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Review

Structural modeling and mechanical characterizing of three-dimensional four-step braided composites: A review

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ABSTRACT

The unique structural features of three-dimensional (3D) braided preforms determine an array of excellent mechanical properties of 3D braided composites, such as high strength and low density, great damage tolerance and fatigue performance. In the present paper, the studies relevant to the structural modeling of 3D braided preforms in recent decades, including fiber inclination model, helix model, three unit cell model, multi-unit cell model, digital element method, etc. have been reviewed and classified into three types, i.e., mechanical equivalence models, unit cell geometrical models and yarn geometrical models. Based on the models, mechanical characterizations of 3D braided composites have been reviewed and discussed.

1. Introduction

Three-dimensional (3D) braiding concept was first proposed in the late 1960s, and then four-step process and two-step process were developed. Florentine perfected the concept of four-step 3D braiding in his patent on Magnaweave apparatus in 1982 [1]. With the rapid development of advanced composites [2], braided preforms have been gradually employed as reinforcement to improve the properties of composites. 3D braided composites are manufactured by solidifying 3D braided preforms with resin matrix. Due to the outstanding structural integrity of 3D braided preforms [3], 3D braided composites present a series of excellent mechanical properties, including high strength and stiffness, energy absorption, outstanding damage toleration and impact resistance [4–7], which result in the extensive applications of 3D braided composites in many distinct fields, such as aeronautics, marine, transportation and other industries [5,8].

To better relate the preform structure to the mechanical performance of composites, many investigations have been made. A series of structural models of 3D braided preforms have been proposed, such as fiber inclination model [9], geometry unit cell [10], representative volume element (RVE) [11,12], three unit cell model [13–16], helix model [17], digital element model [18],multilevel structure [19], etc. In the meanwhile, mechanical characterizations have also been conducted and an array of models and methods have been proposed, such as weighted average model (WAM) [17,20], strain energy model [9], homogeneous theory [21,22], iso-strain model [23,24], iso-stress model and meso-FE model [25]. Based on the above structural and mechanical models, simulation and prediction on the performances, including the dynamic ones, of 3D braided preforms and composites have been enabled, by combining with appropriate boundary conditions and failure criterions [26–28].

In the present paper, after a brief description on braiding process, structural models and mechanical characterizations of 3D braided composites have been reviewed and categorized.

2. Braiding process

The topological features of 3D braided preforms are determined by the interlacing pattern of braiding yarns which further results from the moving rule of yarn carriers in braiding set-up, i.e., the braiding patterns, e.g., '1 × 1', '1 × 2', '1 × 3' [13], where the first number represents the row movement displacement in a single step and the second number for column [1]. In the current article, 3D braided preforms fabricated using 1 × 1 braiding pattern are discussed. Li et al. [1] indicated that the braiding yarns inside a 3D braided preform are inclined in four diagonal directions, while axial yarns, which are fixed and do not move with the yarn carriers, can be added to make five-directional and other multi-directional preforms. The braiding processes of four-step four-directional and five-directional braided preforms are briefly discussed in the following, respectively.

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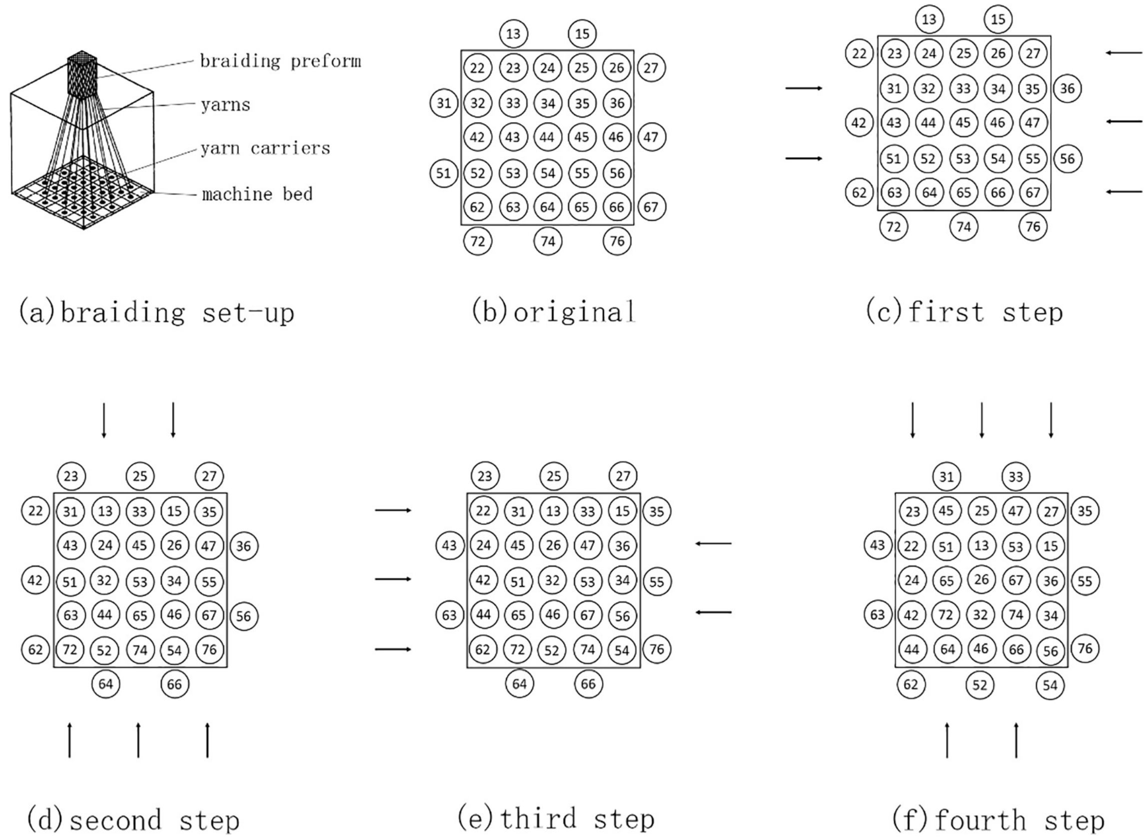

Fig. 1. (a) 3D braiding set-up, (b)-(f) movement rule of braiding carriers in four-step braiding process.

2.1. Four-step four-directional braiding process

The braiding set-up is consisted of machine bed and yarn carriers (Fig. 1a), and the yarn carriers in machine bed move along row and column direction alternately (Fig. 1b-f). In the first step, the yarn carriers move one position alternately along row direction, i.e., odd rows move left while even rows move right; in the second step, yarn carriers move one position alternately along column direction, i.e., odd columns move up while even columns move down; the movements of yarn carriers in the third and fourth steps are reverse to those in the first and second steps, respectively; after four steps, the yarn carrier pattern returns to the original one, i.e., each four steps form one machine cycle. After each cycle, the yarns are packed closely by the 'jamming' action, and the newly formed length of preform is named a pitch.

2.2. Four-step five-directional braiding process

The braiding process of five-directional preforms is much similar to that of four-directional preforms, besides the axial yarns which are inserted between braiding yarns, as shown in Fig. 2, where 'o' represents the braiding yarn carriers while '×' represents the axial yarn locations.

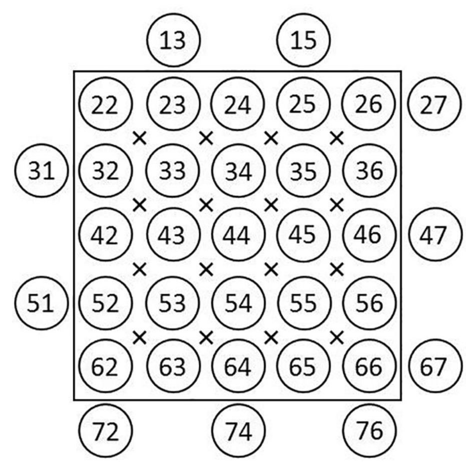

Fig. 2. Braiding plane for five-directional braiding.

3. Structural models

Many of the outstanding mechanical properties of 3D braided composites could be attributed to the unique structure of 3D braided preforms. Thus, many efforts have been made to investigate and model the structural features of 3D braided preforms [29]. In general, the established models can be classified into three types: mechanical equivalence ones, unit cell geometrical ones and yarn geometrical ones (Table 1).

Table 1
Three types of structural models of 3D braided preform.

Model Type	Typical Models
Mechanical equivalence models	Fiber inclination model Helix model …
Unit cell geometrical models	Interior unit cell model Three unit cell model Multi-unit cell model …
Yarn geometrical models	Digital element model Subsection model …