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Multi-size unit cells to predict effective thermal conductivities of 3D four-directional braided composites

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ABSTRACT

Based on the structure of the full unit cell which is formulated by three translational symmetries, three further 180° rotational symmetries of three-dimensional (3D) four-directional braided composites are clarified in this paper. It is for the first time that each rotational symmetry is used to reduce the full unit cell to a half, quarter, and eighth size. The corresponding boundary conditions for thermal analysis are derived precisely according to each rotational transformation. The effective thermal conductivities of composites with different fiber volume fractions and interior braiding angles are calculated by the full, quarter and eighth unit cells. In order to confirm the significance of accurate boundary conditions, additional comparison calculations with adiabatic boundary conditions are conducted and the result reveals that inappropriate boundary conditions may lead to an un-neglectable error in the prediction of thermal conduction behaviours. The numerical model is validated by good agreement between the numerical results and the available experimental ones.

1. Introduction

Three-dimensional (3D) braided composite has been widely studied for its excellent mechanical performance and industry application potential [1–4]. During the production of the composite, the 3D textile should be braided first by a particular braiding process and then solidified with matrix and finally form the composite. The well-known four-step braiding can fabricate 3D four-directional [5], five-directional [6], six-directional and even seven-directional braided textiles [7]. The microstructure of 3D four-directional braided preform and especially the yarns' spatial configuration are analyzed and illustrated according to the braiding process in [5,6]. For the braided composite which is often a periodic structure, its performance is often studied by taking only a representative volume element (unit cell) into account. A unit cell formulated based on the microstructure analysis and the related numerical simulation is a very effective approach used in the study of composites' performance including elastic and shear modulus [8–11], and failure behaviours [12,13]. Similarly, thermal performance of 3D four-directional braided composites can be calculated in the same way [14–17].

As discussed above, the formulation of a unit cell is based on the analysis of the composite microstructure, more specifically it is the geometric symmetries exist in the composite structure that should be identified and analyzed. There are three types of symmetries in the nature, i.e., translations along an axis, reflections about a plane and rotations about an axis. The formulation of a unit cell has two steps: identifying symmetries presented in the composite and deriving corresponding boundary conditions. In relevant works about particle reinforced composites [18], unidirectional fiber reinforced composites [19,20], and several types of woven composites [21–24] symmetries are fully exploited to formulate unit cells of different sizes. However, most studies focus on the mechanical problems and only the corresponding mechanical boundary conditions for unit cells are derived. The thermal problems need thermal boundary conditions. The authors' previous work [25] should be the first time for using unit cells of different sizes to predicting the effective thermal conductivity of plain woven composites, and three reducing-size unit cells are formulated according to translational, reflectional and 180° rotational symmetries and the related thermal boundary conditions are precisely derived. According to the authors' knowledge, for 3D four-directional braided composites most previous works [14–17,26,27] built unit cells by utilizing only the translational symmetries no matter whether it was stated in the papers. A unit cell formulated by translational symmetries can be called a full unit cell.

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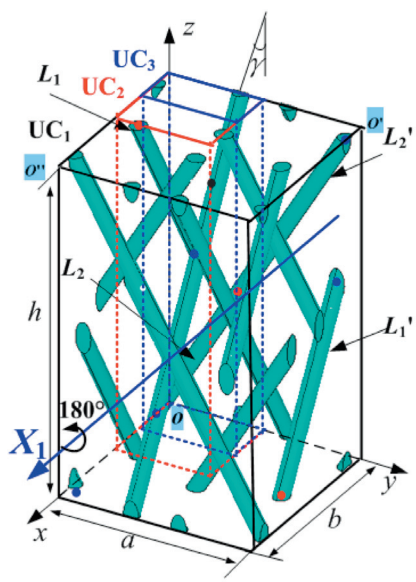
In the present work, it is for the first time that three 180° rotational symmetries exhibited in the full unit cell are clarified based on the microstructure analysis, and three half, quarter and eighth unit cells are formulated according to the three rotational transformations. Thermal boundary conditions of the unit cells are derived step by step. Numerical models based on the full, quarter and eighth unit cells are established to predict the temperature distributions and the effective thermal conductivities of 3D four-directional braided composites.

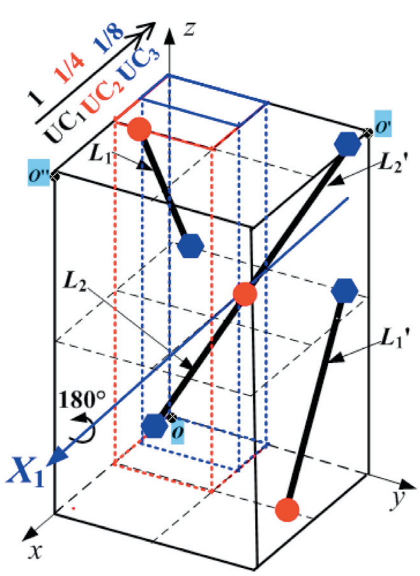
2. The formulation of unit cells

Fig. 1(a) shows the schematic diagram of the full unit cell UC_1, and Fig. 1(b) displays the symmetry of several braiding yarns' orientation and will be discussed later. As shown in Fig. 1, the full unit cell UC_1 depicted by black lines is defined by the domain $0 \leqslant x \leqslant a$ & $0 \leqslant y \leqslant b$ & $0 \leqslant z \leqslant h$, the quarter unit cell UC_2 depicted by red lines is defined by the domain $0 \leqslant x \leqslant a/2$ & $0 \leqslant y \leqslant b/2$ & $0 \leqslant z \leqslant h$, while the eighth unit cell UC_3 depicted by blue lines is defined by the domain $0 \leqslant x \leqslant a/4$ & $0 \leqslant y \leqslant b/2$ & $0 \leqslant z \leqslant h$. After a 180° rotation of UC_1 about axis $X_1 = (x, b/2, h/2)$ a half cell shown in Fig. 2 can be formulated, and after a 180° rotation of the half cell about axis $Y_1 = (a/2, y, h/2)$, a quarter unit cell UC_2 shown in Fig. 3 can be formulated. After a 180° rotation of UC_2 about axis $Z_1 = (a/4, b/4, z)$ an eighth unit cell UC_3 can be ultimately formulated and shown in Fig. 4. For the complexity of the geometric structure, it would be necessary to further illustrate three rotational symmetries exhibited in 3D four-directional braided composite.

Before the illustration of the composites' rotational geometric symmetries, the coordinate transformations resulted from a 180° rotation about the axes should be clarified first. It is clear that an arbitrary node $M = (x_1, y_1, z_1)$ will be transformed to node $M' = (x_1, b - y_1, h - z_1)$ by a 180° rotation about axis $X_1 = (x, b/2, h/2)$, to node $M'' = (a - x_1, y_1, h - z_1)$ by a 180° rotation about axis $Y_1 = (a/2, y, h/2)$ and to node $M''' = (a/2 - x_1, b/2 - y_1, z_1)$ by a 180° rotation about axis $Z_1 = (a/4, b/4, z)$. At this condition the rotational geometric symmetries presented in 3D four-directional braided composite can be further illustrated by transformations of two typical braiding yarns L_1 and L_2 (a half segment of the long yarn) in UC_2 as shown in Fig. 1(b). The braiding yarns can be expressed by the coordinates of the start and end points of each yarn, the blue hexagonal and the red circular points in the figures are assumed to be the start point and the end point, respectively. Then we have $L_1 = (0, b/8, h/2) - (a/2, b/8, h)$ and $L_2 = (a/8, 0, 0) - (a/8, b/2, h/2)$. With a 180° rotation about $X_1 = (x, b/2, h/2)$, yarn L_1 will be transformed to $L_1' = (0, 7b/8, h/2) - (a/2, 7b/8, 0)$, with a 180° rotation about $Y_1 = (a/2, y, h/2)$, yarn L_1 will be transformed to $L_1'' = (a, b/8, h/2) - (a/2, b/8, 0)$, and with a 180° rotation about $Z_1 = (a/4, b/4, z)$, yarn L_1 will be transformed to $L_1''' = (a/2, 3b/8, h/2) - (0, 3b/8, h)$. L_2 will be transformed to $L_2' = (a/8, b, h) - (a/8, b/2, h/2)$, $L_2'' = (7a/8, 0, h) - (7a/8, b/2, h/2)$ and $L_2''' = (3a/8, b/2, 0) - (3a/8, 0, h/2)$ by the three 180° rotations, respectively. The coordinate transformations of the two braiding yarns are summarized in Table 1.



(a) Geometrical model



(b) The symmetry of braiding yarns' orientation

Fig. 1. The full unit cell UC_1.

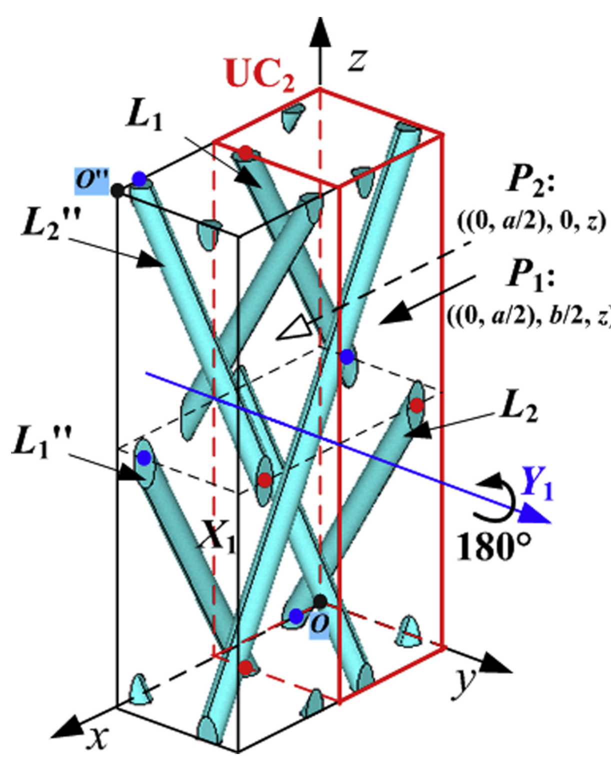


Fig. 2. The half cell.