Construction and Building Materials 162 (2018) 142–154

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mechanical properties of GFRP reinforcing bars at high temperatures

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HIGHLIGHTS

- The studied GFRP bars retain at least 25% of their strength at 400 °C.
- Tensile strength is influenced by the resin content and the thermal properties.
- A new concept for the critical temperatures of GFRP bars is proposed.

ARTICLE INFO

Article history:
Received 26 July 2017
Received in revised form 31 October 2017
Accepted 4 December 2017

Keywords:
GFRP reinforcing bars
High temperatures
Tensile strength
Modulus of elasticity
Thermal degradation
Digital image correlation (DIC)

ABSTRACT

This paper presents experimental results of tensile strength tests on glass fibre reinforced polymer (GFRP) bars at high temperatures. These results are a part of a comprehensive study on characteristics of GFRP reinforcing bars from different manufacturers. To represent real construction practices, commonly used #5 GFRP reinforcing bars with nominal diameter of 16 mm are studied. The reinforcing bars are selected from three different manufacturers to study the potential differences of various products. Besides conventional steady-state temperature testing, tensile tests are conducted under transient temperature conditions. In transient tests, specimens are loaded before heat exposure. Temperature ranges from 25 to 500 °C are considered for the steady-state tests depending on the type of bar, and for the transient temperature tests, bars are loaded to between 25 and 70% of the bar's strength at room temperature. The overall conclusion relating to fire performance of GFRP reinforced concrete members is that the three types of GFRP bars that are tested can retain the expected service stress level of 25% of their original tensile strength up to at least 400 °C, and this temperature can be used as the critical temperature in design.

1. Introduction

While fibre reinforced polymer (FRP) reinforcement is mainly used in the rehabilitation or construction of bridges, enormous potential exists for applications in multi-story buildings, parking garages and industrial structures. In these scenarios, FRP could replace the steel bars in concrete susceptible to corrosion. With the development of FRP bars as primary reinforcement in concrete, a few significant facts regarding the structural behaviour of steel reinforced concrete need thorough investigation and reconsideration. For instance, relatively low modulus of elasticity of GFRP bars results in less favorable serviceability performance such as larger deflections and crack widths. In addition, material characteristics of FRP bars from different manufacturers vary as a function of several factors including the type and proportions of fibre and resin, and the quality control of the final products. FRP materials should be tested using a universal method so that the various products on the market could be examined in a similar way. Several standards and codes have developed procedures to investigate mechanical characteristics [1,2]. Given the fact that FRP reinforcing bars cannot resist the required lateral confining pressure from mechanical grips during the material tests, the test method for FRP bars needs to be different from the conventional steel bars.

One obstacle for FRP reinforcing bars to be widely used in constructions is fire performance of concrete components reinforced with FRP bars. The fire performance of FRP reinforced concrete depends on temperature dependent mechanical properties of FRP and concrete in a fire incident. The effect of fire on the mechanical properties of concrete is well documented; however, the complex behaviour of FRP materials and the emergence of new products require material characteristics of FRP reinforcing bars to be studied continuously. In a recent analytical study on GFRP reinforced concrete members in fire, Adelzadeh et al. [3] stated the need for more quantification of properties of GFRP bars at elevated temperatures. Unlike the mechanical characteristics of FRP materials at

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https://doi.org/10.1016/j.conbuildmat.2017.12.025
0950-0618/

room temperature, none of the standards has developed guidelines for determining material characteristics at elevated temperatures.

Extensive studies are available on the high temperature behaviour of concrete and reinforcing steel [4]. Owing to a comparatively low thermal conductivity, reinforced concrete elements do not require supplemental fire protection to achieve high fire endurance. Adequate fire performance for reinforced concrete could be achieved by providing minimum dimensions and sufficient concrete cover to the steel reinforcement [5]. The critical temperature was first used for steel reinforced concrete member. At critical temperature steel loses half of its original strength, and steel reinforced concrete element can no longer support the loads during a fire. Lie [6] found the critical temperature of reinforcing steel and prestressing steel as 593 and 426 °C [4]. The similar method was used in Canadian CSA S806 [1] to determine the failure temperature of the FRP reinforced concrete elements in a fire. CSA S806 [1] provides a prescriptive method for designing FRP reinforced concrete slabs which is based on the defined critical temperatures (325 °C for GFRP and 250 °C for CFRP). According to Wang et al. [7], the critical temperatures (based on 50% strength loss) are 325 °C for GFRP and 250 °C for CFRP. Robert and Benmokrane [8] have also shown the critical temperature of the tested GFRP reinforcing bars to be around 310 °C.

Embedded in concrete, FRP bars do not burn readily because of a lack of oxygen although the polymer matrix will soften [9]. Thermal and mechanical properties of a matrix depend on the composition and properties of the constituents. One of the significant thermal characteristics of polymers is the glass transition temperature (T_g) around which the polymer's properties can change abruptly [10]. For GFRP, the T_g of the matrix typically varies between 65 and 120 °C [9]. With increase in temperature, especially after T_g, fibres in a composite material continue to support some load in the longitudinal direction. However, the tensile properties of the overall composite are reduced because of a reduction in load transfer mechanism between adjacent fibres when the resin softens. In addition to the degradation of tensile strength of GFRP bars, the concrete to FRP bond degradation is a significant factor in the fire performance of GFRP reinforced concrete [11].

2. Research background

Sayed-Ahmed and Shrive [12] showed that exposing carbon FRP tendons for 24 h at 300 °C made the surface of the tendons dark indicating loss of resin. After 24 h of exposure at 400 °C, fibres on the surface of the bars became loose. Combustion of the matrix occurred during exposure to 500 °C and the tendon became a bundle of loose glass fibres. Bisby [13] assembled experimental data from the literature on the strength of carbon, aramid, and glass fibres at high temperatures. These data showed that carbon fibres were relatively unaffected by heat while aramid and glass fibres lost significant tensile strength at elevated temperatures. Bisby also gathered the results reported in the literature on tensile strength of FRP bars at elevated temperatures. Evidently, mechanical characteristics of all types of FRP bars (carbon, aramid and glass fibres) deteriorated to different extents as temperature rises. The notable scatter in the gathered results occurred because of the various types of resin used in manufacturing as well as fibre volume content of the tested FRP bars. Kumahara et al. [14] studied extensively different forms of FRP reinforcing bars between 60 and 400 °C. In addition to carbon and aramid reinforced composites, they tested GFRP reinforcing bars with two different types of resin: vinylester and polyphenylene sulfide (PPS). PPS is a thermoplastic resin with resistance to heat. The GFRP bars with vinylester resin showed different behaviour from that of bars with PPS. The tensile strength of bars with vinylester decreased at temperatures above 60 °C, and it lost 40 and 60% of their original strength when heated to 250 °C and 400 °C, respectively. By contrast, the GFRP bars with PPS did not suffer from the heat up to 250 °C. The better performance of the latter was believed to be because of the better heat-resistant characteristics of PPS resin compared to vinylester. Experiments conducted by Wang et al. [7] showed that the stress–strain curve of FRP bars remained almost linear at higher temperatures leading to failure. They noted that the reduction of tensile modulus of GFRP was almost negligible up to 400 °C. The studied specimens included GFRP, CFRP, as well as steel reinforcing bars 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 observed a large variability in specimens' strength at temperatures higher than 350 °C, although FRP bars still had a high level of tensile strength and elastic modulus. However, they doubted whether FRP bars should be used at such high temperatures.

There are few reported studies on the elastic modulus of GFRP bars during exposure to elevated temperatures. Kumahara et al. [14] studied the modulus of elasticity of two types of GFRP bars with either a vinyl ester or a thermoplastic, polyphenylene sulfide (PPS) resin. For the first type of bar, the modulus of elasticity at 350 °C decreased to 40% of the room temperature value while the second type showed no sign of degradation in modulus. In addition, Wang et al. [7] showed that modulus of elasticity of GFRP bars remained essentially constant up to 400 °C with a drastic drop in modulus at 500 °C.

There has been a continuous study on the material characteristics of different types of FRP reinforcement [8,15,16]. In the most recent study [17], GFRP bars of 10 mm in diameter were tested. Since all of the previous experiments have focused on small bar sizes #4 and #3 with 12 and 10 mm diameter [7,17], the current study investigated #5 GFRP bars. This is a more widely used size of GFRP bar in construction. In summary, regardless of the significance of tensile strength of FRP reinforcing bars at elevated temperatures, a limited number of experimental investigations have been conducted and reported in the literature. There is a fast-growing number of these products used in construction, and many variables determine the characteristics of FRP bars, such as type and volume of resin. Because of this, comprehensive investigation of the most recent GFRP reinforcing bars was believed an essential step toward designing FRP reinforced concrete structures demonstrating satisfactory fire performance.

3. Experimental program

The objective of this material testing is to assess the properties of GFRP bars at elevated temperatures which enables the designers to calculate the fire resistance of GFRP reinforced concrete members considering the tensile strength of the GFRP bars. Most of the tensile tests of FRP bars at elevated temperatures were conducted in steady-state temperature conditions (heat then load) [7,8]. 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 incident. It is anticipated that the presence of stress in FRP bars during heat exposure accelerates degradation of FRP bars. Consequently, tensile strength tests of GFRP bars have been conducted in both transient temperature and steady-state temperature conditions. The exposure time of specimens to elevated temperatures depends on the target temperature and the heating rate. The slower heating rate results in longer exposure time that may cause unrealistic severity and overestimate strength degradation. Correia et al. [18] heated rectangular coupons with an approximate rate of 7.5 °C/min to a maximum temperature of 220 °C. Katz et al. [19] used 5 °C/min to heat the