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# Effect of interfacial properties on the uniaxial tensile behavior of three-dimensional braided composites

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In this study, a new nonlinear finite element model is presented to investigate the effect of interfacial properties on the uniaxial tensile behavior of three-dimensional (3D) braided composites. A cohesive zone model (CZM) is used to evaluate the debonding behavior of interface between yarn and matrix in this model. Taking account of interface damage mode and several damage modes of yarns and matrix within the braided composites, a numerical parametrical study is conducted to determine a set of reasonable interfacial properties and the failure mechanisms are revealed in the simulation process. In addition, the tensile modulus and strength of 3D braided composites are predicted and compared with the experimental results with a good agreement achieved. The calculated results show that the effect of interfacial elastic modulus on the tensile modulus of 3D braided composites is prominent, and the interface damage controlled by interfacial strength is one of the critical factors resulting in the nonlinearity of the longitudinal tensile stress–strain curves.



## 1. Introduction

The potentialities of 3D braided composites are very tremendous and being widely used in the fields of aviation, aerospace and marine due to their excellent mechanical performances, including large specific stiffness, high specific strength, high energy absorption behavior, high tolerance and outstanding fatigue characteristic [1,2]. A representative volume cell (RVC) is generally used to investigate the macroscopic mechanical properties of braided composites due to their periodic structures [3–7]. So far, remarkable achievements have been obtained on the strength research of 3D braided composites [8–14]. For example, Zako et al. [8] established a progressive damage model of 3D woven composites based on Murakami–Ohno damage theory. And the reduction coefficients were evidently continuous variables, which were controlled by the equivalence stresses and equivalence strains. Gu [9] adopted a mathematical method to predict the uniaxial tensile stress–strain curves of 3D braided preforms without taking the cross-section shape of the yarns into consideration. Zeng et al. [10,11] proposed a multiphase element model to predict the nonlinear mechanical behavior of three-dimensional four-directional (3D4D) braided composites without considering the real structures of the composites. Sun et al. [12] developed a user-defined material subroutine (UMAT) to investigate the three-point bending fatigue behavior of 3D carbon/epoxy braided composites, which could describe the stiffness degradation and fatigue damage evolution process. Xu et al. [13] studied the damage evolution of three-dimensional five-directional (3D5D) braided composites under uniaxial tension, and adopted 3D-Hashin and Tsai-Wu failure criteria to reveal the damage initiation in yarns. Li et al. [14] proposed a micromechanical prediction procedure to simulate the stiffness and strength properties of 3D5D braided composites by using three unit cell models. However, the damage and failure modes of 3D braided composites are complex due to the complexity of their mesoscopic geometrical structures. Except for the damage modes of yarns and matrix, the damage of interface between yarn and matrix (yarn/matrix interface) is also a typical failure mode [15,16]. Thus, it is necessary to determine a set of reasonable interfacial properties for predicting the stress–strain curves of 3D braided composites under uniaxial tension and investigate the effect of interfacial properties on the mechanical behavior of 3D braided composites, which have been studied by few scholars.

With the rapid development of finite element method, it has become a main numerical method for evaluating the interfacial debonding problems. Rybicki and Kanninen [17] proposed a virtual crack closure technique (VCCT) which was computationally effective since the energy release rates could be obtained from only one analysis and the approach got extensive concern by multitudinous scholars [18,19]. Nevertheless, the crack propagation path should be predicted ahead of time since the approach requires the complex numerical algorithms to perceive the crack tip and release constraints on the duplicate nodes with crack propagation. Needleman [20–22] firstly proposed a cohesive zone model

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(CZM) to simulate the debonding problems of particles in the metal matrix. The CZM introduced the phenomenological mechanical relations between the tractions and interfacial separations and then eliminated the stress singularity at the crack tip. For fiber reinforced composites, Jiang et al. [23] proposed a concise constitutive law for cohesive interfaces and introduced a new state variable to track the damage accumulated at the interface. The constitutive equations took the mixed-mode delamination propagation into account in the composites and gratifyingly coped with the mode ratio change during the debonding process. Based on a CZM with linear and exponential constitutive law, Balzani and Wagner [24] developed a finite element to model the three-dimensional mixed mode delamination of unidirectional fiber reinforced composites and indicated that the CZM with exponential form constitutive law could describe the delamination better. Li and Ghosh [25] introduced an extended Voronoi cell finite element model (X-VCFEM) combined with the bilinear and linear CZMs to simulate the initiation and propagation of interfacial debonding and matrix cracking process in fiber reinforced composite materials. Considering the fiber/matrix interface damage, Totry et al. [26,27] adopted a CZM to predict the transverse compressive properties of unidirectional fiber composites and study the effect of interfacial properties on the material properties. Based on a detailed study of the numerical cohesive zone and the extraction of strain energy release rate from this zone, Harper and Hallett [28] proposed a cohesive zone interface element degradation law to analyze the delamination crack propagation under cyclic loading. Taking account of the properties of finite thickness interfaces, Paggi and Wriggers [29] further derived a nonlocal CZM whose shape is dependent on the damage evolution, which provided an appropriate mathematical framework for interpreting molecular dynamics-based stress-separation relationships. In conclusion, the CZM can be used to effectively predict the interfacial debonding behavior and crack propagation by finite element analysis in comparison with VCCT. For 3D braided composites, the complex damage modes of constituents and the effect of interfacial properties on the uniaxial tensile behavior of 3D braided composites need to be studied in more detail as well.

The objective of this paper is to determine a set of reasonable interfacial properties for predicting the longitudinal tensile stress–strain curves of 3D braided composites and investigate the effect of interfacial properties on the mechanical behavior of 3D braided composites under uniaxial tension. In Section 2, the new interior representative volume cells with interfaces are established for 3D4D and 3D5D braided composites according to their meso-structures, and the decohesive element is introduced. Section 3 gives a new 3D damage model with interface damage mode to characterize the damage initiation and propagation in yarns and interface based on the 3D Linde failure criterion and quadratic failure criterion. Subsequently, the periodic boundary conditions and material properties are formulated in Section 4. Then a set of reasonable interfacial properties is determined by a numerical parametrical study. The tensile modulus and strength of 3D braided composites are obtained and the effects of interfacial properties on the mechanical behaviors of 3D4D and 3D5D braided composites are compared in Section 5. Finally, some valuable conclusions are summarized in Section 6.

## 2. Geometry models

### 2.1. RVCs of 3D braided composites

3D4D and 3D5D braided composites both consist of yarns and matrix, but an additional group of axial yarns is introduced into 3D5D braided composites. The 4-step $1 \times 1$ rectangular braiding method [30] is used according to the braiding process. Generally, an interior RVC is chosen from the interior braiding structures of 3D braided composites to analyze their mechanical properties due to the complexity of braiding structures. Fig. 1 shows the meso-geometry structures of interior RVCs, where $\gamma$ is the interior braiding angle between the interior braiding yarns axis and braiding direction and the purple yarns are axial yarns which are parallel to the braiding direction.

Based on the experimental observation [31,32], the sections of braiding yarns and axial yarns on the plane-$xOy$ of 3D braided composites can be considered as hexagon and quadrangle, respectively (shown in Fig. 2). In Fig. 2, $h$ is a braiding pitch length along the braiding direction, which is also the height of RVC. $T$ is the width and length of RVC. According to the geometric relationships in the interior RVC, the related geometric parameters can be derived as follows:

For 3D4D braided composites, we have:

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

$$c = \frac{T}{4} \tag{2}$$

$$w = \frac{\sqrt{2}T}{4} \tag{3}$$

$$\beta = 90^\circ \tag{4}$$

$$V_f = 0.75\varepsilon_1 \tag{5}$$

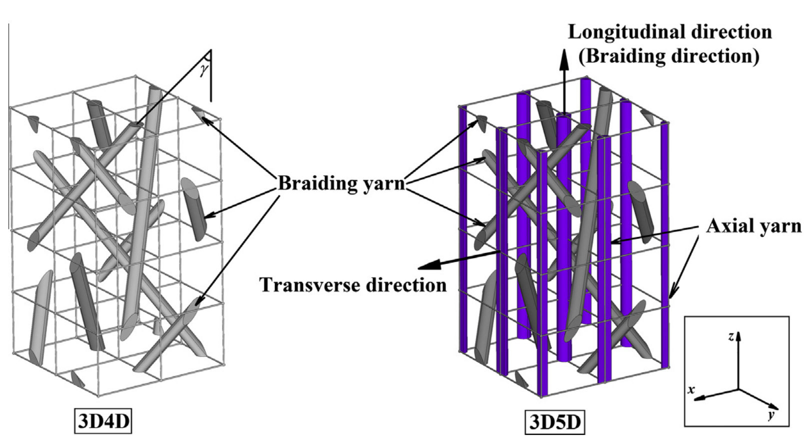


**Fig. 1.** Meso-geometry structures of interior RVCs.