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Influence of temperature on the impact behavior of woven-ply carbon fiber reinforced thermoplastic composites

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ABSTRACT

Experimental investigations were carried out to determine the low velocity impact behavior of woven carbon fabric/polyphenylene sulfide (CF/PPS) laminates at room temperature (RT) and high-temperature (95 °C and 125 °C). The relationships of impact response and damage with temperature were established with the aid of macro- and micro-scopic observations and C-scan inspections. The analysis on impact behavior of CF/PPS composite at RT indicated that increasing incident impact energy led to increased low velocity impact-induced damage initiation and propagation. The results revealed that temperature increasing could lead to evident decrease of stiffness, energy based damage degree and delamination area, as well as evident increase of the permanent indentation. Take the specimens at 15 J and 125 °C as example, the permanent indentation and delamination were increased and decreased by 40.2% and 57.45%, respectively. The temperature influence on impact responses was closely associated with the plastic deformation of matrix and its coupling effect with the resin-rich regions and fiber-bridging mechanism that induced by the specific weave architecture. It has specified that the failure mechanism was transformed from brittle manner to ductile manner with increasing the temperature, which was characterized by the variation of intra- and inter-laminar cracks as well.

1. Introduction

The demand of composite materials in aircraft structures is dramatically growing, driven by the possibilities of weight reduction and improved durability in comparison of that of metals [1]. Due to their high specific strength and stiffness, unlimited shelf life, recyclability, improved processing technologies, excellent damage tolerance and impact toughness [2–6], high-performance thermoplastic composites have been used as wing fixed leading edges, ribs, clips and angled profiles in part of Airbus and Boeing commercial aircrafts as well as rudder and elevators in Gulfstream G650 business jet [7]. Some special aircraft structures, such as surroundings of aircraft's engines are subjected to thermal effect in service. Thus, it is imperative to clarify mechanical properties of thermoplastic composites under different loading conditions at elevated temperatures.

One of the loading conditions of exterior components encountered throughout their service lives is low velocity impact, such as bird strikes (while an aircraft is parked or during taxiing), tools dropped during assembly and maintenance, or runway debris encountered during take-off [8]. In an impact event, the damage may be characterized by indentation, matrix cracking, fiber/matrix debonding, delamination, inter-laminar failure and fiber breakage [9–13]. This damage is extremely dangerous because it significantly reduces the residual mechanical characteristics of the component, and at the same time can leave very limited visible marks on the impacted surface [14]. Generally, the impact-induced damage are strongly dependent on the resin type, fiber reinforcement architecture, lay-up, thickness and temperature [15]. Vieille et al. [16] investigated the effect of matrix toughness on the impact behavior by comparing the responses of TS-based (epoxy) and TP-based (PPS or PEEK) laminates subjected to low velocity impact. Experimental results revealed that fiber breakage, inter-laminar and intra-ply cracking and delamination could be found in all the three composite laminates. The different damage degree mainly depended on the ultimate out-of-plane shear strength and the interlaminar fracture toughness in modes I-II-III of each composite. For TP-based laminates, the matrix plasticization in matrix-rich areas and fiber-bridging respectively played a role in promoting permanent indentation and slow down the propagation of inter- and intra-laminar cracks. Both mechanisms seemed to reduce the extension of damages and the subsequent delamination for a given impact energy. Thus, compared with epoxy-based laminates, TP-based laminates exhibited a better impact resistance. Bibo and Hogg [17] compared the impact responses of different reinforcement architectures including unidirectional prepreg tape, planar 2D fabric and 3D fabric. The toughness of weave composite

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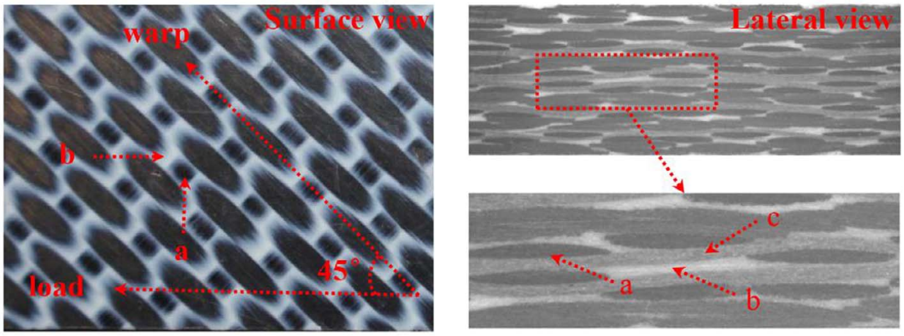

Fig. 1. Weave structure on the surface and lateral observations.

is better than that of unidirectional composites. And the 3D fabric composites have highly delamination resistance. Kim and Sham [18] specially discussed the potential advantages of using woven fabrics as opposed to cross-ply unidirectional prepreg tapes from the viewpoint of the microstructure/property relationship. Baker et al. [19] found that woven composites exhibited less internal damage for a given impact energy than those of unidirectional composites because of damage growth between layers constrained by the weave. Although 3D composites are much tougher than 2D composites [20], 2D woven fabrics are the favorite reinforcement architectures due to the advantage of easy handling [21–23].

The fiber reinforced polymer composite may behave more brittle or more ductile in low or high temperatures compared with RT. The impact responses of epoxy-based composite, TP-based laminates and hybrid composite laminates have been studied at low temperatures [24–28] and high temperatures [13,29–38]. As for epoxy-based composites, Boominathan et al. [32] studied the impact damage in carbon/epoxy laminates at different temperatures (30 °C, 55 °C, 75 °C and 90 °C), found that slopes of impact hysteresis cycles were markedly reduced and the inelastic deformation increased with the increase of temperature. Aktas et al. [35] investigated the impact behavior of glass/epoxy composite laminates at 20 °C, 60 °C and 100 °C, found that the increasing temperature didn't affect the maximum contact force values after the first fiber failure. Up to the perforation threshold, the energy absorbing capability of the specimen reduced with increasing temperature. As for thermoplastic-based composites, Sorrentino et al. [36] elucidated the effect of temperature (20 °C, 60 °C and 100 °C) on impact performances of PEN-based composites reinforced with carbon, Twaron, Vetran and basalt woven fabrics. They found that PEN/Carbon composites had the lowest impact resistance but exhibited increasing impact performances with the increasing temperature, which was attributed to the coupled contribution of the thermoplastic matrix and fiber/matrix interface strength with increasing temperature. Boumbimba et al. [37] focused on the impact behavior of glass fiber/acrylic thermoplastic resin composites modified by all-acrylic block copolymers at −80 °C, 20 °C and 80 °C. The results turned out when the impact temperature decreased laminates exhibited a large impact resistance, and the damage area increased with the increase of both impact energy and temperature. Dubary et al. [38] examined the impact behavior and damage tolerance of hybrid carbon and glass fibers woven-ply reinforced PEEK laminates at 20 °C and 150 °C, demonstrated that temperature had little influence on the impact behavior but a strong effect on the internal and external damages. However, to the author's knowledge, few studies have been published about the low velocity impact behavior of CF/PPS composites at elevated temperatures.

The purpose of the present study is to evaluate the influence of temperature on the low velocity impact behavior of woven CF/PPS composite laminates. Low velocity impact tests have been conducted at different energies at RT. Then two representative impact energies are determined in terms of the impact response and external damage. The high-temperature impact behavior is analyzed with respect to impact response, permanent indentation, external and internal damage, and delamination area with the aid of stereomicroscope and C-scan inspection. The variations of maximum contact force, absorbed energy and damage degree with temperature are discussed. And the transition of impact-induced damage is studied to reveal the effect of temperature on the impact failure mechanism.

2. Experimental methods

The composite materials under investigation in this work were supplied by TenCate Advance Company, which were manufactured from 5-harness satin weave carbon fiber (T300J 3 K) fabrics and PPS resin (Fortron 0214). The fiber volume fraction is 50%. A hot pressing technique was used to obtain the laminates according to the quasi-isotropic lay-up: $[(\pm 45)/(0,90)]_{3s}$ and its thickness was 3.72 mm. The weave structure of the laminate was shown in Fig. 1, where the locations marked as a, b and c denote crossover point, resin- rich region and warp fiber, respectively.

Prior to the impact tests, a three-point bending dynamic mechanical analyzer (DMA) was carried out by Perklin Elmer Pyris Diamond DMA to establish a relationship between the thermal property and mechanical property. Temperature scans from RT to 250 °C with a heating rate of 5 °C and a frequency of 1 Hz was performed in Nitrogen atmosphere.

According to ASTM D7136, the specimens used in the experiments were cut from the plates, with dimension 150 mm × 100 mm by water jet cutting machine, as shown in Fig. 2. The impact tests were conducted on an Instron CEAST 9350 drop weight tower, which equipped with an environmental chamber. The samples were fixed inside the chamber with the clamp apparatus as shown in Fig. 3.

The impactor with a hemispherical nose of 12.7 mm in diameter was used and the total mass including carriage and impactor was 7.45 kg. The instrument is also equipped with an infrared sensor and an anti-rebounding system, which serves to measure the displacement and avoid repeated impact on the specimen after the first impact, respectively. The impact tests were performed at four impact energies of 5, 15, 25 and 35 J at RT, and two impact energies of 15 and 25 J at 95 °C and 125 °C. Three specimens had been tested in each condition. For the impact tests at elevated temperatures, all the specimens at same temperature were kept in the thermostatic environmental chamber, heated at the desired temperature, for 20 min.

After the impact tests, the specimens were examined by SAE-300E Ultrasonic C-scanning microscope with a Olympus Panametrics 9069N probe and Olympus SZX12 stereomicroscope, in order to determine the shape and size of the delamination and damage patterns of the impacted specimens, respectively.