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Analytical prediction of the elastic properties of 3D braided composites based on a new multiunit cell model with consideration of yarn distortion

Kun Xu*, Xiaomei Qian

School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu 611731, People's Republic of China

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ABSTRACT

A new analytical model based on a multiunit cell model (MCM) is developed to study the effects of the yarn distortion and the shell–core structure feature on the elastic properties of 3D four-directional braided composites. An idealized yarn model with consideration of the yarn distortion is proposed to calculate its elastic properties by introducing an average twist angle. Combined with the MCM, the stiffness-volume averaging theory is applied to consider the contribution of all unit cells to the elastic properties of the overall specimen. The variation of the average twist angle for the interior and surface-corner yarns has been accounted for appraising the elastic properties. The predicted elastic properties are in good agreement with the available experimental data, demonstrating the applicability of the analytical model. In addition, the effect of the average twist angle on the elastic properties is discussed and the comparison between the predicted values and the experimental results are conducted. Then the elastic properties of unit cells with their unique microstructure are analyzed. Finally, the effects of the braiding angle, the fiber volume fraction, and the number of the yarn carriers on the elastic properties are discussed in detail. Discussion results have proved that the present analytical model can be utilized to predict the elastic properties of 3D braided composites.

1. Introduction

3D four-directional braided composites (4DBC) have been increasingly attractive in the aeronautics and astronautics industries due to their excellent mechanical properties, such as better out-of-plane stiffness, strength and high impact resistance, etc. However, the microstructure of 3D 4DBC is so complicated that it is difficult to propose a perfect analytical model used for predicting the mechanical properties of 3D 4DBC. In order to make 3D 4DBC widely applied in the industries, many models were proposed to analyze their microstructure and mechanical performance in the past.

Ko and Pastore (1985) first proposed a cuboid unit cell containing four diagonally intersecting yarns to represent the yarn microstructure of 3D rectangularly braided preforms. Yang et al. (1986) studied the effective elastic properties of 3D 4DBC by the 'Fiber inclination model'. Li et al. (1990) analyzed the internal structure of 3D 4DBC by conducting the experimental investigation and later identified that the surface structure was obviously different from the interior region. Mohajerjasbi (1993) studied the mechanical properties of 3D 4DBC by a finite element method (FEM) and an analytical method, respectively. Wang and Wang (1995) conducted an analysis of the topological structure of 3D 4DBC and defined three distinct types of unit cells for the interior, surface, and corner regions, respectively. Chen et al. (1997, 1999) reported a microstructure model consisting of three types of unit cells based on the experimental observation of 3D 4DBC and further presented a multi-phase finite

* Corresponding author. Tel.: +86 28 61831882, fax: +8602861831882.
E-mail address: xukun@uestc.edu.cn (K. Xu).

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element model for predicting their elastic properties. Tang and Postle (2001) predicted the tensile and shear moduli of 3D 4DBC by the mathematical modeling. Sun et al. (2003) applied the homogenization theory and the incompatible multivariable FEM to predict the mechanical properties of 3D 4DBC. Sun and Sun (2004) studied the elastic properties of 3D 4DBC based on a digital-element model. Yu and Cui (2007) developed a two-scale method to predict the mechanics parameters of 3D 4DBC. Recently, Shokrieh and Mazloomi (2012) presented an analytical method for the stiffness calculation of 3D 4DBC according to a unit-cell partition scheme with an angle oriented at 45° with respect to the edges of the rectangular specimen. Zhang and Xu (2013) proposed a FEM for predicting the mechanical properties of 3D 4DBC based on a three-unit cell model, namely, the interior, surface, and corner unit cell model. Lu et al. (2014) proposed a new 3D FEM to investigate the effect of interfacial properties on the thermophysical properties of 3D 4DBC. Zhang et al. (2014) investigated the impact compressive behavior and failure modes of 3D braided composites based on an idealized unit cell model. Xu and Qian (2015a) developed a new multiunit cell model (MCM) based on the microstructure analysis of 3D 4DBC. It can be seen that the aforementioned efforts have contributed a lot to a better understanding of the mechanical behaviors of 3D 4DBC.

Previous studies have shown that the microstructure of 3D 4DBC directly determines their mechanical properties in macro-scale. However, as an extremely important microstructure feature, the distortion phenomenon of the braiding yarns resulting from the braiding process has never been considered in the abovementioned models. Actually, Chen et al. (1997) investigated the microstructure of 3D 4DBC by observing the SEM micrographs in detail. Their research clearly indicates that the distortion phenomenon of the braiding yarns in the preform is obvious and uncovers such a fact that all filaments of a braiding yarn are no longer parallel with the central axis of the braiding yarn along its extension orientation. Therefore, it is just an idealized assumption to regard the braiding yarns as unidirectional fiber-reinforced composites with parallel fibers for the mechanical modeling. Especially, it is noted that the aforementioned models almost made the same assumption and fail to consider the effect of the actual distortion of the braiding yarns on the mechanical properties of 4DBC.

Up to now, to the author's knowledge, the work on studying the effect of the yarn distortion on the mechanical properties of 3D braided composites is extremely limited. Fang et al. (2009) established the FEM based on an interior unit cell to study the effect of the yarn distortion on the mechanical properties of 3D 4DBC. Studies show that the distortion of the braiding yarns has a significant impact on the mechanical performance. However, it is noted that Fang et al. (2009) only applied the numerical results based on the interior unit cell model to represent the mechanical properties of the overall specimen, which not only has obvious limitation in precise prediction but also has high computational cost. Since the microstructure of 3D 4DBC is different for the interior, surface, and corner regions, the effect of the shell–core structure feature on the mechanical properties should be taken into account. However, the shell–core structure feature has not been considered by an analytical MCM with consideration of the yarn distortion.

The objective of this paper is to propose a new analytical model for evaluating the effects of the yarn distortion and the shell–core structure feature on the elastic properties of 3D 4DBC based on the MCM. Since the distortion condition of the braiding yarns is very complicated, it is difficult to describe the key feature of the braiding yarns exactly by a theoretically perfect method. For simplicity, an idealized yarn model considering the yarn distortion is proposed to compute its elastic properties by defining an average twist angle. Combined with the MCM, the stiffness-volume averaging theory is applied to consider the contribution of all unit cells to the elastic properties of the overall specimen. The variation of the average twist angle for the interior and surface-corner yarns has been accounted for appraising the mechanical properties. In addition, the effects of the twist angle, the braiding angle, the fiber volume fraction and the number of the yarn carriers on the elastic properties are discussed in detail. Finally, some valuable conclusions are drawn herein.

2. Multiunit cell model with consideration of the yarn distortion

3D 4DBC have proved to be a kind of composites with the typical shell–core structure. According to the MCM of 4DBC developed by Xu and Qian (2015a), 3D 4DBC consist of five kinds of unit cells, i.e., the interior, the exterior surface, the interior surface, the exterior corner and the interior corner unit cells. The distribution of the five kinds of unit cells is shown in Fig. 1.

As illustrated in Fig. 1, the interior unit cell is the smallest periodic structure for the interior region. There are four kinds of surface unit cells altogether, i.e., surface unit cells *A*, *B*, *C*, *D*. Each surface unit cell is composed of the exterior and interior surface unit cells. It is noted that the yarn orientation of all surface unit cells in the opposite surfaces of the specimen takes on antisymmetrical permutation, for example, surface unit cells *A* and *C* as shown in Fig. 1. Meanwhile, the yarn orientation of surface unit cells in the adjacent surfaces of the specimen shows mirror-symmetry distribution, such as surface unit cells *A* and *B*. Fig. 1 also shows the corner unit cell contains the exterior corner unit cell and the interior corner unit cell. In addition, it is noted that the yarn orientation of the corner unit cells located in the four angles of the rectangular specimen takes on four different permutations.

The main structural parameters for five kinds of unit cell models are illustrated in Fig. 2 (Xu and Qian, 2015a). From Fig. 2(a), the angle of the yarn inclination on the surface of composites is denoted as the braiding angle α and γ represents the interior braiding angle of the interior braiding yarns. The braiding pitch length of the model is defined as h. W_i and T_i denotes the width and thickness of the interior unit cell, respectively. As shown in Fig. 2(b), W_s and T_s represents the width and thickness of the surface unit cell, respectively and θ is the surface braiding angle of the surface braiding yarns. θ_s is defined as the surface projection angle between the projection of the surface braiding yarn on the surface and z-axis. From Fig. 2(c), W_c and T_c denotes the width and thickness of the corner unit cell, respectively. β represents the