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Finite element analyses on three-point low-cyclic bending fatigue of 3-D braided composite materials at microstructure level

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ABSTRACT

This paper presents numerical analyses of fatigue behaviors of three-dimensional (3-D) 4-step rectangular braided composite material under three-point low-cyclic bending. A microstructure model of the 3-D braided composite was established to calculate the bending fatigue deformation and failure with a finite element method (FEM). The stiffness degradation and failure morphologies were obtained from the FEM results and compared with those from experimental. The stress distributions, stress hysteresis and failures of fiber tows and resins at different parts of the 3-D braided composite material have been collected from the FEM calculations to analyze the fatigue failure mechanisms. The influences of the braided preform microstructure on the fatigue damage were discussed. It is found that the surface yarns share more loads than the yarns of the inner part. The stress concentration appeared at the regions with larger changes of fiber tow orientation angles. The fatigue damage evolutions were also used to explain the mechanical behaviors degradation. The crack generation and fatigue damages development of the braided composite appeared at early stages and followed by crack propagation afterwards. A series of damage evolution at the different loading cycles were obtained to unveil the fatigue damage mechanisms. From the investigation, the fatigue resistance of 3-D braided composite could be optimized from improving the mechanical behaviors of surface fiber tows and decreasing the change of fiber tows orientation angles.

1. Introduction

Three-dimensional (3-D) braided composites have been widely used in structure engineering, for example, tubes and T-beams. Due to the three-dimensional integrated braided preform structure, three-dimensional braided composites have higher interlamination shear strength and damage tolerance than laminated composites [1–3]. The fatigue deformation and failure of 3-D braided composite are the important mechanical behaviors for braided composite materials under long-time services.

The fatigue studies of braided composite materials start from 2-D braided structure. Tate et al. [4,5] investigated the fatigue performance of biaxial braided composites at a stress ratio of 0.1. It was observed that a sigmoidal function could be used effectively to represent the fatigue life behavior. The load controlled tension–tension fatigue tests ($R=0.1$) were conducted at the frequency of 10 Hz with constant amplitude. They also performed extensive tension–tension fatigue tests on biaxial braided carbon/epoxy composites for various braid angles. Goyal and Whitcomb [6] presented that a glass braid tow was probably more susceptible to initiation of tensile fatigue damage than a carbon braid tow of a geometrically similar braid. Fujihara et al. [7] tested bending fatigue properties of braided laminated composites at three different braiding angles (15°, 20°, and 25°). 20° braiding angle gave better fracture resistance under fatigue loading. Li et al. [8] used the microscale modeling technique to examine and predict the deformation and damage observed in tests of straight-sided specimens. By comparing the analytical results with those obtained experimentally, the applicability of the developed model was assessed and the failure process was investigated. Song et al. [9] discussed the results of a finite element (FE) based micromechanics study of the compressive damage development mechanisms of 2-D triaxial braided carbon fiber composites. Huang [10] modeled and characterized the ultimate bending strength of laminated braided fabric reinforced composites, and he found that the predicted load–deflection curves up to the third-ply failure for a number of the braided carbon-epoxy laminates agree reasonably well with the experimental results.

The fatigue researches of 3-D braided composite are mainly limited in experimental testing. Compared with 2-D braided structure, the fatigue investigations on the 3-D braided composite are insufficient. Only a few works have been conducted so far. For example, Liao et al. [11] examined the bend–bend fatigue behavior of 3-D integral braided carbon/carbon composites (3-D C/C) under

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load control at a sinusoidal frequency of 10 Hz. It is revealed that the interfacial sliding abrasion played an important role in the fatigue failure process, and the extent and speed of sliding abrasion were controlled by the level of applied stress. Li et al. [12] studied tension–tension fatigue properties and the effect of braiding structures on the fatigue properties of three dimensional braiding composites. It was found that the braiding angles have a great influence on the fatigue properties of 3-D braiding composites and the residual strength of the specimens is higher than the static test strength. Zhao et al. [13] reported the bending fatigue behavior of a four-step 3-D rectangular braided composite at different stress levels.

For 3-D braided composite modeling, the simplified geometrical models were often used to analyze the fatigue behaviors because of the complicated structure of braided composite and difficulties of failure criteria. Miravete et al. [14] developed a new analytical micromechanical approach valid for three-axial as well as 3-D braided composite. Shokrieh and Mazloomi [15] introduced a multi-unit cell model to calculate the stiffness of three-dimensional four-directional braided composites. Sun et al. [16] applied a unit cell model to predict fatigue behavior of 3-D carbon/epoxy braided composite. However, the microstructure deformation and failure mechanisms were not revealed in all above-mentioned models. The complex and integrated braided preform structure leads to the difficulty of explaining the fatigue behaviors. This is also the reason that why the fatigue behaviors of 3-D braided composite materials were few reported at microstructure level so far.

Here we will report, for the first time, the fatigue deformation and damage of 3-D 4-step rectangular braided composite under three-point low-cyclic bending fatigue based on a microstructure geometrical model. The influences of the braided preform structure on the fatigue damage mechanisms are analyzed from the stress distribution and deformation of fiber tows and resins. The stiffness degradation and damage morphologies of the 3-D braided composite will be obtained from finite element analyses (FEA) and compared with those in experimental qualitatively. From such an investigation, the fatigue behaviors of 3-D braided composite materials could be optimized from the microstructure designs and fiber tows' orientations and arrangements.

2. Materials and fatigue tests

2.1. Materials

The carbon fiber tows (Toray®, T300-6K) were used for braiding the 3-D rectangular braided preform with a 4-step1 × 1 braiding technique. The array for the braided preform was 29 × 5. The sketch diagram of 3-D braided preform is shown in Fig. 1. The solution composed of epoxy resin (TDE-85) combined with a curing agent (N, N-dimethyl benzyl amine) and an accelerating agent (HK-021 Me-THPA) was injected into the preform with a resin transfer molding technique to manufacture the 3-D braided composite. The curing temperature was 130 °C for 2 h, followed by 150 °C for 1 h, 160 °C for 8 h, and finally 180 °C for 3 h. The final specimens used for testing were cut with high-pressure water jet along the longitudinal direction. Table 1 shows the structure parameters of the 3-D braided composite materials. Fig. 2 shows the photograph of surface and cross-section of the 3-D 4-step braided composite panel.

2.2. Quasi-static bending and bending fatigue tests

The quasi-static and fatigue three-point bending tests were conducted using a servo-hydraulic testing machine (model MTS 810.23). The ASTM D790 standard was chosen for the tests. According to the description of ASTM D790 Section 7.5, a span-to-depth ratio larger than 16:1 may be necessary (32:1 or 40:1 are recommended) for high-strength reinforced composites. The quasi-static bending tests were conducted at a constant velocity of 2 mm/min. As shown in Fig. 3, the specimen was placed on two supporting rollers with spacing 100 mm, and the pressing roller was located at the center of the top surface. These three rollers had the same diameter of 20 mm and length of 70 mm, which is provided with a MTS 810.23 testing machine. From Eqs. (1) and (2) (F is the load applied at the central point of the specimen, ΔF is the increment of F, Δf is the central deflection increment, l is the supporting roller's span, and b and h are the width and thickness of the specimen, respectively), the average bending modulus (E_f) and ultimate stress (σ_{ult}) of the 3-D braided composite were calculated by averaging 10 specimens, and the values are 97.6 GPa and 615 MPa with coefficients of variation 1.52% and 2.36%,

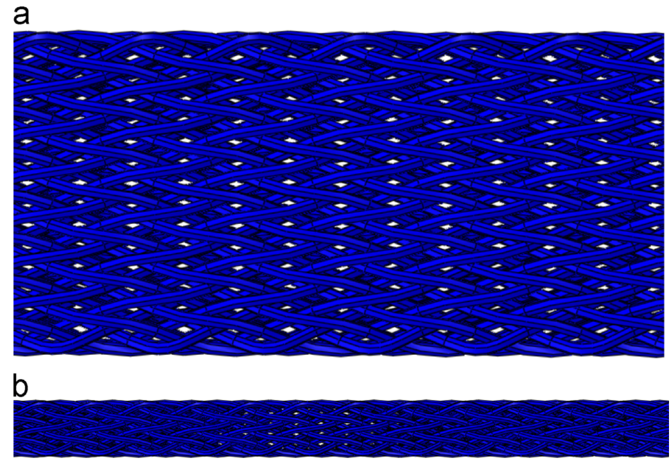

Fig. 1. Sketch diagram of 3-D braided preform: (a) front view and (b) cross-section view.

Table 1
Structure parameters of 3-D braided composite.

Yarn numbers in braiding array	179
Preform dimensions (mm)	125 × 25 × 3
Fiber volume fraction (%)	58
Braiding angles (deg)	28 ± 3
Braiding distance (mm)	3.0

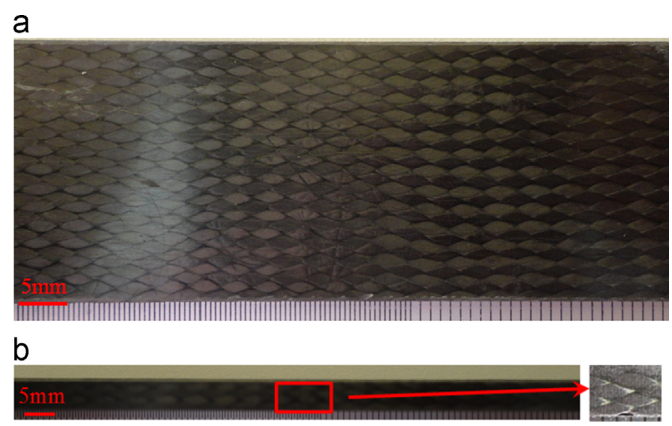

Fig. 2. Photograph of surface and cross-section of the 3-D braided composite materials: (a) front view and (b) cross-section view.