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# Computational analysis of fatigue behavior of 3D 4-directional braided composites based on unit cell approach

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ABSTRACT

The fatigue behavior of 3D 4-directional braided composites was investigated based on the unit cell approach. First, the unit cell models of 3D 4-directional braided composites with different braiding angles and fiber volume fraction were built up using ABAQUS. Then, the fatigue behavior of the 3D 4-directional braided composites was analyzed, and the effect of fatigue loading direction on the fatigue damage evolution and fatigue life was studied. Finally, the effect of braiding angles and fiber volume fraction of the unit cell on the fatigue behavior of 3D 4-directional braided composites was analyzed. These results will play an important role for evaluating the fatigue behavior of 3D 4-directional braided composites in engineering.



## 1. Introduction

Three-dimensional (3D) braided composite has been used widely in engineering. The distinct feature of 3D braided composites is that there is not interlaminar crack and delamination compared with that of laminated composites. However, only when mechanical properties of 3D braided composites are correctly characterized could the composite structures applied in engineering be optimized.

The mechanical properties and strength characterizations of the 3D braided composite using the representative unit cell were reported in many references. Yu et al. [1] predicted the mechanics parameters of 4-step three dimensional braided composites, including stiffness parameters and strength parameters using the two-scale method (TSM). Zheng et al. [2] studied the yarn architecture of 3-D braided composites products by the four-step $1 \times 1$ braiding technique by means of a control volume method in conjunction with experimental investigation and a numerical method, respectively. Sun et al. [3] used digital element approach, which treats textile composite manufacturing process as a nonlinear solid mechanics problem, to investigate the complicated microstructure of 3D braided rectangular preform. Gu et al. [4,5] studied the influence of the strain rate on the uniaxial tensile behavior of 4-step 3D braided composites, and the ballistic perforation test results of 4-step 3D braided Twaron/epoxy composites, which were subjected to impact by conically cylindrical steel projectile, were presented. Also, the damage evolution of the 3D braided composite is simulated. Fang et al. [6] studied the effect of yarn distortion on the mechanical properties of 3D four-directional braided composites, and analyzed the progressive damage behavior of 3D four-directional braided composites with large braid angle subjected to uniaxial tension [7]. Lu et al. [8] studied the effect of interfacial properties on the uniaxial tensile behavior of three-dimensional braided composites. Drach et al. [9] proposed an efficient procedure to process the textile simulation data and generate realistic finite element meshes of woven composites. Dong et al. [10,11] studied tensile strength of 3D braided composites in the microscope view, where non-linear progressive damages under tensile loading steps were conducted in their article. However, the experimental studies on the properties and strength characterizations of the 3D braided composite are scarce as yet. Zaman et al. [12] fabricated a high density 3D-four directional carbon/carbon composite by hot isostatic pressure impregnation carbonisation using coal tar pitches. And the thermo-oxidative, thermophysical and ablation properties of the composite were determined. Li et al. [13] preformed compressive experiments on the 3D braided composites with different braiding parameters in three directions (longitudinal, in-plane and transverse) at room and liquid nitrogen temperature (low as −196 °C). Li et al. [14] presented experimental

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characterization of the effect of cut-edge on the tensile, compressive and flexure properties in the braiding direction of the 3D braided composites.

It is obvious that most of numerical and analytical works devoted to mechanical properties and strength characterizations of the 3D braided composite. However, the fatigue behavior of 3D 4-directional braided composites has not been reported till now. In this paper, the fatigue behavior of 3D 4-directional braided composites was analyzed based on unit cell approach, and the effect of braiding angles and fiber volume fraction of the unit cell on the fatigue behavior was studied.

## 2. FEM model of the 3D 4-directional braided composites

### 2.1. Microstructure modeling of 3D 4-directional braided composites

The basic Cartesian braiding process involves four distinct Cartesian motions of groups of yarns termed rows and columns. For a given step, alternate rows are shifted a prescribed distance relative to each other. The next step involves the alternate shifting of the columns a prescribed distance. The third and fourth steps are simply the reverse shifting sequence of the first and second steps, respectively. A complete set of 4-directionals is called a machine cycle, which is shown in Fig. 1 [12].

The geometric structure of unit cell of 3D 4-directional braided composites is shown in Fig. 2. The length, width and height of the unit cell are $a \times b \times c$ including 19 yarns with 7 main fibers ($f_1$–$f_7$ as shown in Fig. 2). As shown in Fig. 2, the braiding angle ($\gamma$) is defined as the angle between the yarn and the braided axis as follow:

$$\tan\gamma = \frac{\sqrt{a^2+b^2}}{c} \tag{1}$$

And the fiber volume fraction ($\psi$) can be determined as:

$$\psi = \frac{\pi D^2\sqrt{a^2+b^2+c^2}}{abc} \tag{2}$$

where $D$ is the diameter of the yarn.

The FEM model of the unit cells of 3D 4-directional braided composites is built in ABAQUS according to the geometric structure in Fig. 2. The unit cells with braided angles of 20°, 25°, 30°, 35° and 40° are shown in Fig. 3, and the unit cells with fiber volume fraction of 30%, 35%, 40%, 45% and 50% are shown in Fig. 4.

### 2.2. Fatigue damage criterion

#### 2.2.1. Strength degeneration criterion

The degradation of strength during fatigue cycling is assumed to follow a simple linear degradation per cycle. This has the advantage that only the expected life at each stress level is needed and this can be obtained from the SN curve or constant life diagram. A comparison of many candidate models recently concluded that the linear model was preferred based on its simplicity and conservative predictions [15,16]. The residual strength in the fiber and matrix is given by [17]:

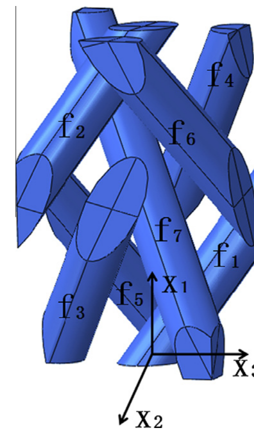


**Fig. 2.** Geometric structure of unit cell.

$$R^r = R^s - \sum_{i=1}^{m}(R^s - \sigma^i_{\max})\frac{\Delta n}{N_f(\sigma^i_{\max})} \tag{3}$$

where $m$ is the number of fatigue cycle blocks, $R^r$ is the residual strength after the $m$ blocks, $R^s$ is the static strength at the initial, $\sigma^i_{\max}$ is the maximum stress during the $i$th block, $N_f$ is the number of cycles to failure in constant amplitude fatigue at $\sigma^i_{\max}$. $N_f$ is obtained from the SN curve which is often approximated with a power law of the form:

$$\sigma_{\max} = AN_f^{-B} \tag{4}$$

Fig. 5 shows a schematic of the drop in strength due to a complex load history. This schematic is composed of blocks of different stress levels each with different mean and alternating stress levels. Fracture occurs when residual strength degrades to a level at or below the stress levels developed during any fatigue cycle.

#### 2.2.2. Stiffness degeneration criterion

Experimental testing has shown that early stage damage occurs during initial fatigue cycling followed by a long period where the damage accumulation rate is quite low. Finally the accumulated damage reduces the capacity of the material to resist the stresses and there is a relatively rapid drop to failure. The modulus of the material is reduced as damage increases. True modulus is difficult to measure experimentally in fatigue testing

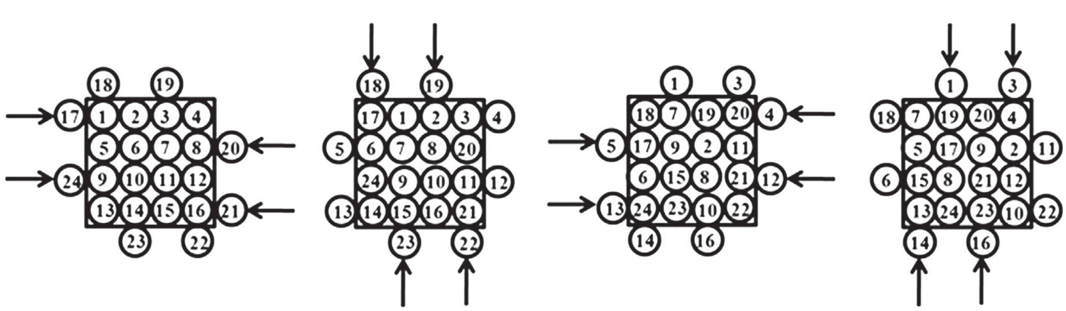


**Fig. 1.** Braiding process of 3D 4-directional braided composites [12].