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Experimental investigation on the compression properties and failure mechanism of 3D braided composites at room and liquid nitrogen temperature

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ABSTRACT

The compressive experiments on the 3D braided composites with different braiding parameters are performed in three directions (longitudinal, in-plane and transverse) at room and liquid nitrogen temperature (low as −196 °C). Macro-Fracture morphology and SEM micrographs are examined to understand the deformation and failure mechanism. The results show that the stress–strain curves and the compression properties are significantly different in the longitudinal, in-plane and transverse direction. Meanwhile, the compression properties at liquid nitrogen temperature are improved significantly than that at room temperature. Moreover, the damage and failure patterns of composites vary with the loading directions and test temperature. At liquid nitrogen temperature, the brittle failure feature becomes more obvious and the interfacial adhesion capacity is enhanced significantly. In addition, the compressive properties and failure mechanism at room and liquid nitrogen temperature can be significantly affected by the braiding angle and the fiber volume fraction.

1. Introduction

Three-dimensional (3D) braided composites have been widely used in many industries due to the advantages over the conventional laminated composites, including through-thickness reinforcement, high damage tolerance, anti-ablation capability, etc. [1,2]. One of the important applications of technological progress to modern cryogenic devices is the use of 3D braided composites in their construction. When 3D braided composites are used for spacecraft cryogenic structures, i.e., liquid nitrogen tanks of launch vehicles, they are loaded under compressive, bending or some other impacts. The mechanical properties of materials are extremely important in liquid nitrogen low temperature environments. It is essential in cryogenic applications of 3D braided composites that the accumulated damage can be predicted and the effect of such damage on the response and fracture behavior of the structures can be determined [3–5].

Most publications on 3D braided composites have been devoted to the investigation of their behavior at room temperature. Yang et al. [6] first studied the elastic properties of 3D braided composites using a "fiber inclination model" which is based on a simplified unit-cell constructed with four inclination unidirectional laminas. Chen et al. [7] analyzed the geometrical and structural parameters of braided composites and mathematical relations for yarn volume fraction, yarn jamming factor, braiding angle and braiding pitch have been developed. Tang and Postle [8] conducted the non-linear deformation of 3D four directionally braided composites using the finite element method and Sun et al. [9] developed the incompatible displacement element and hybrid stress element to predict the mechanical behavior of braided composites. Zeng et al. [10] calculated Young's modulus and Poisson ratio of braided composites with the transverse cracking by a simplified damage model. Yu and Cui [11] developed a two-scale method to calculate mechanical parameters of 3D braided composites. They demonstrated that braiding angle and fiber volume fraction are important influential parameters on stiffness and resistance of composites. Li et al. [12] presented an experimental characterization of the effect of cut-edge on the bending properties of 3D braided composites. Their results showed that the cut-edge along the thickness brings notable cut-down on the strength of the composites with a smaller braiding angle. Recently, Fang et al. [13] analyzed the damage

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propagation of representative volume cells by using an anisotropic damage model in finite element method to evaluate the non-linear behavior of the 3D braided composites with big braiding angle. In addition, Li et al. [14] studied the temperature effects on the bending properties and failure mechanism of 3D E-glass/epoxy four-directionally braided composites. The results have shown that mechanical performance decreases with the increase of the temperature, at higher temperature, the composite becomes softer and plastic. It gets damaged with the micro-cracks of the matrix and debonding of fibers from the matrix.

In addition to the above mechanical properties, several researches have also been carried out on the compressive behavior and failure mechanism of 3D braided composites. Yau et al. [15] studied longitudinal compressive failures of three-dimensionally braided composite I-beams. Their results indicated that 3-D braided I-beams had a high degree of through-the-thickness strength due to no delamination during the failure process. Yerramalli et al. [16] analyzed compressive splitting failure of composites using modified shear lag theory. In this study, the use of a shear lag model in conjunction with the elasticity equations leads to a simple analytical expression to determine the compliance changes for both unsteady crack growth as well as steady state crack propagation under compressive loading. Calme et al. [17] observed the static behavior of 3D braided composite rings under the lateral compression and obtained the absorbed energy at the linear elastic state from analytical stress–strain relations. Chen et al. [18] conducted longitudinal compressive tests for 3D five-directional carbon/epoxy braided composites by using shot-gauge plate sample method. They found braiding angle and fiber volume fraction had significant influence on the mechanical properties of 3D five-directional braided composites, but the linear density of yarns had little effect. Sun et al. [19] investigated the longitudinal compressive properties of 3D four-directionally E-glass/epoxy braided composites at quasi-static and high strain rates. However, the experiments they carried out did not fully reveal the compressive properties according to different braiding parameters. Li et al. [20–22] also experimentally studied longitudinal and transverse compressive properties and failure mechanism of 3D five-directional carbon/phenolic braided composites at room temperature. Recently, Fang et al. [23] reported the longitudinal compressive mechanical properties of the braided composites by combing damage theory and finite element method. In their study, it has been demonstrated that the compressive mechanical behavior of the braided composites with lower braiding angle is sensitive to the fiber initial imperfection of braiding yarn.

Actually, the loading direction, braiding parameters and testing temperature are the important factors which can affect the compressive properties and failure mechanism of 3D braided composites. However, the previous studies carried out so far were concerned with the compressive properties of 3D braided composite along the longitudinal direction which seldom focused on the other two directions (In-plane and transverse direction). Moreover, few works discussed on the effect of braiding parameters and the environment test temperature has not been referred to, especially, the compressive properties of 3D braided composites at liquid nitrogen temperature (low as $-196\,^{\circ}$C) have not been reported so far.

In this paper, the compressive properties of 3D braided composites with different braiding angles and fiber volume fractions in three directions (longitudinal, in-plane and transverse direction) are examined experimentally at room and liquid nitrogen low temperature. The damage and fracture morphology of the composites after compressive failure are observed from the macroscopic and microscopic view and the failure mechanism is demonstrated. Finally, the influences of braiding parameters on the compression properties and failure modes of composites at room and liquid nitrogen low temperature are also analyzed. The aim of our study is to establish the database for the potential application of composites in the fields of aerospace. It is expected that the study can provide an experimental basis for the structural design of the 3D braided composites at room and liquid nitrogen temperatures.

2. Materials and samples

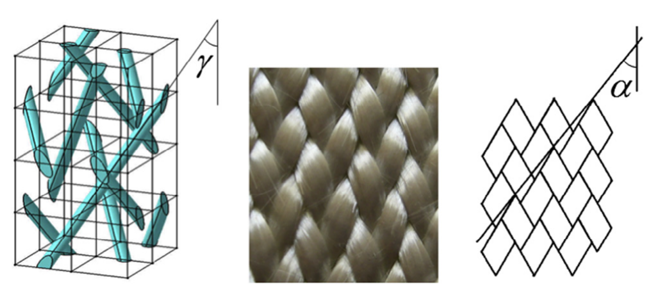
3D braided preforms are formed by interlacing braid yarns each other by four-step 1×1 braid method [24]. The high strength E-glass yarns are employed for braiding yarn of 3D braided preforms in this study. The TDE-86 expoy resins are injected into the 3D braided preforms by the resin transfer molding (RTM) process and then consolidated to produce the 3D braided composites. Fig. 1a illustrates the fiber architecture of the interior unit of the 3D four-directional braided composites used in this study, where γ is the interior braiding angle between the interior braiding yarn axis and the Z-axis. For 3D braided composites, it is difficult to measure the interior braiding angle γ, while the braiding angle α is measured frequently, see Fig. 1b. The relationship between the interior braiding angle γ and the braiding angle α can be derived as:

$$\tan\gamma = \sqrt{2}\tan\alpha \tag{1}$$

The composites are cut, and the in-plane size of the composite samples for compressive tests at room and liquid nitrogen temperature is 7.5 mm(length) × 7.5 mm(width) × 5 mm(thickness). A series of samples with different braiding parameters have been considered in the present study. Fig. 2 shows that the photographs of 3D braided composite samples and the cross-sectional distribution from three directions can be observed clearly. The specifications of the samples tested are summarized in Table 1.

3. Experimental procedure

Since there are no standards of cryogenic compression test for 3D braided composites, the sample configuration and test procedure were followed by the ASTM standard D3410-87 and Chinese GB1448-83 about fiber reinforced composites. The dimension for the sample with 7.5 mm(length) × 7.5 mm(width) × 5 mm(thickness) is adopted, because it is small enough to satisfy the requirement of the testing loading of machine under liquid nitrogen temperature and the current dimension can effectively avoid the buckling and end cracking during compression, on the other hand, the sample includes at least three period unit cell configurations which can truly reflect the interior structure of braided composites and then decrease the effect of size-dependency. The compression test under three directional loading at room and liquid nitrogen temperature (low as -196 °C) is carried out on a MTS tester. At low temperature, a sweating guarded hot compressive fixture has been developed by modifying the one specified at room tempera-



(a) Interior unit cell (b) 3D braided prefrom surface

Fig. 1. The fiber architecture of 3D four-directional braided composites.