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Experimental and analytical analysis of the effect of fibre treatment on the thermomechanical behaviour of continuous carbon textile subjected to simultaneous elevated temperature and uniaxial tensile loadings

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ABSTRACT

In the case of fire, the carrying capacity of the textile-reinforced-concrete (TRC) depends greatly on the thermomechanical behaviour of the reinforcement textile at elevated temperatures. Carbon textiles are manufactured in industry as commercial products for application in TRC. The treatment of carbon fibres by products of different natures in the manufacturing chain also influences the thermomechanical behaviour and mechanical property evolution as a function of temperature. This paper presents an experimental study on the tensile behaviour of three different continuous carbon textiles subjected to simultaneous mechanical loading and elevated temperatures (varying from 25 °C to 600 °C). The results on three carbon textiles are compared to understand the effect of fibre treatment on the thermomechanical behaviour of carbon textile. The experimental results are used to calibrate a prediction analytical model (Mouritz and Gibson), which can be applied to the thermomechanical estimation of carbon textile under different temperature and mechanical conditions.

1. Introduction

In the field of civil engineering, the construction industry is in need of a new shift. One way to face this need is exploring the use of alternative building materials. Composite materials are often used to repair and/or strengthen the structural elements (slab, beam, column...) of old civil engineering works. These composite materials can also be used as supporting elements in new structures [1,2]. Over the past two decades, textile-reinforced concrete (TRC) composite material (carbon fibre, glass fibre, aramid fibre, etc.) has become increasingly widely used to repair or strengthen structures [2–4]. The textile in composite material plays a very important role in the carrying capacity and stiffness of composite materials. Among textiles used, carbon textile provides better supported load capacities, high strength, and high Young's modulus to traction [5,6]. This is the main reason for the manufacture of carbon textiles as commercial products for application in TRC composite to repair and/or strengthen structural elements of existing construction works (bridge, building, tunnel, etc.) [7]. Following paragraphs present the previous studies that have focused on TRC and FRP behaviours under fire or different temperatures. The objective of this study ends the introduction of this paper.

1.1. TRC behaviour under fire or different temperatures

Several studies have been conducted at ambient temperature on the tensile or bending behaviour of textile-reinforced concretes [8–10]. In the case of fire in a civil engineering structure strengthened by carbon-textile-reinforced-concrete composite (bridge, building, tunnel, etc.), composite material is simultaneously subjected to mechanical loading and elevated temperatures (potentially up to 1200 °C). Until now, studies on the fire behaviour of TRC material have been rare because of experimental difficulties linked to fire tests. Some fire tests have been performed on thin, high-performance concrete plates, reinforced with basalt fibre-reinforced polymer mesh [11], on carbon fibre-reinforced, fine-grained concrete [12], and on I-shaped beams, reinforced with glass-fibre and carbon-fibre mesh grids [13,14]. A few studies have been investigated on the residual mechanical behaviour of TRC after exposure to elevated temperatures [15–18]. Few studies have been conducted on the thermo-mechanical behaviour of TRC. The thermo-mechanical behaviour of a carbon fabric-reinforced cementitious matrix composite (at temperatures ranging from 20 °C to 120 °C) [19] and that of a basalt fabric-reinforced

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cementitious matrix composite (at temperatures ranging from 20 °C to 400 °C) [20] have been performed. The effects of simultaneous mechanical loading and elevated temperature (for temperatures ranging from 20 °C to 400 °C) on the behaviour of the glass TRC have been experimentally studied [21]. Few researchers have focused on behaviour of TRM versus FRP composite as strengthening materials at high temperatures that were evaluated in shear, bond and flexure [22–24]. The thermomechanical behaviour of the TRC composite depends on several factors such as the nature and configuration of the textile reinforcements, the reinforcement ratio, the nature of the matrix, and the pre-impregnation of the textiles by different products. Among these factors, the load capacity of the carbon textile at elevated temperatures strongly influences the thermomechanical behaviour of the TRC composite because the TRC matrix is strongly damaged under elevated temperature conditions. At ambient and low temperature levels, the tensile uniaxial behaviour of TRC shows a stress–strain curve with three distinguishable phases corresponding to the TRC behaviour before the matrix cracking (first phase), during the matrix cracking (second phase), and during the post-cracking of the matrix (third phase) [20,21]. At ambient temperature and low temperature level, during the third phase of the stress–strain curve of TRC, the concrete matrix is completely cracked, so there is the only work of continuous textile before the rupture of the composite. Understanding the thermomechanical behaviour of the continuous textile reinforcement makes it possible to estimate the thermomechanical behaviour of TRC. This justifies the need to study the thermomechanical behaviour of the continuous reinforcement textile.

1.2. FRP behaviour under fire or different temperatures

In the literature, there were few studies on the effect of fire or elevated temperatures on the behaviour of reinforcement textiles or continuous fibres reinforced polymer (FRP) products to strengthen structures. In their recent works, Rambo et al. [20] carried out tests on samples of basalt textiles in a preheating–cooling regime with five temperature levels (25 °C, 75 °C, 150 °C, 200 °C, and 400 °C). They also explained the contribution of a styrene-acrylic latex coating to the residual behaviour of basalt textile. The fire behaviour of a carbon/epoxy laminate composite for aircrafts [25] and the fire stability of the carbon fibre-reinforced polymer (CFRP) shell [26] have been studied. Boyd et al. [27], Bausano et al. [28], Feih et al. [29] and Mouritz et al. [30] have performed experimental and numerical studies on polymer composite (glass fibre, carbon fibre) under fire condition or heat flux conditions. The tensile performance of the basalt fibe-epoxy laminate [31] and the carbon-epoxy laminate [32] under combined one-sided radiant heating and axial tensile loading have been performed. Some studies have focused on elevated temperature behaviour of CFPR [33–38]. Most of these studies showed the evolution of the mechanical properties of carbon fibres or CFRP according to temperature. In the work of Green et al. [34], the carbon fibres were practically unaffected by an elevated temperature up to 1000 °C, whereas the CFRP composite lost most of its resistance at 600 °C. Wang et al. [37] presented their study on ‘‘preheated-cooled” CFRP composite specimens for residual behaviour at temperature levels ranging from 22 °C to 706 °C. Yu and Kodur [38] tested CFRP rod or strip specimens at elevated temperatures. Nguyen et al. [39] conducted the characterization of pultruded carbon fibre reinforced polymer (P-CFRP) under two elevated temperature-mechanical load cases: residual and thermo-mechanical regimes. All works also showed a reduction in tensile strength and rigidity of CFRP composite with increasing temperature. Otherwise, the fire/heat and mechanical performance of the glass-reinforced epoxy composites (glass FRP) has been performed [40–42]. The microstructure and mechanical properties of carbon microfiber reinforced geopolymers at elevated temperatures have been experimentally studied [43]. The thermomechanical properties and bond characteristics of different fiber (carbon, basalt, glass) reinforced polymer rebars at elevated temperatures (from 20 °C to 500 °C) have been experimentally investigated [44]. The mechanical properties of CFRP laminates at elevated temperatures and freeze–thaw cycling (for temperatures ranging from -50 °C to 150 °C) have been studied [45]. The thermomechanical properties of glass fibre reinforced GFRP reinforcing bars at high temperatures (ranging from 25 °C to 500 °C) have been experimentally identified [46]. The cyclic thermal effects (for temperatures ranging from 20 °C to 200 °C) on the mechanical behaviour of CFRP laminate [47] or FRP [48,49] have been investigated.

1.3. Objective of this study

To the best of the authors' knowledge, no results are available concerning experimental tests with simultaneous mechanical and elevated temperature loadings carried out on continuous carbon textile specimens. There are also no results regarding the effect of fibre treatment on the thermomechanical behaviour of continuous carbon textile at elevated temperatures. With the synthesis of previous research works, some scientific questions can be asked: Is it possible to experimentally obtain the ‘‘stress–strain” relation of continuous carbon textile when it is subjected to combined thermal and mechanical loadings (at elevated temperatures)? What is the thermomechanical behaviour of continuous carbon textile at elevated temperatures? What is effect of fibre treatment on the thermomechanical behaviour of continuous carbon textile (evolution of mechanical properties according to temperature, modes of rupture)? What analytical model allows the mechanical property evolution of continuous carbon textile according to temperature to be predicted? The aim of this work is to contribute in answering these questions. This work will also provide the scientific community with experimental data concerning the thermomechanical behaviour of three continuous carbon textiles (with different fibre treatments).

This paper presents an experimental study on the tensile behaviour of three different continuous carbon textiles subjected to simultaneous mechanical and elevated temperature loadings. By using an innovative thermomechanical machine (TM20kN-1200C), direct tensile tests on specimens of three continuous carbon textiles (with fibres treated by different products) were carried out at different temperature levels varying from 25 °C to 600 °C. The results on three carbon textiles were compared to understand the effect of fibre treatment on the thermomechanical behaviour of carbon textile. In this article, an analytical model will be chosen and calibrated to predict the effect of temperature on the thermomechanical behaviour of carbon textiles. In the following sections of this paper, experimental work including the use of equipment, test specimens and test procedure are presented (Section 2). The experimental results will then be presented, analysed and discussed (Section 3). The analytical modelling work will then be shown (Section 4). This paper ends with a presentation of main conclusions and future works.

2. Experimental work

This section presents the used equipment, used materials, specimen production and preparation, summary of specimens, and tests and test procedure.