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Computational schemes on the bending fatigue deformation and damage of three-dimensional orthogonal woven composite materials

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ABSTRACT

This paper reports a computational scheme on three-dimensional orthogonal woven composites (3DOWC) fatigue behavior under three-point low-cycle bending. Based on three-point cyclic bending fatigue tests, a microstructure model was established at yarn level for predicting the fatigue behaviors. The stiffness degradation and damage morphologies of the 3DOWC were obtained from finite element analysis (FEA) and compared with those from experimental. The stress distribution, energy absorption and damage morphologies in the different parts of the 3DOWC sample were obtained to analyze fatigue failure mechanisms. The influences of warp yarns, weft yarns and Z-yarn systems were discussed. It is found that warp yarn system bears the most cyclic load as well as energy absorption. The stress concentration area was located in the central loading area, especially in the warp yarns that is close to the Z-yarns side and its channels. The triangle damage area was gradually generated from up to down in the stress concentration area as the loading cycle increased.

1. Introduction

Three dimensional (3D) textile structural composite materials have been widely applied to the manufacturing of engineering structures in which the high delamination resistance is required [1–3]. As one of the frequently-used 3D structural textile composites, 3D orthogonal woven composites (3DOWC) have high stiffness and strength along warp, weft, and thickness directions due to the noncrimp feature of fiber tows in 3D orthogonal woven fabric (3DOWF) [4]. Furthermore, the unique Z-yarn embedded along the thickness direction leads to the high delaminating resistance and high strength along in-plane direction and through-thickness direction.

During the investigations of fatigue behaviors of 3D textile composites, Dadkhah et al. [5] performed compression–compression fatigue experiment of 3D woven composites under load control and found that composite fail by formation of kink band. It was found that as under monotonic loading, the principal mechanism of failure is kink band formation in the primary load bearing tows. Zhu et al. [6] tested low cycle fatigue behavior of 3D orthogonal Tyranno fiber reinforced Si–Ti–C–O matrix composites. The low cycle fatigue tests of an orthogonal three-dimensional (3-D) Tyranno fiber reinforced Si–Ti–C–O (SiC) matrix composites were conducted with a sine wave form under stress and strain controls at room temperature. It was shown that the asymmetric response of strain or stress occurs between tension and compression. Karahan et al. [7] and Bogdanovich et al. [8] reported in-plane tension–tension fatigue behavior and quasi-static tensile behavior and damage of carbon fiber composite reinforced with non-crimp 3D orthogonal woven fabric respectively. The in-plane tension–tension fatigue behavior of the carbon fiber/epoxy matrix composite reinforced with non-crimp 3D orthogonal woven fabric was tested. It was revealed that the maximum cycle stress corresponding to at least 3 million cycles of fatigue life without failure is in the range of 412–450 MPa for both loading directions. Avanzini et al. [9] investigated fatigue behavior and cyclic damage of PEEK short fiber reinforced composites. Fatigue strength and failure mechanisms of short fiber reinforced composite have been investigated on cyclic creep, fatigue damage accumulation and modeling, particular in presence of both fillers and short fibers as reinforcement. Sun et al. [10] studied the bending fatigue of 3DOWC under different loading stress level. The S–N curve was obtained to illustrate the relationship between applied stress levels and number of cycles to failure. The stiffness variation was recorded to present the degradation of mechanical properties of the 3DOWC during the process of fatigue loading. Yao et al. [11] analyzed static and bending fatigue properties of ultra-thick 3DOWC, and found the residual strength, modulus of both warp and weft direction have a sharp reduction stage in the early part of fatigue cycling and a

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more gradual decrease followed stage. Jin et al. [12] compared quasi-static three point bending and fatigue damage behavior of 3D angle-interlock woven composite with 3DOWC. The S–N curves were obtained to demonstrate the comparison of fatigue life under various stress levels between three-dimensional angle-interlock woven composite and three-dimensional orthogonal woven composite.

In 3D woven composite materials, the warp, weft and thickness fiber tows will have different damage and degradation process cyclic loading. How to characterize the composite material's damage from the preform structure is important to design the 3D woven composite for the cyclic loading application. However, the influence of 3D orthogonal woven preform structure on the cyclic bending fatigue damage mechanisms has not been well studied so far and also not reported in above-mentioned investigations. Here we report the stress distribution, fatigue deformation and damage of the 3DOWC under three-point cyclic bending from a microstructure model approach. A microstructure model at yarn level is established to calculate the fatigue behavior. The stiffness degradation and damage morphologies of the 3DOWC will be obtained from the finite element analyses (FEA) and compared with those from experimental. The bending fatigue failure mechanisms will be analyzed.

2. Experimental details

2.1. Materials

(1) Three-dimensional orthogonal woven fabrics (3DOWF).

The 3DOWF was prepared with E-glass fiber tows. The specifications are listed in Table 1 and the structure diagram and photograph are shown in Fig. 1.

(2) Resin and composite consolidation.

Resin (AROPOL™ INF 80501-50), curing agent (AKZO M-50) and accelerating agents (cobalt octoate) were mixed with the proportions of 100:1.5:2 by weight. Using vacuum assisted resin transfer modeling (VARTM) technique, the 3DOWC was cured under 80 °C for 4 h and then room temperature for 24 h. The fiber volume fraction of the 3DOWC was approximately 43.7%. The size of the coupon was 200 × 20 × 9.64 mm (length × width × thickness).

2.2. Quasi-static bending and fatigue tests

Both quasi-static bending and fatigue tests were conducted on MTS 810.23 materials testing system. The quasi-static bending tests were performed at a constant speed of 2 mm/min. From Eqs. (1) and (2), the calculated bending modulus (E_f) and the ultimate failure stress σ_{ult} were 27.58 GPa and 543.0 MPa, respectively.

$$E_b = \frac{l^3 \Delta F}{4bh^3 \Delta f} \quad (1)$$

$$\sigma_b = \frac{3Fl}{2bh^2} \quad (2)$$

where E_b is the bending modulus, σ_b is bending stress, F is the load at the central of the specimen. ΔF is the increment of F, Δf is the central deflection increment, l is the span between two supporting roller, b and h are the width and thickness of specimen.

A sinusoidal wave-form load at 3 Hz was applied to the test species with a stress ratio R ($\sigma_{\min}/\sigma_{\max}$ in one cycle) of 0.1. The tests were performed with the stress level $\sigma_{\max}/\sigma_{ult}$ of 60% (the ratio of the applied maximum stress $\sigma_{\max}$ in one cycle to the ultimate static bending stress σ_{ult}) under the room temperature. The maximum stress $\sigma_{\max}$ equals to 325.8 MPa.

3. Modeling

3.1. Microstructure model

Based on the microstructure of 3D woven preform and the impregnated resin, the geometrical model was established and assumed that all the fiber tows were completely wetted by resin during composite consolidation. All the fiber tows were considered to be in fiber/resin form, i.e., the fiber tows were completely impregnated with resins. The geometrical model of warp yarns, weft yarns, Z-yarns, resin and the entire 3DOWC structure are

Table 1
Specifications of 3D orthogonal woven fabric sample.

Component	Length (mm)	Width (mm)	Thickness (mm)	Volume (%)	Layers	Linear density/Tex	Density/(ends/cm)	Layers	Fabric size (mm)
Warp	4.00	1.4	0.26	27.46	17	400 × 2	5	17	401
Weft	4.24	1.4	0.26	30.93	16	400 × 2	4.7	16	523
Z-yarn	–	0.4	0.1	1.11	–	28 × 2	5 × 4.7	–	–

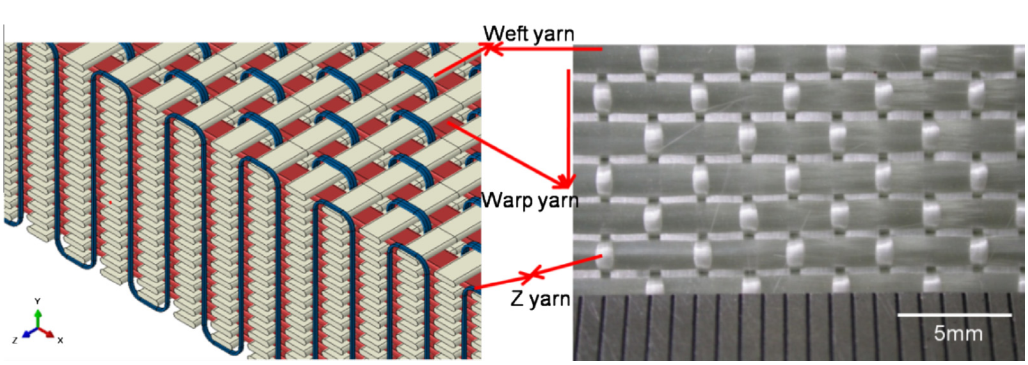

Fig. 1. Structure diagram and photograph three dimensional orthogonal woven fabric.