Composites Science and Technology 154 (2018) 53–63

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

An experimental investigation of the temperature effect on the mechanics of carbon fiber reinforced polymer composites

Zian Jia, Tiantian Li, Fu-pen Chiang, Lifeng Wang*

Department of Mechanical Engineering, State University of New York at Stony Brook, Stony Brook, NY 11794, USA

ARTICLE INFO

Article history:
Received 8 September 2017
Received in revised form
27 October 2017
Accepted 15 November 2017
Available online 16 November 2017

Keywords:
Carbon fiber reinforced polymer composites
Temperature effect
Strain rate effect
Toughening mechanism
Microbuckling
Kinking

ABSTRACT

Carbon fiber reinforced polymer (CFRP) composites are increasingly used in civil, naval, aerospace, and wind energy applications, where they can be frequently exposed to harsh temperature conditions and under static and dynamic loads. The extreme temperature conditions and dynamic loading are critical for CFRP composites structural design as the constituent polymer properties are highly sensitive to temperature and strain rate. This work experimentally investigates the effect of temperature, ranging from −100 °C to 100 °C, on the mechanical properties of CFRP composites under static and dynamic three-point bending tests. The results reveal that CFRP composites provide enhanced flexural strength, maximum deflection, and energy absorption at lower temperatures (−60 °C, −100 °C) while relatively poor performance at a higher temperature (100 °C). Experimental images from the post-mortem photographs, scanning electron microscopy, and high speed videos are implemented to observe various failure behaviors including microbuckling, kinking, and fiber breakage at different temperatures. Analytical modeling is further applied to reveal the underlying mechanisms responsible for these temperature dependent mechanical behaviors. The findings reported here provide insights into the study of the temperature effect on the mechanical response of CFRP composites, which expands the way to design stiffer, stronger and tougher CFRP composites.

1. Introduction

Carbon fiber reinforced polymer (CFRP) composites are widely used in aerospace [1], naval [2], automotive [3], and civil [4] applications due to their high stiffness to weight ratio and high strength to weight ratio. For example, using CFRP instead of metals in automobile vehicles is reported to bring a weight reduction factor as high as 15, significantly improving fuel efficiency, maneuverability, and payload capacity of the vehicles [5]. Compared with traditional materials (e.g. metals), carbon fibers have greater fatigue resistance, better long-term stability, lower thermal expansion and excellent corrosion resistance. Such advantages make CFRP a potential candidate for a wide range of applications in various and extreme environmental conditions [6]. Many efforts have been devoted to the study of CFRP composites under various environmental elements, including moisture [7,8], ultraviolet (UV) radiation [9], and extreme temperatures [10]. Compared with the long-term degradation caused by UV radiation and moisture, which can be resolved by a protective coat together with lifetime monitoring, the temperature changes often happen in a relatively short time and thus can be catastrophic, like the well-known shipwreck of *Titanic* caused by the ductile-brittle transition of steel at a frigid temperature. Similarly, the mechanical properties of the polymer matrix (i.e., modulus, strength, and toughness) are highly temperature dependent [11]: as temperature increases, it transits from a hard glassy state to a soft rubbery state and the modulus can be several orders lower; as temperature decreases, it becomes brittle and cracks propagate easily. Therefore, the mechanical responses of CFRP composites at various temperatures need to be studied carefully such that using them at unfavorable temperatures could be avoided.

Previous investigations on the temperature effect mainly focus on the tensile and compressive experiments of unidirectional CFRP laminates at cryogenic temperatures (−269 °C, −196 °C). These results have been reviewed by Reed [12], showing that the elastic modulus of CFRP increases 10% when cooling to the temperature of −269 °C ~ −196 °C and the tensile strength of CFRP composites increases as well at extremely low temperatures (−196 °C). However, the effect of temperature on the compressive strength of CFRP

---

* Corresponding author.
E-mail address: lifeng.wang@stonybrook.edu (L. Wang).

https://doi.org/10.1016/j.compscitech.2017.11.015
0266-3538/

remains inconsistent in different studies. A more recent study [13] on the tensile and bending tests of quasi-isotropic and cross-ply laminates at 20 °C, −60 °C and −150 °C indicates that both the strength and the toughness of the CFRP decrease at lower temperatures. Models have also been proposed to correlate composite properties and the temperature for the study of higher temperature effect, assuming that any relaxation in the polymers requires overcoming the constraints of secondary bonds. The matrix shear response [14], heat flux [15], and mass loss [16] in CFRP are important at elevated temperatures.

All these studies have laid a solid foundation to study the temperature effect on the mechanics of CFRP, but there are still challenging issues to be addressed. First, the temperature range, −100 °C–100 °C, has become more important due to recent applications. For example, commercial airplanes (Boeing 777) cruise at 13 km altitude where the ambient temperature is around −60 °C [17]. The temperature range of a low-earth orbit satellite is typically from −170 °C to 120 °C [18]. The lowest and highest temperatures ever measured on the earth ground level are −90 °C in Antarctica [19] and 57 °C in California [20], while a theoretical estimation gives the maximum ground surface temperature in the range of 90 °C–100 °C in extreme conditions [21]. Second, the inconsistency of the reported mechanical properties hinders the utilization of CFRP composites at extreme temperature conditions. The discrepancy may come from many aspects [13,22–24], including the laminate manufacturing (matrix cure level, fiber waviness/alignment) and the differences in testing techniques (grip method and sample size) [25]. Third, the dynamic response of CFRP composites at various temperatures is largely unexplored, considering that vehicles, infrastructures, naval ships, and submarines are particularly susceptible to low velocity impacts. More importantly, the low temperature conditions could further facilitate the initialization and propagation of cracks under dynamic loading.

In this paper, we systematically investigate the temperature effect on the mechanical properties of CFRP composites using static and dynamic three-point bending tests with a temperature range −100 °C–100 °C. The dependency of failure strength, energy absorption, and failure patterns on the temperature is studied. The dynamic effect is highlighted by comparing impacts at different velocities. Finally, the failure mechanisms and the effect of thermal stress are discussed with the aid of theoretical analysis.

2. Experimental methods

High strength carbon fibers (50% volume fraction) reinforced vinyl ester provided by Graphtek LLC is used in this research. The properties of the constituent materials at room temperature are summarized in Table 1. The CFRP specimens are prepared with a dimension of 101.6 mm × 12.7 mm × 1.5 mm and the longitudinal direction of the specimen is cut along the fiber direction (Fig. 1 upper right).

Table 1
Material properties of carbon fiber and vinyl ester matrix at room temperature.

	Carbon Fiber	Vinyl Ester
Modulus, GPa	227	3.5
Tensile strength, MPa	$2.8–5.1 \times 10^3$	70–80
Poisson's ratio	0.3	0.3
Elongation at failure	1.40%	4–6%
Density, g/cm^3	1.8	1.15
Coefficient of thermal expansion α , $\times 10^{-6}$/°C	−4(longitudinal)	16–22

2.1. Static three-point bending test

The static three-point bending tests are performed using a MTS mechanical tester (C43) with a 1 kN load cell following the ASTM d790-10 standard [26]. A MTS Advantage™ environmental chamber (temperature accuracy ±1 °C) is used to enable mechanical tests at various temperatures. Here, the temperatures −100 °C, −60 °C, −20 °C, 25 °C, 60 °C and 100 °C are considered. For each temperature, five specimens are tested and all specimens are kept in the chamber for 20 minutes to achieve homogeneous temperature distribution before the tests. All the experiments are conducted in a quasi-static regime with a constant strain rate of 0.01 (at the out surface of the midspan). The load-displacement curves measured from the three-point bending tests are then transferred into the flexural stress strain behaviors based on the measured dimensions of the specimens. The following equations [26] are adopted to calculate the effective flexural stress σ_f and flexural strain ε_f :

$$\sigma_f = 3PL\Big/2bd^2\left[1+6(D/L)^2-4(d/L)(D/L)\right], \tag{1}$$

$$\varepsilon_f = 6Dd\Big/L^2, \tag{2}$$

where σ_f and ε_f are the stress and strain in the outer surface at midspan, D is the deflection at the center of the beam, P is the load applied at the middle of the span, L is the support span, b and d are the width and depth of beam respectively.

2.2. Dynamic three-point bending test

Dynamic tests are performed using a modified split Hopkinson pressure bar (SHPB) [27,28] system with a liquid nitrogen cooled environmental chamber. Images of the specimens at various loading conditions are taken at a rate of 40000 FPS by a high-speed imaging camera (Photron SA1.1) (Fig. 2). Impact speed is controlled by the pressure of the gas reservoir. The temperature inside the environmental chamber is tuned with liquid nitrogen circulation and monitored with four thermal couples located at separate locations. When the control valve is opened, the high-pressure air accelerates the striker which then transfers its momentum to the impactor that impacts the specimen with the designed dynamic three-point bending condition. The specimens for the dynamic tests are the same as the ones for the static three-point bending tests. The mass of the impactor is 335.26 g and the impact speed (3 m/s to 15 m/s) is achieved by controlling the pressure level. Displacement history and velocity history of the impactor is calculated by digital image correlation (DIC) with commercial software VIC-2D (Correlated Solution Inc.). The energy mitigation capacity of the composites is estimated by kinetic energy loss during the impact

$$E_{dynamic} = KE_{res} - KE_{ini}, \tag{3}$$

where KE_{ini} and KE_{res} are the initial and residual kinetic energy of the impactor. The minimum penetration velocity is also obtained to quantify the penetration resistance of the composite. In addition, the flexural strain rate of the specimen is related to the impact velocity by $\dot{\varepsilon} = 6dv/L^2$ where d is the depth, L is span of the beam, and v is the impact velocity. In our experiments, the relation simplifies to $\dot{\varepsilon} = 2.93v$.