MECHANICAL PROPERTIES OF FIBRE REINFORCED POLYMER REINFORCEMENT FOR CONCRETE AT HIGH TEMPERATURE

MECHANICAL PROPERTIES OF FIBRE REINFORCED POLYMER REINFORCEMENT FOR CONCRETE AT HIGH TEMPERATURE

Emma McIntyre*, Antonio Bilotta, Luke Bisby*, Emidio Nigro****

* BRE Centre for Fire Safety Engineering, School of Engineering, The University of Edinburgh, UK
e-mails: emma.mcintyre@ed.ac.uk, luke.bisby@ed.ac.uk

** Department of Structures for Engineering and Architecture, University of Naples Federico II, Italy
e-mails: antonio.bilotta@unina.it, emidio.nigro@unina.it

Keywords: Fire, FRP, Experimental, High temperature, Concrete reinforcement.

Abstract. *Fibre reinforced polymer (FRP) bars are increasingly being used as replacement of steel reinforcing bars in the design and construction of concrete buildings. However, the deterioration of mechanical properties of FRP materials on heating is, in general, not well known and has not been well characterized for the wide variety of FRP materials currently available; this hinders application of FRP materials in many cases. To better understand the complexities of FRP bars' response at high temperature, an experimental study into the tensile mechanical response of FRP reinforcing bars at high temperature is presented. The results of dynamic mechanical analysis (DMA) and thermogravimetric analysis (TGA) tests are used to evaluate the glass transition temperature (T_g) and decomposition processes (T_d) of a specific commercially available glass FRP (GFRP) reinforcing bar for concrete reinforcement. Results are presented from direct tensile tests on the FRP bars at different steady-state temperatures varying from 20°C to temperatures at which crystallization of the resin occurs (i.e. 500°C). These are compared against results from the small-scale characterization tests and semi-empricial models available in the literature. Finally, a novel model for the reduction in tensile strength of FRP materials at high temperature, which requires only small scale DMA and DSC testing, along with a small number of tension tests at elevated temperature, is proposed.*

1 INTRODUCTION

Fibre reinforced polymer (FRP) reinforcing bars have considerable advantages as compared against steel reinforcement (in particular their resistance to electrochemical corrosion) and are thus increasingly being used for internal reinforcement of sustainable and durable concrete structures. FRP reinforcement is particularly common as flexural reinforcement for reinforced concrete beams and slabs. A key concern for the behaviour of concrete member reinforced with FRP bars is their response during exposure to fire. The mechanical and bond properties' of FRPs deteriorate at high temperatures, and this has the potential to cause reductions in load carrying capacity and stiffness of FRP reinforced concrete structural elements, particularly those working in flexure [1, 2].

While it is well known that FRP bars suffer reductions in mechanical and bond strength at elevated temperature, the wide variety of available specific, proprietary FRP materials of different composition makes it very difficult to make broad generalizations regarding quantification of their high temperature mechanical and bond properties. Thus, each candidate FRP material must be separately characterized through numerous tensile and bond pullout tests at elevated temperature before it can be used with confidence by designers. This investment in testing is expensive, inefficient, and time consuming, and as a result the required data are not available for most currently available FRP reinforcing materials; this hinders the widespread application of FRP materials in concrete buildings.

2 BACKGROUND

The current paper focuses on a single type of commercially available glass FRP reinforcing bar for concrete. It is very well established that the mechanical properties of FRPs deteriorate (as for all structural materials) with increasing temperature. The limiting temperature for 'adequate' performance of FRP materials is commonly taken to be the glass transition temperature T_g of the polymer matrix [1, 2], which is typically in the range of 90–200°C for the epoxy or vinylester matrix, manufactured using a pultrustion process, that are used for concrete reinforcing applications (although it is noteworthy that degradation in mechanical properties may be observed even before T_g (see below). Also, because of the anisotropy of pultruded unidirectional FRP materials, transverse and bond properties are more severely affected by elevated temperatures than the longitudinal properties; transverse and shear strength and stiffness decrease rapidly in the range of T_g.

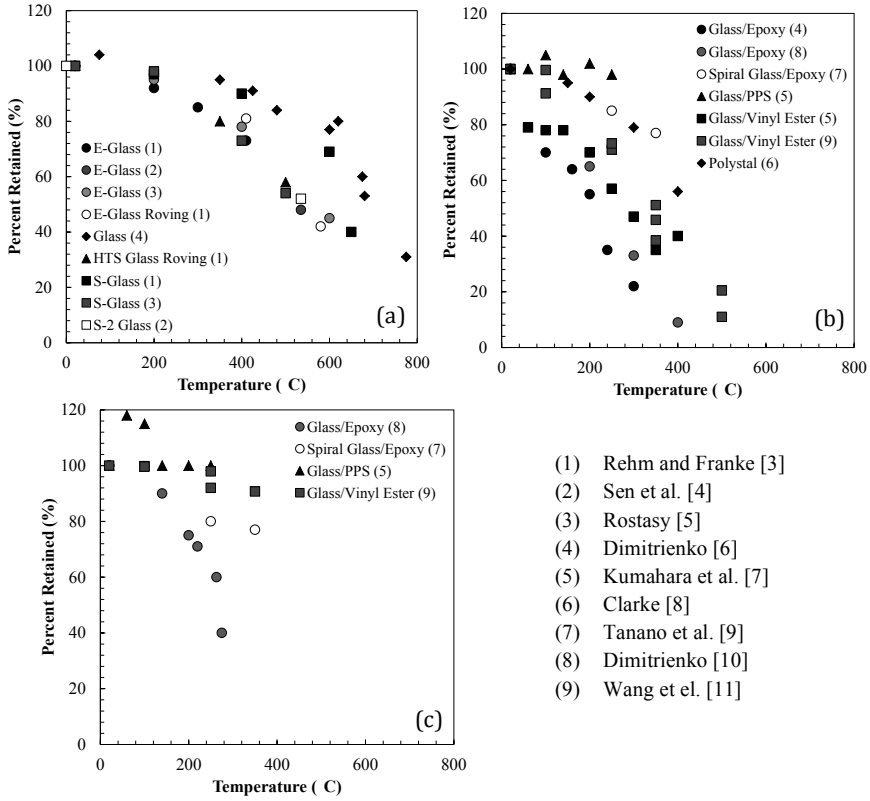

Figure 1. Summary of available data on the high temperature performance of: (a) bare glass fibres, (b) glass FRP bars (with cold anchorage), and (c) GFRP bar to concrete bond (pullout strength).

Several research studies are reported in the literature studying the high-temperature mechanical properties FRP materials and their constituent materials; a full review of these has been presented previously by Bisby et al. [12]. Degradation of mechanical properties is governed by the properties of the polymer matrix, since commonly available fibres are relatively more resistant to thermal effects; however, quantification of the degradation in tensile strength and stiffness of specific FRP products remains a significant challenge as already noted.

Fig. 1 shows the temperature-dependent ultimate tensile strength of bare glass fibres, the ultimate tensile strength of GFRP bars, and the tensile elastic modulus of GFRP bars used as reinforcement for concrete, at elevated temperature, based on data available in the literature and assembled by Bisby [12]. These figures demonstrate that both bare glass fibres and glass fibre reinforced polymer bars are sensitive to elevated temperature, however the FRPs are considerably more sensitive than the bare fibres themselves. This is because load sharing between the fibres is reduced at temperatures in the range of T_g, due to loss of the resin's ability to transfer loads through shear stresses, resulting in reduced bulk strength for the GFRP bars as compared with bare fibres (for which load sharing has no relevance).

There is considerable scatter in all three plots shown in Figure 1. This is expected given the wide range of possible matrix formulations, fibre orientations (spiral and braided fibres in some cases), and fibre volume fractions represented in the data. It appears that some GFRP materials are more sensitive to elevated temperature than others, and that generalizations are hard to make. A central purpose of the current paper is to attempt to define the minimum suite of tests needed to credibly characterize the expected reductions of mechanical properties of FRP bars at elevated temperature, without the need to perform a wide range of tensile tests over a range of temperatures from ambient, through the glass transition (T_g), and increasing above the resin decomposition temperature (T_d).

3 EXPERIMENTAL PROGRAMME AND RESULTS

3.1 Materials Characterization Testing

Dynamic mechanical analysis and TGA tests were performed in order to determine the glass transition temperature (T_g) and the decomposition temperature (T_d) for the GFRP bars studied herein.

T_g is a characteristic value for FRP materials which is used to nominally differentiate between stiff, glassy and soft, rubbery states of the polymer resin matrix; it is widely assumed to represent a limiting temperature for structural use of FRP materials and is often presented by FRP bar manufacturers as a single point value. However, in the current study (and in reality) T_g is defined using various currently accepted definitions over a range of temperatures within the region representing different stages of resin transitioning (softening).

Dynamic mechanical analysis (DMA) is one of a variety of test methods that can be used to determine T_g for an FRP material. The test works by applying an oscillatory load to a small sample of FRP and measuring the load versus displacement response of the sample with increasing temperature. As output, DMA testing gives the variation in storage modulus (effectively the elastic modulus of the sample), as well as a parameter called 'Tan δ' where δ is the phase angle between the elastic and viscous responses of the sample under sinusoidal loading. On the basis of these data, T_g can be defined by one of a number of definitions, three of which are shown in Figure 2(a). T_{g_Onset} is defined by the intersection of tangent lines defined by initial slope and the maximum negative slope of the storage modulus reduction curve; $T_{g\_Midpoint}$ is defined by the temperature at which the maximum negative slope of the modulus reduction curve is observed, and $T_{g\_Tan\,\delta}$ is defined by the peak value of the tangent of the phase angle, Delta. These definitions are essentially arbitrary, but they all relate to a softening of the polymer resin from which the FRP is made. Figure 2(a) shows that for the GFRP material used in the current study the T_g values are: T_{g_Onset} = ##°C; $T_{g\_Midpoint}$ = ##°C, and $T_{g\_Tan\,\delta}$ = ##°C.

Thermogravimetric analysis (TGA) essentially measures mass loss with increasing temperature. This test is useful in determining the temperatures at which the organic polymer resin from which an FRP material is manufactured undergoes decomposition by breakdown of chemical bonds and pyrolysis, eventually leaving only the inorganic fibres (in the case of glass FRPs where there is no oxidation of the glass fibre themselves). TGA testing can also give an indication of the approximate fibre volume fraction of an FRP material, since the bulk of the mass remaining after the polymer resin burns off can be attributed to the fibres (with a small amount of residual polymer char). T_d suffers from the same problems in definition as T_g based on its output, a mass loss curve for instance like the one given in Figure 2(b) for the glass FRP treated herein; in this case T_d has been taken as ##°C.

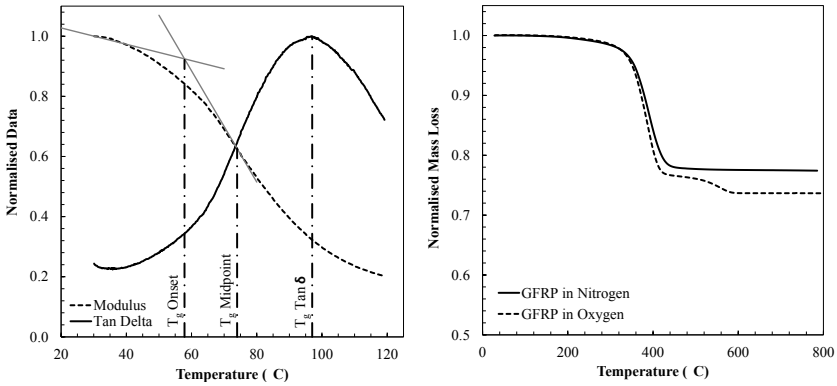

Figure 2. Results of (a) DMA and (b) TGA tests on the GFRP bars tested in the current study.

3.2 High-Temperature Tensile Tests

In addition to the small-scale materials characterization tests described in the preceding section, direct tensile tests were performed on glass FRP bars over a range of temperatures. The overall testing setup is shown in Figure 3 and a summary of the tests performed and their results is given in Table 1.

Table 1. Details of the Experimental Programme. Table 1.

Specimen ID	Temperature (°C)	Peak Load (kN)	Tensile Strength (MPa)	Failure Mode
25a	25	86.40	764	Anchor Failure
25b	25	101.44	897	Coating Failure
25c	25	119.24	1054	Bar Rupture
59a	59	100.24	886	Bar Rupture
59b	59	101.23	895	Bar Rupture
74a	74	92.18	815	Bar Rupture
74b	74	93.52	827	Bar Rupture
100a	100	90.50	800	Bar Rupture
100b	100	83.88	742	Bar Rupture
111a	111	85.28	754	Bar Rupture
111b	111	72.45	641	Anchor Failure
111c	111	86.74	767	Bar Rupture
150a	150	78.10	691	Bar Rupture
200a	200	79.91	707	Bar Rupture
315a	315	79.58	704	Bar Rupture
315b	315	78.80	697	Bar Rupture
375a	375	36.39	322	Bar Rupture
375b	375	38.62	341	Bar Rupture
440a	440	55.05	487	Bar Rupture
440b	440	43.98	389	Bar Rupture
495a	495	16.90	149	Bar Rupture
495b	495	15.14	134	Bar Rupture

All tension tests were performed using an Instron 600LX materials testing frame with an integrated environmental chamber capable of heating samples up to a maximum temperature of 600^{o}C. Because FRP bars have low transverse strength and cannot be gripped in wedge-action or lateral hydraulic anchors, individual samples of FRP bar were potted within steel anchors using a microsilica-filled epoxy resin

system. The steel anchors were then connected to the loading frame crossheads and the bars were loaded in tension until failure.

It should be noted that the steel potted anchors were maintained outside of the environmental chamber during testing, thus ensuring cold anchorage and avoiding bond failures. This is important because the bond between FRP bars and concrete is known to be highly sensitive to elevated temperature exposure. The current study is interested in mechanical properties of *well-anchored* FRP materials, and inherently assumes that a cold anchorage zone is provided in order to avoid bond pullout failures.

All tension tests were performed under steady-state thermal conditions wherein the bars were heated up to their test temperature at a rate of ##°C until the target test temperature was reached, the sample was held at the target temperature for ## minutes, and the loading was then applied in displacement control at a crosshead stroke rate of ## mm/min until failure.

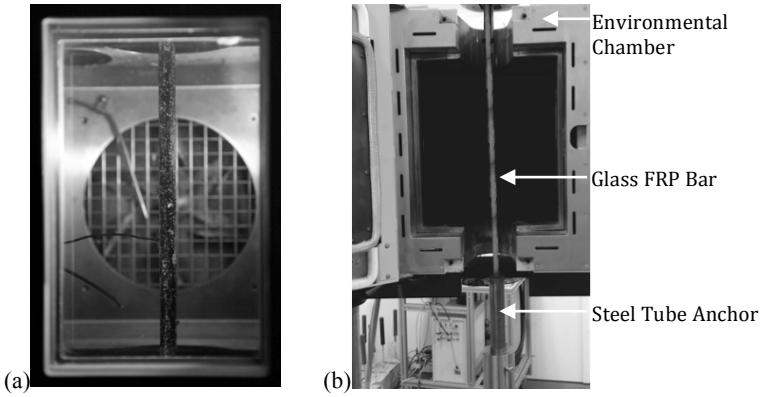

Figure 3. Schematic and photo of test setup for tension tests using DIC strain measurement.

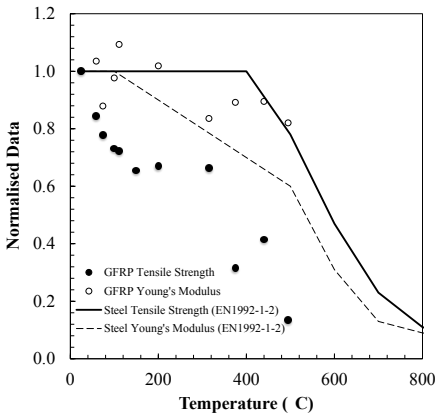

Figure 4. Reduction in ultimate tensile strength and tensile elastic modulus with increasing temperature for the bars tested in the current study (Eurocode 2 [13] reduction curves for mild steel reinforcement included for comparison).

Figure 4 provides a visual summary of the tension test results in terms of ultimate tensile strength and tensile elastic modulus (both normalized the value at ambient temperature). The tensile strength is considerably reduced at even mildly increased temperatures (for instance >##% reduction at T_{g_Onset}), whereas the tensile elastic modulus appears to be less sensitive to elevated temperature exposure. This agrees in general with the bulk of the data available in the literature (refer to Figure 1). Also included in

Figure 4 are the Eurocode's recommended strength and modulus reduction curves for mild steel reinforcement at elevated temperature, indicating that GFRP bars are more sensitive in terms of strength reduction, but possibly less sensitive with respect to stiffness reduction (notwithstanding the scatter in the experimental data).

A change in failure mode was also observed with increasing temperature. At ambient temperature the bars exhibited sudden and violent rupture, whereas at temperatures well above T_g the failure mode was gradual and non-violent and was characterized by loss of interaction between the individual fibres due to resin softening and crystallization.

4 SEMI-EMPIRICAL MODELLING

As stated earlier, the central goal of the current study was to define the minimum suite of tests necessary to predict the reduction in strength (and ideally also stiffness) for a given FRP reinforcing bar product while avoiding the needed to perform a large number of difficult, costly, and time-consuming elevated temperature tension tests. A number of analytical and semi-empirical models for reduction in mechanical properties of FRP materials with increasing temperature are available in the literature [#].

Most previous authors in this area have noted a link between the glass transition response of the FRPs polymer resin (i.e. storage modulus reduction curve from DMA testing) to a reduction in mechanical properties for the FRPs themselves, leading to a 'step' reduction in tensile properties with increasing temperature in the region of T_g. A smaller number of prior authors have also linked a second step reduction in tensile properties to decomposition of the resin in the region of T_d. However, most of the resulting models require curve fits to experimental data and so they do not avoid the need to perform a large number of tension tests.

On careful inspection of the tension test data shown in Figure 4, a two-step reduction response is apparent, with the first step appearing to be linked to the T_g response of the resin and the second appearing to be linked to its T_d response. The level of the plateau between the first and second steps will depend on the specific fibres and resin used in the FRP, as well as its manufacturing process, fibre volume fraction, etc. On the basis of the ultimate tensile strength data given in Figure 4, the plateau for the glass FRP bars treated herein appears to be in the range of 0.7 when normalized to ambient temperature strength.

Using the rationale presented above, it is possible to propose both the minimum suite of tests needed to predict the tensile strength of a given pultruded FRP bar at elevated temperature, and a model to give the necessary information for use by designers (clearly this proposal must be verified by tests on other candidate FRP bars; this work is currently underway by the authors). The minimum suite of tests is:

1. DMA to determine the storage modulus reduction with temperature up to $2T_g$;
2. TGA to determine the mass loss curve with temperature up to $1.2T_d$ (note that the coefficient 1.2 is essentially arbitrary);
3. A minimum of 2 to 3 direct tension tests on the FRP bar in question at a temperature in the range of $(T_g + T_d)/2$ to define the first plateau; and
4. A minimum of 2 to 3 direct tension tests on the FRP bar in question at a temperature in the range of $1.2T_d$ to define the second plateau;

The model is then described by the following equations (with reference to Figure 5, below):

$$k_f = \frac{f_T}{f_{amb}} = \alpha_g + k_1 \cdot \left(1 - \alpha_g\right) \cdot \alpha_d + k_2 \left(1 - \alpha_g\right) \cdot \left(1 - \alpha_d\right) \tag{1}$$

Where f_t is the ultimate tensile strength at temperature T and f_{amb} is the ambient temperature ultimate tensile strength. The first step in the reduction of tensile strength with temperature is given by:

$$\alpha_g(T) = \frac{\frac{E'_T}{E'_{amb}} - \frac{E'_g}{E'_{amb}}}{1 - \frac{E'_g}{E'_{amb}}} \; for \; 20°C < T < 2T_g \qquad \text{with} \quad \begin{aligned} E'_T &= E'(T) \\ E'_{amb} &= E'(T_{amb}) \\ E'_g &= E'(2T_g) \end{aligned} \qquad (2)$$
$$\alpha_g(T) = \alpha_g(2T_g) = 0 \; for \; T > 2T_g$$

Where E'_T, E'_{amb}, and E'_g are the normalized storage modulus values at T, ambient temperature, T_{amb}, and twice T_g (from DMA testing). The second step in the reduction of tensile strength is given by:

$$\alpha_d(T) = 1 \; for \; 20°C < T < 2T_g$$
$$\alpha_d(T) = \frac{m_T - m_d}{m_{2T_g} - m_d} \; for \; 2T_g < T < T_d \qquad \text{with} \quad \begin{aligned} m_T &= m(T) \\ m_{2Tg} &= m(2T_g) \\ m_d &= m(T_d) \end{aligned} \qquad (3)$$
$$\alpha_d(T) = \alpha_d(T_d) = 0 \; for \; T > T_d$$

Where m_T, m_{2Tg}, and m_d are the normalized mass loss values at T, twice T_g, and T_d (from TGA testing). The coefficients k_1 and k_2 represent the plateaus and are given by:

$$k_1 = \frac{f_{T_1}}{f_{amb}} \text{ and } k_2 = \frac{f_{T_2}}{f_{amb}} \quad \text{with} \quad T_1 = \frac{T_g + T_d}{2} \text{ and } T_2 = 1.2 \cdot T_d \qquad (4)$$

Where f_{T1} and f_{T2} are the tensile strengths of the bar in the first and second plateaus, delineated by T_1 and T_2 as shown. The above equations lead to the predicted reduction in tensile strength (for the specific FRP bar treated in the current study) shown in Figure 5. The agreement between the test data and the analytical prediction is reasonable in this case, although additional tensile test data are needed to corroborate the agreement. Such tests are underway. Also underway are tests on other glass (and carbon) FRP bars in order to verify that the model can equally be applied to other FRP materials from various manufacturers and with various fibre and resin types.

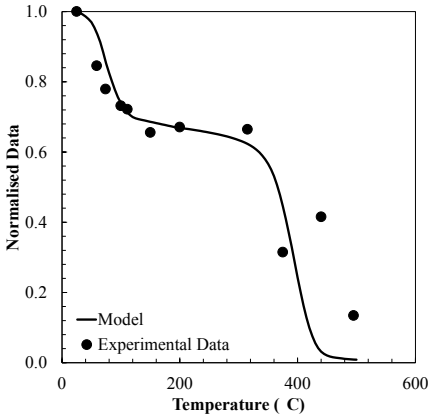

Figure 5. Comparison of application of available models to the experimental data presented herein.

5 CONCLUSIONS

The mechanical (tensile) response of FRP bars is assessed as a function of tensile stiffness and ultimate tensile strength. The results demonstrate that the ultimate strength of the specific glass FRP bars

studied herein reduces more rapidly than the tensile stiffness on heating, and that significant strength reductions become obvious at temperatures above the lowest of the glass transition temperatures in the defined range (T_{g_Onset}). The initial trend of the tensile strength reduction correlates well with the storage (elastic) modulus reduction curve obtained during DMA testing. Severe deterioration of mechanical properties, both strength and stiffness, are obtained only after reaching the thermal decomposition temperature, T_d, of the FRPs' polymer resin. This indicates that well-anchored FRP materials may be able to retain a considerable proportion of their tensile strength at temperatures well above T_g (by any defensible T_g definition).

It has been demonstrated that DMA and TGA tests may be suitable small-scale tests to use for development of analytical predictive models for reduction of tensile strength of GFRP bars with temperature. A possible predictive mode has been proposed which relies on a comparatively small suite of necessary tests in order to define all relevant parameters. While the model shows promise, additional testing is needed before it should be applied in practice.

REFERENCES

[1] Bisby, L.A. and Kodur, V.K.R., "Evaluating the fire endurance of concrete slabs reinforced with FRP bars: Considerations for a holistic approach", *Composites: Part B*, 38(5-6), 547–558, 2007.

[2] Nigro, E., Cefarelli, G., Bilotta, A., Manfredi, G. and Cosenza, E., "Fire resistance of concrete slabs reinforced with FRP bars. Part I: experimental investigations on the mechanical behavior", *Composites: Part B*, 42, 1739–1750, 2011.

[3] Rehm, G. and Franke, L., *Kunstharzgebundene Glasfaserstabe als Bewehrung im Betonbau Deutscher Ausschuss fur Stahlbeton*, Heft 304, 1979.

[4] Sen, R., Mariscal, D. and Shahawy, M., "Durability of Fiberglass Prestensioned Beams", *ACI Structural Journal*, 90(5), 525-533, 1993.

[5] Rostasy, F., *Fiber Composite Elements and Techniques as Non-Metallic Reinforcement of Concrete*, Brite Project 4142/BREU-CT 91 0515, Evaluation of Potentials and Production Techniques of FRP, Technical Report Task 1, 1992.

[6] Dimitrienko, Y.I., *Thermomechanics of Composites under High Temperatures*, Klewer Academic Publishers, London, UK, 1999.

[7] Kumahara, S., Masuda, Y., Tanano, H. and Shimizu, A., "Tensile Strength of Continuous Fibre Bar Under High Temperature', *FRPRCS-I*, American Concrete Institute, Detroit, USA, 731-742, 1993.

[8] Clarke, J., *Alternative Materials for Reinforcement and Prestressing of Concrete*, Blackie Academic and Professional, Glasgow, UK, 1993.

[9] Tanano, H., Masuda, Y., Kage, T., Fukuyama, H., Nishida, I. and Hashimoto, T. "Fire Resistance of Continuous Fibre Reinforced Concrete", *FRPRCS-II*, E&FN Spon, London, UK, 368-375, 1995.

[10] Dimitrienko, Y.I., "Thermomechanics of Composite Materials and Structures under High Temperatures: 1. Materials", *Composites: Part A*, 28A, 453-461, 1997.

[11] Wang Y.C., Wong P.M.H. and Kodur V. "An experimental study of the mechanical properties of fibre reinforced polymer (FRP) and steel reinforcing bars at elevated temperatures", *Composite Structures,* 80, 131-140, 2007.

[12] Bisby, L.A., Green, M.F. and Kodur, V.K.R., "Response to fire of concrete structures that incorporate FRP", *Progress in Structural Engineering and Materials*, 7(3), 136-149, 2005.

[13] CEN, *BS EN 1992-1-2*, European Committee for Standardization, Brussels, Belgium, 2004.