and levelled before each test, maintaining the specimen's correct position is a key item in tests. At a rate of 5°C/ min, the coils of the furnace apply heat until the target temperature is reached. In order to ensure a uniform temperature distribution in the outer and inner parts of the bar, the specimen is exposed to the target temperature for an additional 15 minutes. Then, according to CSA-S806, the specimen is loaded using stroke control with a rate between 250-500 MPa. This load rate was achieved by moving the actuator down at a rate of 8 mm/min until failure occurred.

Table I. Steady state test results

Furnace Temperature (˚C)	Specimen ID	Average Bar Temperature In Failure (˚C)	Failure Load (kN)	Normalized Retained Strength (%)	Tensile Strength Using Nominal Area (MPa)
25	25-1	25	342	101%	1727
25	25-2	25	335	99%	1692
25	25-3	25	340	100%	1717
150	150-1	133	216	64%	1091
150	150-2	133	228	67%	1151
200	200-1	177	227	67%	1147
200	200-2	177	197	58%	995
200	200-3	177	199	59%	1005
250	250-1	222	162	48%	818
250	250-2	222	178	52%	899
250	250-3	222	188	55%	949
300	300-1	266	167	49%	844
300	300-2	266	169	50%	856
300	300-3	266	158	47%	798
350	350-1	311	126	37%	636
350	350-2	311	163	48%	825
350	350-3	311	141	41%	712
350	350-4	311	126	37%	636
400	400-1	355	144	42%	727
400	400-2	355	138	41%	697
400	400-3	355	137	40%	692

It can be seen from Table I that the failure load of the bars for different tests performed at the same temperature are similar. Although GFRP bars are made from long fibres, they are not continuous and some scattering results are observed when local defects of GFRP are located in the heat-exposed length of bar. Consequently, the mechanical properties of the composite material are dependent on the matrix performance. As temperature increases, the matrix decomposes and has less contribution in load transfer between fibres. As a result, non-continuous fibres and local defects become significant in the tensile strength of bars.

Figure 4 shows the failure load and normalized tensile strength (strength at elevated temperature divided by that at room temperature) as a function of exposed heat in steady state condition tests.

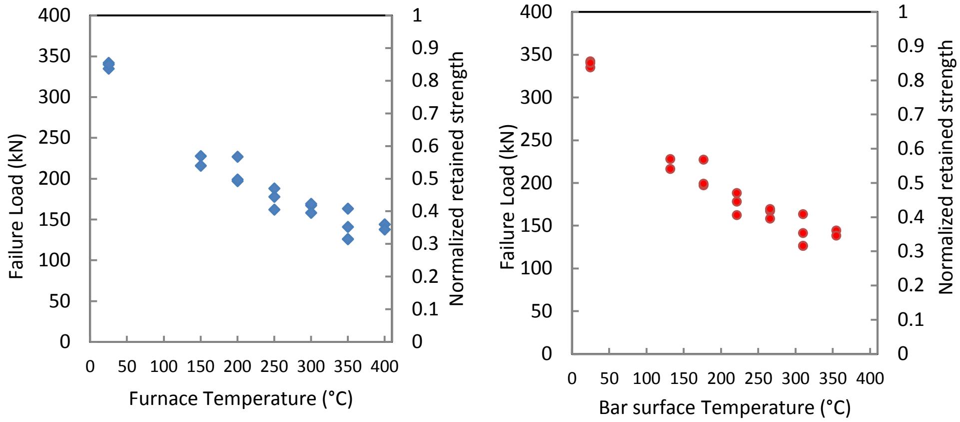

Figure 4. Tensile strength degradation in steady state tests (#5 GFRP bars): (Left) as a function of furnace temperature; (Right) as a function of bar surface temperature

Transient Tests

Table II summarizes the transient test results. In transient conditions, the bars were loaded up to a predefined load at room temperature. Specimens were tested at five various stress levels. While under constant applied load, the temperature was increased at a rate of 5°C/ min until bar rupture. The temperature at which failure occurred was recorded as the failure temperature. Analyzing the transient test results shows that GFRP bars at high temperatures as high as around 540 °C still carried fairly reasonable tensile stresses of 22% of their ultimate strength at room temperature. It is expected that the presence of stress in the bar during heat exposure will intensify and accelerate degradation of the bars. In the transient tests, cracks in the outer sand coating of the reinforcing bars occurred at lower temperatures compared with the steady state tests.

Table II. Transient test results

Applied Load (kN)	Specimen ID	Applied Tensile strength (MPa)	Applied Stress Ratio (%)	Furnace Temperature (˚C) in Failure
75	75-1	379	22%	216
75	75-2	379	22%	228
120	120-1	606	35%	227
120	120-2	606	35%	197
160	160-1	808	47%	199
160	160-2	808	47%	162
160	160-3	808	47%	178
180	180-1	909	53%	167
180	180-2	909	53%	169
200	200-1	1010	59%	158
200	200-2	1010	59%	126
342	Ambient-1	1729	101%	25
335	Ambient-2	1690	98%	25
340	Ambient-3	1715	100%	25

As shown in Figure 5, a sudden drop in failure temperature occurred at specimens loaded above 180 kN. In comparing the steady state and transient condition test results it should be considered that steady state specimens have experienced an additional 15 minutes of constant heat exposure after reaching the target temperature. Since in transient condition tests temperature is continuously increasing and there is no constant temperature period as provided in steady state tests, the recorded failure temperature in transient tests should be interpreted taking into account that actual failure temperature is lower than recorded values if compared to the results of steady state tests.

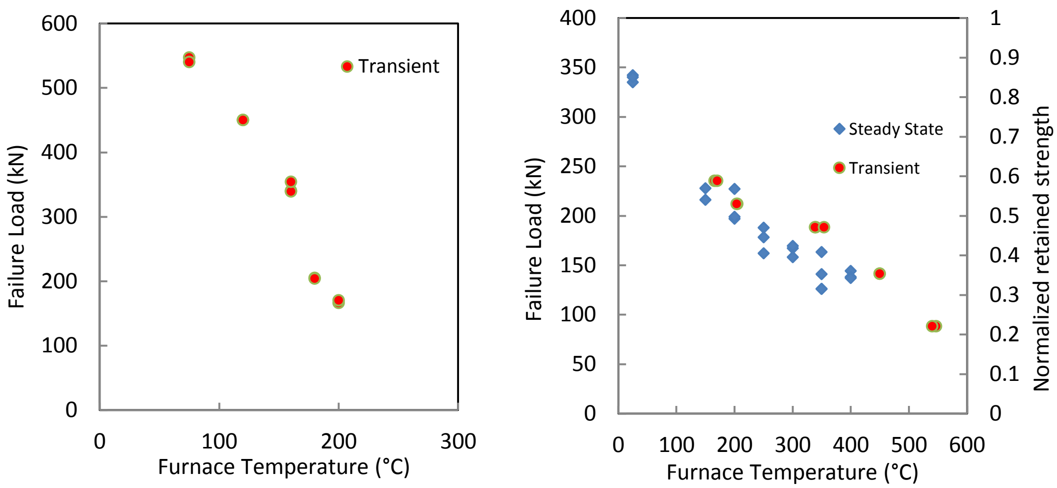

Figure 5. (Left) Tensile strength degradation in Transient tests (#5 GFRP bars); (Right) comparison of transient test results to steady state tests

Figure 6 shows the failure modes of specimens at various levels of preloading in the transient condition tests. As it can be seen, the failure mode changes from a gradual failure at high temperatures to a more sudden mechanism at lower temperatures.

Figure 6. Samples after transient test: from left to right applied tensile loads are 75, 120, 160, and 200 kN, and failure temperatures are 547, 450, 340 and 160 °C respectively

CONCLUSIONS

High modulus #5 GFRP bars widely used in bridge and parking garage construction were tested at high temperatures. Testing bars under two testing conditions have made it possible to compare results and develop a more realistic understanding of GFRP bar strength at high temperatures as could be expected in a fire. Variation and scattering of tensile test results at higher temperatures are greater than those at ambient temperature. This could be attributed to local defects of non-continuous glass fibres which become more influential in the heat-exposed length of bars. Loss of mechanical properties of the matrix will magnify the negative effects of local imperfections of the fibres. Transient condition test results showed that increasing the sustained loads in GFRP bars negatively influences the high-temperature strength of the bars. Transient condition test results are a more realistic representation of a fire situation in GFRP reinforced concrete members.

ACKNOWLEDGEMENTS

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC), Queen's University, MITACS Canada, and the Ministry of Transportation of Ontario (MTO) for support of these experiments. Also, many thanks go to Pultrall Inc. for providing funding, materials, and technical support.

REFERENCES

1. Saafi, M., *Effect of fire on FRP reinforced concrete members.* Composite Structures, 2002. **58**(1): p. 11-20.
2. ACI-440.1R, *Guide for the Design and Construction of Concrete Reinforced with FRP Bars* American Concrete Institute, Detroit, Michigan, 2006.
3. Ezzeldin, S.-A. and N.G. Shrive, *Smart FRP Prestressing Tendons: Properties and Prospects.* Proceedings of the Second Middle East Symposium on Structural Composites for Infrastructure Applications, 1999: p. P. 80-93.
4. Wang, Y., P. Wong, and V. Kodur, *An experimental study of the mechanical properties of fibre reinforced polymer (FRP) and steel reinforcing bars at elevated temperatures.* Composite structures, 2007. **80**(1): p. 131-140.
5. Weber, A., *Fire-resistance tests on composite rebars.* Proceedings of CICE2008, Zurich, Switzerland, 2008.
6. Robert, M. and B. Benmokrane, *Behavior of GFRP reinforcing bars subjected to extreme temperatures.* Journal of Composites for Construction, 2009. **14**(4): p. 353-360.
7. Emma R.E. McIntyre, Antonio Bilotta, L.A. Bisby, and E. Nigro. *Mechanical Properties of Fibre Reinforced Polymer Reinforcement for Concrete at High Temperature*. in *8th International Conference on Structures in Fire*. 2014. Shanghai, China. p. 1227-1234.
8. Adelzadeh, M., H. Hajiloo, and M.F. Green, *Numerical Study of FRP Reinforced Concrete Slabs at Elevated Temperature.* Polymers, 2014. **6**(2): p. 408-422.
9. Alsayed, S., et al., *Performance of glass fiber reinforced polymer bars under elevated temperatures.* Composites Part B: Engineering, 2012. **43**(5): p. 2265-2271.
10. CSA-S806, *Design and construction of building components with fiber-reinforced polymers.* Canadian Standards Association. Mississauga, Ontario, Canada: , 2012.
11. Micelli, F. and A. Nanni, *Tensile characterization of FRP rods for reinforced concrete structures.* Mechanics of composite materials, 2003. **39**(4): p. 293-304.
12. Johnson, D.T.C., *Investigation of Glass Fibre Reinforced Polymer Reinforcing Bars as Internal Reinforcement for Concrete Structures*. 2009, M.Sc thesis, University of Toronto.