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Investigation on the tensile properties of three-dimensional full five-directional braided composites

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ABSTRACT

Longitudinal tensile behaviors of three-dimensional full five-directional (3DF5D) braided composites are simulated using finite element methods (FEMs). A representative volume cell (RVC) with periodical boundary conditions is adopted to calculate the mechanical properties of the composites. In addition, the yarns are considered as uniaxial fiber-reinforced composites, and the effective mechanical properties are obtained from a RVC of yarns by using the collision algorithm. Based on the Linde failure criterion, a new damage model is proposed to describe the damage initiation and evolution in yarns, and then the longitudinal tensile strengths are predicted. Beyond this, deformation of braided preforms and pore defects are also considered in the computational model. Numerical results show that the longitudinal damage in yarns contributes to the failure of composites, and the prediction is compared with the experimental results with good agreement achieved.

1. Introduction

The potentialities of three-dimensional (3D) braided composites are very wide, including high specific strength, large specific stiffness, and excellent ablation resistance. They are the combination of traditional braiding process and advanced composite technology, and gradually receive a particularly attention in load-bearing structures [1,2]. Comparing with three-dimensional four-directional (3D4D) braided composites, three-dimensional five-directional (3D5D) braided composites have better mechanical properties in the braiding direction due to the adding of axial yarns. However, based on the microscopic observation of 3D5D braided composites, there still exist a lot of gaps in the braided preforms, resulting in a limitation of fiber volume fraction (shown in Fig. 1a). Consequently, Liu et al. [3,4] proposed a new concept named three-dimensional full five-directional (3DF5D) braided preforms, in which additional reinforced yarns were added to fill in the gaps (shown in Fig. 1b). Subsequently, Huang [5] fabricated the 3DF5D braided composites, and measured the mechanical properties of the new composites, which proved their larger fiber volume fraction and better axial mechanical properties than 3D5D braided composites. Thus, it is of great importance to establish the realistic structure model and further predict the mechanical properties of 3DF5D braided composites accurately. However, there were few works dealing with the finite elements analysis of the new composites, and researchers mainly focused on the studies of 3D4D and 3D5D braided composites.

Representative volume cell (RVC) was generally used to investigate the properties of braided composites due to their periodic structures, and many models have been developed [6–9]. Up to now, great achievements have been obtained on the elastic properties [10–13] and thermo-physical properties [14–16] of braided composites. For strength prediction, Lu et al. [17] firstly introduced an empirical strength criterion, which took the volume ratio of failure elements into consideration. However, no stiffness degradation was applied on failure elements, and the predicted strength might be overestimated. Gu [18] predicted the uniaxial tensile stress–strain curve of 3D braided preforms in a mathematical way without considering the cross section shape of yarns. Zeng et al. [19,20] proposed a multiphase element model and predicted the nonlinear response of 3D4D braided composites, but the model was too simple to reflect the actual structures. Yu and Cui [21] studied the tensile properties of 3D4D braided composites via the two-scale finite element methods, and Dong and Feng [22] simulated the progressive damage of composites with the asymptotic expansion homogenization method. On the elliptic or approximately elliptic yarn cross section hypothesis, the contacts of the yarns were ignored. Based on the polygon section assumption of yarns, Xu and Xu [23] analyzed the damage evolution under longitudinal tension for 3D4D and 3D5D braided composites, and 3D-Hashin and Tsai-Wu failure criteria were adopted to describe the damage initiation of yarns. However, for the stiffness reduction method, the damage evolution of composites is strongly dependent on the reduction coefficients, which are correlated with the local

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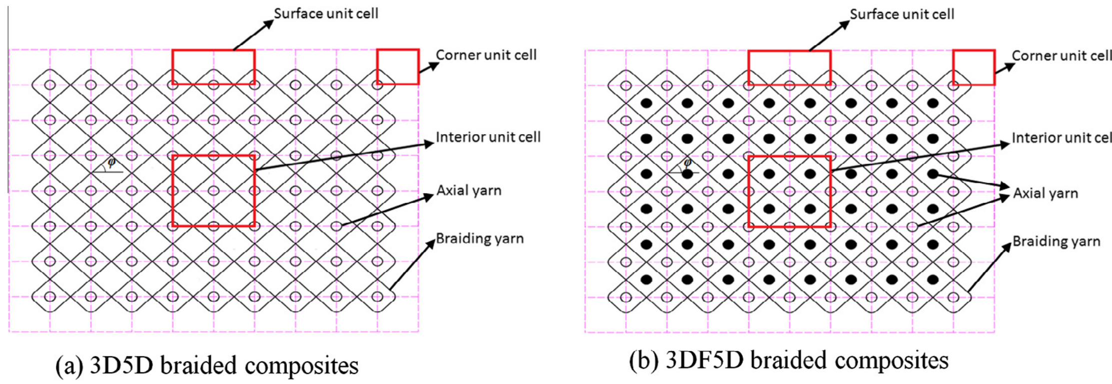

Fig. 1. Sketches of the cross sections of braided preforms.

stress and strain of failure elements. Based on the continuum damage mechanics, Fang et al. [24,25] and Zhou et al. [26] modified the 3D-Hashin failure criterion and characterized the damage initiation and evolution modes of composites. Reduction coefficients introduced by Murakami's damage theory [27] were controlled by the equivalence stresses and equivalence strains, which were evidently continuous variables. However, six different damage factors needed to be defined, leading to a large number of equations and complicated simulations. Sun et al. [28] studied the three-point bending fatigue behaviors of 3D carbon/epoxy braided composites, and developed a user-defined material subroutine (UMAT), which can characterize the stiffness degradation and fatigue damage evolution. To predict the strength properties of 3D braided composites, Li et al. [29,30] proposed a theoretical approach based on bridging model [31].

The present work is focused on the prediction of the longitudinal tensile behaviors of 3DF5D braided composites by the multi-scale simulation methods. In Section 2, a new interior RVC of 3DF5D braided composites is established with considering the deformation of braided preforms. In addition, a RVC of yarns is also established by using the collision algorithm. Section 3 gives a new 3D damage model to characterize the damage initiation and evolution in yarns based on the Linde failure criterion, which can obviously simplify the damage factors to two variables. After that, periodic boundary conditions and simulation process of the RVC are formulated in Section 4. Then the numerical simulation results are obtained and discussed. The effects of braided parameters, deformation of braided preforms and pore defects on the tensile properties of braided composites are also discussed in Section 5. Finally, some valuable conclusions are drawn in Section 6.

2. Geometry models

2.1. RVC of braided composites

The braided preforms of 3DF5D braided composites are comprised of two basic groups of yarns, braiding yarns and axial yarns. According to the braiding process, the yarns move under the guidance of the carriers, and the 4-step 1×1 rectangular braiding method [32] is used. Based on the typical structure of the braided preforms, three kinds of RVCs (i.e. interior RVCs, surface RVCs and corner RVCs) [6] are extensively used to predict the mechanical behaviors of the braided composites. Generally, if the row number and column number of yarn carriers are large enough, surface RVCs and corner RVCs can be ignored reasonably. Consequently, interior RVCs are the only consideration for our following finite element analysis.

During the manufacturing process of composites, the braided preforms can be deformed by the load of shaping [33]. Thus, the construction and dimensions of yarns are naturally changing to adapt the size of mould (shown in Fig. 1). Specifically, the shape of an interior RVC is changing correspondingly from square to general rectangle, and the yarn horizontal deflection angle φ, meaning the angle between the projection direction of braiding yarn axis on braiding plane (plane perpendicular to braiding direction) and the row direction, is not necessarily equal to 45°. The transverse cross sections of braiding yarns and axial yarns are converted appropriately as well.

Fig. 2 shows the meso-geometry structure of an interior RVC of 3DF5D braided composites. In Fig. 2, h is a braiding pitch length along the braiding direction, which is also the height of the RVC. W_a and W_b are the length and width of the RVC, respectively. γ is the interior braiding angle between the interior braiding yarn axis and braiding direction. According to the directions of yarns, an interior RVC includes four groups of braiding yarns, which are in green, red, yellow and purple in Fig. 2, respectively. The yarns in dark blue and light blue are axial yarns, which are parallel to the braiding direction. For an interior RVC, the axial yarns of 3DF5D braided composites are twice as many as that of 3D5D braided composites. According to the geometric relationships in the interior RVC, we have:

$$W_a = h \tan\gamma \cos\varphi = h \tan\alpha \tag{1}$$

$$W_b = W_a \tan\varphi \tag{2}$$

where the braiding angle α is the angle between the grain direction of braiding yarns on the surface and the braiding direction.

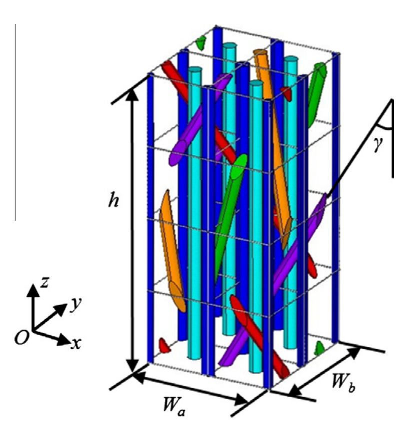

Fig. 2. Meso-geometry structure of an interior RVC.