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Thermal ageing degradation mechanisms on compressive behavior of 3-D braided composites in experimental and numerical study

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ABSTRACT

This paper reports the thermal ageing degradation mechanisms on compressive damage behaviors of pure epoxy resin and 3-D carbon fiber/epoxy braided composites. The epoxy resin and the 3-D braided composite have been aged in air for 1, 2, 4, 8, and 16 days at 180 °C. The compressive testing results and the scanning electron microscope (SEM) observations revealed that the epoxy resin degradation only occurred within regions close to surface layer. The inner parts of the epoxy resin were protected from the ageing oxidation by the outside oxidized layer. The compressive behaviors degradation of the braided composite is attributed to the epoxy resin degradation and interface debonding. The numerical study (Finite element analysis, FEA) illustrates the interface crack propagation. The interface degradation and crack propagation are the main mechanisms of the compressive behaviors degradation after the several-day's high temperature ageing.

1. Introduction

Three-dimensional (3-D) braided composite is widely used in aeronautical engineering due to its high damage tolerance and fatigue resistance [1]. The mechanical behaviors degradation of the 3-D braided composites under long time high temperature ageing is the key to aircraft design. There are many investigations on thermal degradations of polymer-matrix composites. Different methods have been used to investigate the effect of accelerated thermal degradation on polymer materials and composite materials [2–7]. Tsotsis [8–10] found that the weight loss during thermo-gravimetric test could not be used as criteria for material acceptance. The mechanical behaviors degradation should be characterized after thermal ageing. For the ageing test, it was found that the elevated pressure may be a good tool to reduce ageing time for the materials subjected to long exposures in oxygen-containing environments at elevated temperatures [11–13].

So far, the thermal ageing studies are mainly focused on laminated composite. As for 3-D braided composite, Song et al. [14] studied the change of tensile properties of 3-D braided composites after different ageing times at different high temperatures. They found that the ageing time had a significant effect on tensile strength of the composites. Fan et al. [15] investigated the influence of thermo-oxidative ageing on impact properties of braided composites and laminated plain woven fabric composites.

In this paper, we will concentrate on the compressive behaviors of 3-D carbon fiber/epoxy braided composites after thermal ageing. Because the braided preform is embedded into the resin matrix, the compression behaviors are more dependent on the resin and more sensitive to thermal degradation. The compressive behaviors of the epoxy resin and the braided composite after thermal ageing will be presented. A finite element analysis (FEA) model was developed to reveal the failure mechanisms of the braided composite from the resin ageing and fiber/resin interface crack.

2. Experimental

2.1. Materials

The materials used in this study were T700S-12 K carbon fiber supplied by Toray Inc. (Japan) and JA-02 epoxy resin supplied by Changshu Jiafa Chemical Inc. (China). The 3-D braided perform (shown in Fig. 1) with square cross section of 11 × 11 braiding yarn arrays, was manufactured with a four-step 1 × 1 braiding technique. Epoxy resin was injected into the braided preform with vacuum assisted resin transfer molding (VARTM) technique. For comparison between the braided composite and the pure epoxy resin, an epoxy cube was prepared. Both the pure epoxy resin and the braided composite were consolidated with the same curing process: 90 °C/2hrs +110 °C/1hr +130 °C/4hrs. As shown in Fig. 2,

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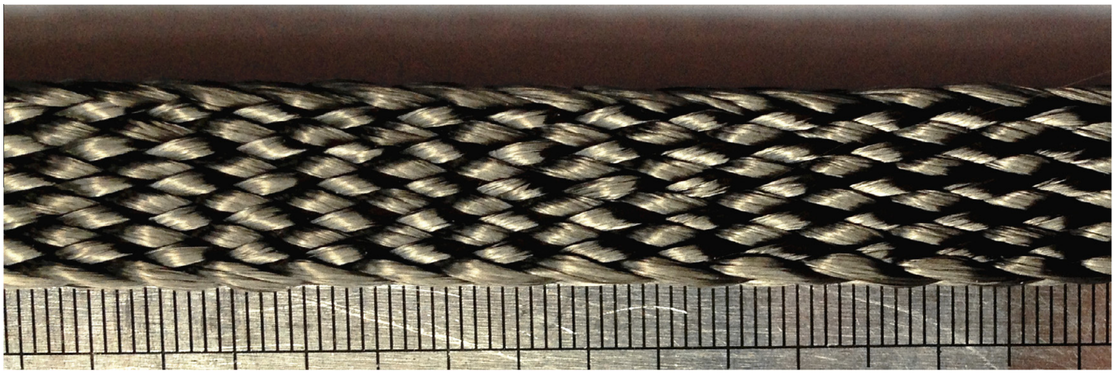

Fig. 1. Three-dimensional carbon fiber rectangular braided perform in 11 × 11 array.

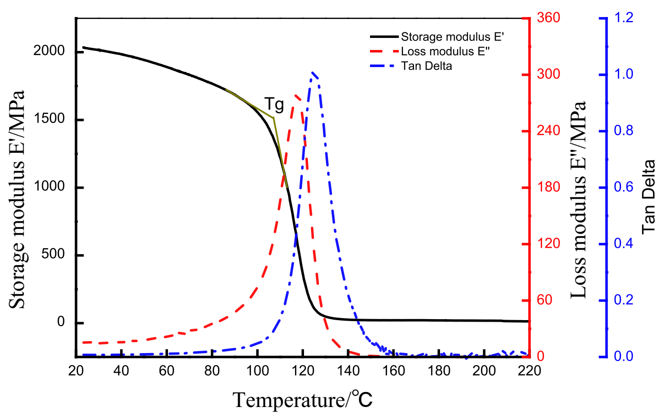

Fig. 2. DMA temperature sweep results of epoxy resin.[16]

the glass transition temperature (T_g) of the epoxy resin is 110 °C based on our previous dynamic mechanical analyses (DMA) results [16]. The braided composite was cut into about 12.2 mm along longitudinal direction which equals to the size of the braided cross section, i.e., the size of the braided composite cube is 12.2 × 12.2 × 12.2 mm. The epoxy cube has the same size with the braided composite coupon. The surface braiding angle for the braided composite is 20°. The fiber volume fraction is 38%.

2.2. Thermal ageing

All testing coupons were pretreated in an oven for 1 h at 80 °C and then divided into six groups. One group (base group) was tested for comparing the ageing effect with other groups after several-day's ageing at 180 °C.

The other five groups were aged for 1, 2, 4, 8, and 16 days at 180 °C in air respectively. When the ageing time reached, the specimens were cooled down to ambient temperature and placed into tight plastic bags to prevent moisture absorption.

2.3. Microscopy observation

Scanning electron microscopy (SEM) photographs and optical microscopy photographs were used to observe the morphologies of all the coupons after thermal ageing. The microcracks and fiber surfaces were observed for illustrating the thermal ageing effect on composite coupons. The color change and the thickness of the oxidized layer in the pure epoxy resin were also observed.

2.4. Compression test

Compression tests were performed on MTS 810 material test system and the compressive speed was set as 2 mm/min. The tests were at room temperature (20 °C). Each test was repeated three times and the average compressive behaviors were obtained. Fig. 3 shows the out-of-plane compression.

During the compression tests, the compression load was obtained from the loading sensor of the MTS 810 tester and the compression deformation was assumed to equal to the stroke of the loading cell. Then the engineering stress of the composite coupons was the quotient of the load and the cross-section area. The engineering strain is the quotient of the stroke of the loading cell and the coupon size along compression direction. Because the transverse strain was not measured, the strain gauge was not used to measure the local strain of the composite coupon. The engineering stress–strain curve was obtained to compare the compressive behaviors degradation after the composite ageing.

3. Modeling

3.1. Geometrical modeling

Based on the microstructure of 3D braided preform and the impregnating resin, the geometrical model was established as shown in Fig. 4. It was assumed that all the fiber tows were completely impregnated by resin during the composite VARTM consolidation. In the finite element model, there were 279,282 solid elements for the entire microstructure model, where 252,141 elements for the epoxy resin and 23,045 elements for yarns and 4096 elements for the clamp.

3.2. Material properties

There are gaps among fibers in a fiber tow. The gaps will be filled with resin during composite fabrication. It is more accurate to consider a fiber tow as a transversely isotropic unidirectional composite rather than a pure carbon fiber tow. The bridging model of Huang [17] was used for calculating the stiffness matrix of the fiber tow. It was assumed that the mechanical properties of the fiber tow remained unchanged because the carbon fibers were relatively stable during thermal ageing. The mechanical behaviors of the epoxy resin after ageing were introduced into the model to calculate the compressive behaviors. Then the temperature-independent constitutive relationships could be avoided for the numerical study. Only the elastic–plastic constitutive relationships of the epoxy resins were used for FEA calculation.