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Mechanical properties of pultruded carbon fibre-reinforced polymer (CFRP) plates at elevated temperatures

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ABSTRACT

The use of fibre-reinforced polymer (FRP) composites is becoming increasingly widespread in civil infrastructure for strengthening and repair applications as well as whole FRP members and structures. A question which, however, continually arises from all stake-holders is the performance of FRP materials under elevated temperatures. An accurate understanding of the material properties and behaviour of FRP at such high temperatures is crucial, and they are necessary pieces of information that are surprisingly scarce in the literature. This paper therefore presents the mechanical properties of pultruded carbon fibre-reinforced polymer (CFRP) plates at elevated temperatures. More specifically, CFRP pultruded plate coupons were tested at steady and transient states for temperatures ranging from approximately 20 to 700 °C. The tests showed that, for the temperature ranges 20–150 °C and 450–706 °C, reductions of the tensile strength of the pultruded CFRP plate occurred. Between these temperature ranges, the tensile strength decreased by a small amount, while at 300 °C the ultimate strength was approximately 50% of the room-temperature strength. In addition, the tensile strength of the plate was as low as 7% of the room-temperature tensile strength at the approximate peak temperature of 700 °C. Finally, an equation that relates the tensile strength of the plate to the entire tested temperature range which has been calibrated with all the test data is proposed.

1. Introduction

Existing reinforced concrete (RC) infrastructure can be strengthened and repaired with externally bonded fibre-reinforced polymer (FRP) composites or externally mounted post-tensioned FRP tendons and plates. An abundance of research exists on the experimental validation of these various strengthening technologies to RC structural members at room temperature or common operating conditions (e.g. [1,2]). There is, however, a distinct lack of research on the characterization of FRP construction materials as well as the strengthening of RC structures strengthened with FRP composites at elevated temperatures and under fire conditions.

Fibre-reinforced polymer composites consist of fibres embedded in a resin matrix [1]. The commonly used fibres of carbon and glass can withstand a high temperature, and in the case of carbon fibres this temperature can exceed 2000 °C [1]. The epoxy used in the resin matrix and also the epoxy used to bond the FRP composite to concrete surfaces, however, degrades mechanically with increased temperature. Such degradation commences before the glass transition temperature, T_g, is reached. In this case, the ability of the resin matrix to transfer forces amongst the fibres is lost in addition to the ability of the resin to transfer forces between externally bonded FRP strengthening to the adjacent concrete substrate [3]. The T_g value can lie in the range 50–90 °C for commercially available products used in civil infrastructure applications [4], and, interestingly, such temperatures can be reached on surfaces exposed to direct sunlight in hot environments. Research on the ability of insulation systems to keep the temperature in the epoxy below critical temperatures for a certain period of time is gaining momentum [5–8]. Such research on insulation systems is, however, outside the scope of this paper.

Of the limited research undertaken to date on FRP-strengthened members exposed to elevated temperatures, Kodur et al. [9] have provided design guidance. Such guidance represents a culmination of tests on FRP-strengthened RC structural elements such as beams, slabs, and columns, conducted under elevated temperatures. Such testing [6,10–12], though, has considered the behaviour of the entire strengthened member and not the individual materials and components. In addition, the tests were conducted in a transient state manner in which the member was initially loaded and then a fire curve (e.g. [13]) applied. More recently, Foster and Bisby [4] identified a lack of research and understanding of the mechanical properties of FRP strengthening systems in isolation that are available to the construction industry. They also identified a lack of research on the bond between the FRP and the concrete substrate. The work presented in [4] was therefore directed towards enhancing the limited research on the mechanical properties of commercially available FRP materials under elevated

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Nomenclature

a, b, c coefficients for Eq. (1)
$P(T), P_{initial}, P_R, k_m, T_{central}, R_n$ coefficients for Eq. (2)
A, B, C, n coefficients for Eq. (3)
E_{normal} elastic modulus at normal room temperature
T surface temperature of specimen
T_g glass transition temperature
f mechanical property in question (ultimate strength, elastic modulus, or bond strength)
f_0 room-temperature value of mechanical property in question (ultimate strength, elastic modulus, or bond strength)
$f_{u,T}$ ultimate stress at temperature T °C
$f_{u,normal}$ ultimate stress at normal room temperature (i.e. 22 °C)
$\varepsilon_{u,normal}$ strain corresponding to the ultimate strength at normal room temperature

temperatures. In their experimental study, they investigated the mechanical properties of FRP bar and plate products under elevated temperatures. More specifically, they conducted tensile coupon tests, single-lap FRP-to-FRP bond tests, direct tension (pull-off) FRP-to-concrete bond tests, and FRP-to-concrete double-lap shear bond tests after exposure to temperatures of up to 400 °C. In all cases, the strengths were found to decrease at various rates as the temperatures were increased. The tests conducted by Foster and Bisby [4] were focused on the post-fire behaviour. Other researchers [14,15] have also investigated the behaviour of FRP composite materials for temperatures up to 200 °C. Furthermore, Cao et al. [16] investigated experimentally the tensile properties of CFRP and hybrid FRP sheets at elevated temperatures, ranging from 16 to 200 °C, and the strengths were found to reduce by up to 40%. In general, information on the high-temperature and residual properties of FRP composites used in civil applications is still quite scarce, especially for the pultruded FRP products which are widely used in civil applications. Investigations of reinforced concrete, steel, stainless steel, and concrete-encased steel composite structures at elevated temperatures have been conducted [17–22].

The purpose of the study reported herein is to measure the mechanical properties of CFRP (herein simply FRP) pultruded plates at temperatures ranging from room temperature (approximately 22 °C) up to high temperatures which may be expected in a fire (i.e. 700 °C). Flat coupon specimens were prepared from commercially available pultruded FRP plates and then tested to failure in tension in a universal testing machine while under the influence of various steady-state or transient temperature histories. In the steady-state tests, the test specimens were heated to a specified temperature and then the tensile test was carried out. In the transient tests, the specimens were loaded to a certain stress level and then the temperature was increased until the test specimens failed. The transient-state tests are considered more realistic in a fire; however, for completeness, both steady-state and transient-state tests were conducted. Furthermore, a unified equation for predicting the ultimate strength of pultruded FRP plates at elevated temperatures, which has been calibrated with the test data presented herein, is finally proposed.

It is important to note here the practical implications and applications of the results presented in this paper in the context of strengthening concrete structures with FRP composites. The tests show that the specific CFRP plates can withstand temperatures up to 400 °C while still retaining about half of their tensile capacity. This is important information in the case of strengthening concrete members with unbonded post-tensioned plates with which the end anchorages are protected from heat. However, in the case of concrete members strengthened with externally bonded CFRP plates, the thermal resistance of the epoxy used to bond the plate to the concrete will be the limiting factor. In such cases the epoxy will lose its ability to function at temperatures typically below 100 °C, unless an epoxy of high thermal resistance is used. Once the epoxy degrades in strength, the externally bonded plate will simply detach, and the strengthening effect will be lost.

2. Experimental investigation

2.1. Testing device

An MTS 810 universal testing machine of 250 kN capacity was used for the tensile coupon tests, while the temperature was applied by a high-temperature MTS 653 furnace which was controlled by an MTS 409.83 temperature controller. The grips of the universal testing machine, in addition to the mounted furnace, the furnace controller, and an FRP specimen, are shown in Fig. 1. The furnace, which was capable of reaching a maximum temperature of 1400 °C, gained its heat from six pairs of silicon carbide heating elements arranged in three zones, as shown schematically in Fig. 2. Insulation plates separated these three zones in order to enable more uniform heating and better temperature control. Three internal thermocouples were located inside the furnace to measure the air temperature, as shown in Fig. 2. Since the internal thermocouples were not in contact with the test specimens, the temperature detected by the internal thermocouples was higher than the surface temperature of the specimens. Therefore, three external thermocouples were used to measure the surface temperature of the specimens, and the temperature measured from these thermocouples was considered as the real temperature of the specimens in this study. These thermocouples in contact with the test specimens were labelled (in reference to Fig. 2) as No. 1 (upper chamber and left-hand side of the FRP coupon), No. 2 (central chamber and left-hand side of the FRP coupon), and No. 3 (central chamber and right-hand side of the FRP coupon). The highest temperature reading of the three thermocouples was selected as the failure temperature of the specimen, since the failure should have occurred at the hottest position of the FRP plate. The accuracy of the internal and the external thermocouples is 0.25% and 0.2%, respectively.

2.2. Testing procedure

2.2.1. Steady-state tests

In the steady-state tests, the specimens were heated to a specified temperature then loaded until failure while the same temperature was maintained. After reaching the desired temperature, times of either 5 or 30 min were maintained before loading, which allowed the epoxy to undergo physical and chemical changes. After such time, the tensile load was then applied to the specimens until failure. During the heating-up and holding stages, the test specimens were unrestrained (i.e. gripped at one end only) in order to enable thermal expansion. After the holding time had been reached, the grips at the other end of the specimens were closed and then the specimens were tested (while still under the influence of temperature) to failure. The heating rate of the furnace was 50 °C/min. In addition, the tests were undertaken in a ram displacement control mode at a constant rate of 2 mm/min.

2.2.2. Transient-state tests

In the transient-state tests, the test specimens were initially gripped at both ends and loaded in a load-controlled manner. Prior to heating, the specimens were loaded in order to achieve stress levels of nominally 1000, 1500 and 2000 MPa, which represented