Construction and Building Materials 165 (2018) 395–412

Contents lists available at ScienceDirect

Construction and Building Materials

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

Characterization of pultruded carbon fibre reinforced polymer (P-CFRP) under two elevated temperature-mechanical load cases: Residual and thermo-mechanical regimes

Phi Long Nguyen [a,b], Xuan Hong Vu [a,*], Emmanuel Ferrier [a]

[a] *Université de Lyon, Université Lyon 1, Laboratory of Composite Materials for Construction (LMC2), 82 bd Niels Bohr, F-69622 Villeurbanne, France*

[b] *Ho Chi Minh City University of Transport, Faculty of Construction Engineering, Campus 1: Number 2, D3 Street, Ward 25, Binh Thanh District, Ho Chi Minh City, Viet Nam*

HIGHLIGHTS

- Experimental identification of the P-CFRP thermomechanical and residual behaviours.
- Evolution of the P-CFRP thermomechanical (TM) and residual (RR) proprieties.
- Curves of the TM properties of the P-CFRP are lower than those of the RR properties.
- Failure modes of the P-CFRP depend on the temperature and the test process.
- Adjusted models can predict the P-CFRP properties under different test conditions.

ARTICLE INFO

Article history:
Received 28 May 2017
Received in revised form 19 November 2017
Accepted 29 December 2017

Keywords:
Pultruded carbon fibre reinforced polymer (P-CFRP)
Elevated temperature
Thermomechanical behaviour
Residual behaviour
Stress-strain curve
Analytical models

ABSTRACT

Pultruded carbon fibre reinforced polymer (P-CFRP), a polymer matrix composite material, has been increasingly used in industry, science, equipment and engineering in recent decades. In civil engineering, when a structure reinforced with pultruded carbon fibre reinforced polymer (P-CFRP) is subjected to fire, both the structure and the CFRP reinforcement are concurrently affected by elevated temperature (potentially up to 1200 °C according to the standard ISO 834-1) and mechanical load. This study focuses on characterization of the mechanical performance of P-CFRP under thermal action. In Eurocode, the mechanical properties of both concrete and steel are reduced as the temperature rises, but the performance of P-CFRP has not been clearly mentioned. This paper studies the evolution of the behaviour of P-CFRP through tensile tests addressing the impacts of elevated temperature (varies from 20 °C to 700 °C) and mechanical loading on the material. This study features two types of tests: the thermal mechanical tensile properties test and the residual tensile test. The results show that the P-CFRP has linear behaviour in each temperature condition for both test types and that the tensile properties including the tensile strength and modulus are generally reduced as the applied temperature increases from 20 °C to 700 °C. The results also show that the thermomechanical strength of P-CFRP is lower than its residual strength at the same level of applied temperature. The thermomechanical strength of P-CFRP was obtained with direct tensile test at an elevated temperature level (T) performed on P-CFRP specimen. The residual strength of P-CFRP was obtained with the tensile test at ambient temperature performed on preheated-cooled P-CFRP specimen that was preheated up to the same temperature level (T) and then progressively cooled until ambient temperature. In addition, the failure modes associated with the loading path and different temperature levels are identified. They provide the references to the thermomechanical state at which material failure happens. The experimental results are used to calibrate two prediction models, which can be applied to the thermomechanical estimation of structures reinforced with P-CFRP under different temperature and mechanical conditions.

* Corresponding author.
E-mail addresses: phi-long.nguyen@etu.univ-lyon1.fr, long.nguyen@ut.edu.vn (P.L. Nguyen), Xuan-Hong.Vu@univ-lyon1.fr (X.H. Vu), emmanuel.ferrier@univ-lyon1.fr (E. Ferrier).

https://doi.org/10.1016/j.conbuildmat.2017.12.244
0950-0618/

1. Introduction

In recent decades, there has been an increase in the use of pultruded carbon fibre reinforced polymer (P-CFRP) in civil engineering for both reinforcing and retrofitting structures. With its light weight, high strength and good corrosion resistance and fatigue properties, P-CFRP is normally used to reinforce the tensile working region to enhance the strength, stiffness and ductility of concrete structures such as columns, beams and slabs. Since its first application in civil engineering, there has been an urgent need to evaluate the working capability of P-CFRP in fire conditions. Considerable research has concentrated on the evolution of the mechanical performance and properties of P-CFRP as a function of temperature. The following sections present previous experimental studies, analytical models of the temperature-dependent behaviour of CFRP and the objective of this study.

1.1. Experimental research on temperature-dependent behaviour of CFRP

Some studies have focused on the fire behaviour of steel-reinforced concrete structures that are strengthened with carbon fibre-reinforced polymer (CFRP) (with or without fire protection systems) [1–10]. The behaviour of steel-reinforced concrete beams, externally reinforced with carbon fibre-reinforced polymer (CFRP), under high-temperature loading (up to 500 °C) has also been studied [11,12]. The fire behaviour of a carbon/epoxy laminate composite for aircraft has been investigated [13]. When a fire occurs, structures are simultaneously subjected to heat (potentially up to 1200 °C according to the standard ISO 834-1 [31]) and mechanical loading. To intensively observe the fire responses of a structure, it is very important to measure mechanical loading, temperature, and deformation, as they indicate the working status of structures. However, it is difficult to identify the mechanical response of structures in elevated temperature conditions due to the influence of the high temperature on the measurement devices. For this reason, there have been only a few studies of the behaviour of CFRP material under fire or thermomechanical high-temperature loading. CFRP experiences degradation in its tensile properties at elevated temperature. Over past decades, several research efforts have studied the evolution of tensile performance of CFRP using two popular procedures: in the first procedure, specimens are heated up to a predefined temperature, then mechanically tested until rupture following a direct tensile test programme (thermomechanical procedure); in the second procedure, after being heated to a predefined temperature and then cooled to ambient temperature, specimens are tested following a direct tensile test programme (residual procedure).

Several studies have been carried out regarding the thermomechanical behaviour of CFRP. Y.C. Wang et al. performed a series of tensile tests on CFRP rods at temperatures ranging from 20 °C to 600 °C following the thermomechanical procedure [14]. The results showed that the tensile strength of CFRP decreased approximately 50% as the temperature increased up to 240 °C and at 600 °C, the strength had decreased almost 90%. K. Wang et al. measured the tensile strength of pultruded strips following the thermomechanical procedure at temperatures ranging from 22 °C to 706 °C [15]. The results demonstrated that the tensile strength of the pultruded CFRP strip decreased approximately 50% at 350 °C, and more than 80% at 600 °C. Yu and Kodur studied the influence of temperatures between 20 °C and 600 °C on the degradation of the tensile properties of CFRP pultruded strips and rods following the thermomechanical procedure [16]. The results showed that the tensile strength decreased by approximately 50% for strips and 40% for rods at 300 °C, and by approximately 90% for both strips and rods at 600 °C. On the other hand, the tensile modulus decreased approximately 30% for both strips and rods at 400 °C and 67% and 47% at 500 °C for strips and rods, respectively. Cao et al. tested the thermomechanical tensile strength of CFRP sheets with two different methods of loading control at temperatures between 16 °C and 200 °C [17,18]. The results indicated that tensile strengths of CFRP sheets are significantly reduced with increasing temperature. From 16 °C to 55 °C, the tensile strength decreased by approximately 30% and then varied slightly around that value as the temperature increased to 200 °C. In the thermomechanical tests in the studies mentioned above, the evolution of the Young's modulus of CFRP according to temperature has been not clearly identified.

There have been some studies conducted on the residual behaviour of CFRP using the residual procedure mentioned above. Hamad et al. [19] described the evolution of the residual tensile properties of sand-coated carbon fibre reinforced polymer (CFRP) bars for temperature levels ranging from 23 °C to 375 °C. Foster et al. observed the evolution of the residual tensile properties of a carbon-epoxy system from 20 °C to 400 °C [20]. The results showed that the residual strength of the material decreased approximately 20% for temperatures up to 300 °C, and approximately 80% at 400 °C. The tensile Young's modulus varied less than 10% up to 400 °C.

When subjected to a thermal load, most thermosetting resins and amorphous polymers show one major transition, which occurs in a narrow range of about several tens of degrees called the glass transition temperature (Tg). For commercial products used in civil infrastructure applications, Tg varies between 50 °C and 90 °C [21]. When the temperature in the material reaches the transition temperature of the polymer matrix, the matrix becomes softer and the material's mechanical properties (Young's modulus and tensile strength) are significantly reduced. Therefore, the contribution of the matrix to the composite tensile strength gradually becomes negligible. This contribution reduces to zero after total decomposition of the matrix, characterized by the decomposition temperature T_d (250–500 °C) [22,23]. The matrix decomposition process usually releases heat, smoke, soot and toxic/combustible volatiles [22]. This may hasten matrix decomposition itself and influences the mechanical properties of the fibre. Carbon fibre alone is intrinsically resistant to high temperatures. Its modulus decreases only above 500 °C and its tensile strength begins to slightly decrease starting at 400 °C [24]. Thus, at low temperatures (between 20 °C and temperatures around the glass transition temperature of the matrix), a reduction in stiffness of an FRP composite can be primarily attributed to matrix degradation. The composite tensile strength at very high temperatures is generally controlled by the fibre. Although the individual carbon fibres can maintain their mechanical strength at high temperatures, when they are combined with resin in a composite, the strength of the composite at high temperature can significantly decrease approximately 400 °C. This is due to the softening and degradation of the polymer matrix at temperatures above its glass transition temperature. Thus, the mechanical load sharing function is degraded and the individual fibres can be overloaded and broken, gradually inducing ultimate rupture of the CFRP [25].

Among studies that address the elevated temperature performance of CFRP, there are few experimental studies that provide data regarding the stress-strain relationship, due to technical or experimental difficulties with measuring deformation at high temperature. Y. C. Wang's experiments were conducted by pulling on cylindrical specimens of CFRP in the temperature range of 20–600 °C [14]. However, according to the authors, the displacement sensor system failed to record distortion data for tests at very high temperatures (over 400 °C) due to the oxidation of the polymer matrix. K. Wang observed the stress-strain relationship on