An Efficient Method for Geometric Modeling of 3D Braided Composites

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ABSTRACT

To estimate the precise mechanical properties of a three-dimensional (3D) braided composite, a geometric study is needed. Because of the complexity of the yarn paths inside the preform, the geometric modeling for 3D braided composites is always time consuming. In this paper, an efficient method, namely preform boundary reflection (PBR), is proposed for motion model construction in geometric studies. Furthermore, a CAD simulation system using novel combinations of parameters was developed for integral geometric descriptions of 3D braided preforms. Compared with the traditional method, the new method significantly simplifies the simulation process without affecting the precision of geometric structure. As a result, the structure design for composite preforms is effectively accelerated. The new method establishes a foundation for microstructure and mechanical properties analysis of preforms with complex geometric structures.

Keywords: 3D braided preform; Motion model of yarns; Preform geometric structure; Computer Aided Design (CAD) system

INTRODUCTION

Three-dimensional (3D) braided composites are being widely used in the fields of aeronautics, space, marine, automotive and sport recreation products due to high stiffness and strength at low density, high-energy absorption and excellent fatigue characteristics [1]. 3D braided preforms are manufactured by intertwining two or more braid yarns oriented in different directions. These preforms have excellent mechanical properties in any material direction. Many structures with complex shapes and high damage resistance can be formed in this manner. For example, I beam, H beam, and tubular-shaped preforms can be made. The construction and characterization of 3D braided composites has been an area of significant research in recent years [2].

The mechanical properties of a textile composite are determined by several factors- the properties of the matrix and the properties of the reinforcing material and geometric structure of the composite, especially the yarn orientation and distribution. Thus an effective method for modeling of the preform and composite will be useful in predicting the final mechanical properties [3, 4].

Since 1980s, many researchers have suggested models for rectangle braided structures these are mainly based on simple, mathematically-based unit models. The fiber architecture of rectangle braided preforms was first represented as a unit cell by Ko [5]. Li modeled the rectangular braided preform unit cell by modeling the braiding process [6]. Chen and Byun divided the unit cells into several regions such as corner, surface and interior regions [7, 8]. Wang developed a dynamic CAD system considering braiding process, the yarn's friction force, applied force, and the yarn's contact condition [9]. Chen used least squares methods to predict the trend line of yarn movement in the unit model [10]. Zhang improved Chen's method in the surface and corner regions and extended the method to 3D coordinate space [11]. Shao analyzed the spatial location of the yarn preforms and represented the yarn path as a Bezier curve [12].

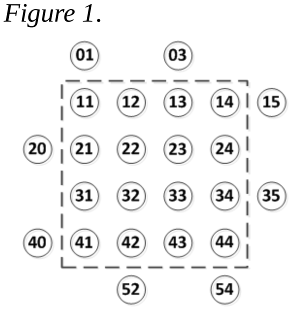
Although many motion models of yarn paths have been proposed for geometric structure simulation, the existing models are mainly based on the simple structures, i.e. the numbers of rows and columns in the main part are small. There have been few studies about the efficiency of the simulation, which determines the time required for the design of large and complex geometric structure. From the standpoint of preform property prediction and production, the geometric structure constructed by the model must be simplified without distortion, compared with the real one. Therefore, the motion model for the yarns in the preform must be optimized.

Based on yarn movement during the 3D four-step braiding process, an efficient preform boundary reflection (PBR) method is proposed here for the yarn motion model. Using Matlab, Visual C++ and SolidWorks, the geometric structure of 3D braided preform with arbitrary braiding parameters can be automatically generated based on the simplified motion model without affecting the simulation results. The novel PBR method is also compared with the traditional least-squares method in terms of computational time and simulation results.

FOUR-STEP BRAIDING PROCESS

Braiding Procedure

The preform topological structure is realized through the permutation of the yarn carrier on a machine bed by row and column track movements. The yarns are arranged in rows and columns to form the main part, which determines the shape of the preform, and additional yarns are added to the outside of the main part in alternating locations, as is shown in *Figure 1*.



FUGURE 1. The initial arrangement of yarn carriers for 4 × 4 square braid.

Figure 2 shows the basic concept of the four-step 1:1 rectangular braiding method. First, the rows and then the columns are moved, both in alternating directions. These movements are next reversed in the last two steps to complete on machine cycle. Four steps of motion per machine cycle used to braid the yarns. As these steps of motion continue, the yarns move throughout the cross-section and are interlaced to form the final structure.

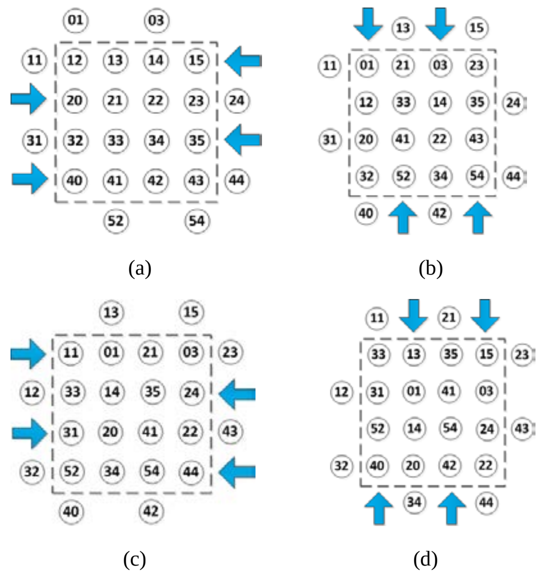


FIGURE 2. Schematic diagram of carrier movement in a machine cycle ([4×4] braiding).

Yarn Topology and Unit Model

The vertical four-step braiding machine with a rectangle carrier bed was used in this research, as shown in *Figure 3*.

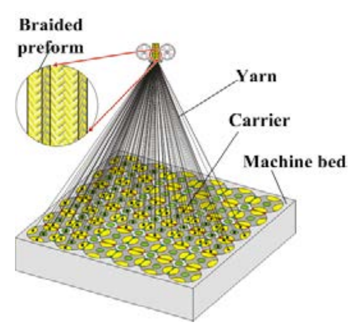


FIGURE 3. Vertical braiding.

The carriers on the machine bed move to interlace the yarns. The number of carriers in the horizontal direction and vertical direction make up the basic processing variables. The total number of braiding yarns is

$$N = mn + m + n \quad (1)$$

where N is the number of braiding yarns, and m and n are the number of rows and columns in main body.

Figure 4 shows the schematic diagram of carrier movement in a four-step motion.

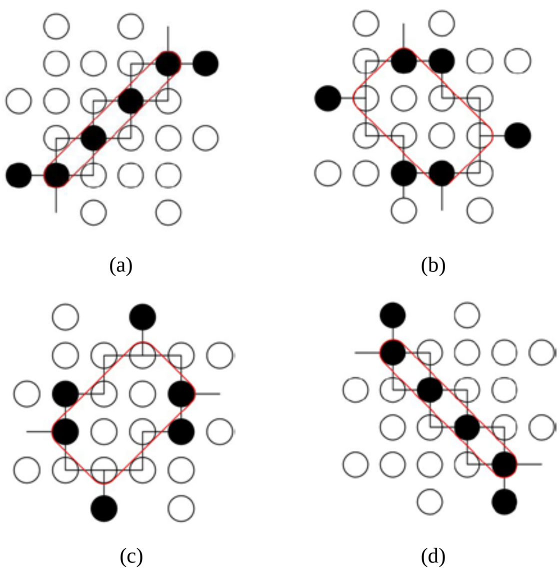


FIGURE 4. Classifications of carrier trace and yarn path for $[4 \times 4]$ braiding. The carrier trace is represented by black line; the corresponding yarn path is represented by red line.

The carrier is classified by its moving trace on the machine bed and refers to carrier groups. For the Cartesian pattern, each path can define a group of yarns and their positions. The carrier distributions and yarn paths of a certain group are illustrated in *Figure 4*. A general rule for the number of yarn groups Y in an $[m \times n]$ (m is the number of rows and n is the number of columns) rectangular preform is given by

$$Y = GCD(m, n) \quad (2)$$

where GCD is the greatest common divisor. All group in an $[m \times n]$ preform have equal numbers of yarns, i.e.

$$S = N / Y \quad (3)$$

where S is the number yarns in each group. If there are more carrier groups, the fabricated perform becomes more compact and dense.

Because the four-step machine cycle is repeated during the process, the structure of the braided preform shows a repeating pattern. Consequently, the yarn unit can be modeled by one cycle of motion. A repeat, which means the number of operating cycles required for a carrier to return to the initial position on the machine bed, is

$$N_s = 4S \quad (4)$$

Taking the $[4 \times 4]$ square braiding as an example, the total number of yarns is N = 24. The number of yarn groups is 4. The number of yarn carriers which have the same path in each group is S = 6 (black circles shown in *Figure 4*). Each yarn carrier moves N_s = 24 steps back to the initial position.

MODELING METHODS

In the 3D braiding process, the yarns follow zig-zag traces before compacting. However, when a uniform yarn-compacting action, jamming, is imposed, the yarns will be straightened and repositioned in the space due to yarn tension. In the perform interior, all the braiding yarns contact with each other and the yarn axis remains straight in spite of the lateral deformation at yarn surface [11].

In order to accurately simulate the geometric structure at the yarn level, the following four assumptions are proposed:

(1) The yarn has a round cross-section with a variable radius R, thus all coordinates in the motion equations describe the center of the yarn.
(2) The braiding process is stable and the braided structure is uniform and consistent along the length of interest.
(3) All yarns in the braided perform have identical constituent material, size and flexibility.
(4) The interior yarn packing factor is used for all regions of the preform (interior, surface and corner)

Least Squares Method

In Chen's work [9], the coordinates of the yarn positions in the preform are fit to a straight line using the least-squares method. Assuming the coordinate vectors of the yarn positions on $X-Y$ plane after *i* steps can be expressed as

$$p_i = [x_i \quad y_i],\ i = 1, 2, \cdots k \tag{5}$$

According to the discipline of the shuttle movement,

$$p_{i+2} - p_i = p_{i+3} - p_{i+1} \tag{6}$$

Constructing a straight line between these points

$$p(t) = A + Bt,\ 0 \le t \le k \tag{7}$$

where $A = [a_x \quad a_y]$ and $B = [b_x \quad b_y]$.

Combining with Eq. (7), the following condition is required to fulfill

$$p'(t) \big/ \left| p'(t) \right| = (p_2 - p_0) \big/ \left| p_2 - p_0 \right| \tag{8}$$

Solving Eq. (8), we have

$$b_x = \frac{x_2 - x_0}{y_2 - y_0} b_y \tag{9}$$

Considering Eq. (9) as constraining conditions, the objective function is

$$J = \sum_{i=0}^{k} \left| p(i) - pi \right|^2 + \lambda (b_x - \frac{x_2 - x_0}{y_2 - y_0} b_y) \tag{10}$$

where λ is a LaGrange arithmetic operator.

In order to minimize *J*, the following equations should be satisfied,

$$[\frac{\partial J}{\partial a_x} \frac{\partial J}{\partial b_x} \frac{\partial J}{\partial a_y} \frac{\partial J}{\partial b_y} \frac{\partial J}{\partial \lambda}] = 0 \tag{11}$$

Since the preform is fabricated in Z-direction, the coordinates of yarn positions are spatial lines. Furthermore, SEM micrographs show that the surface and corner regions of the real preform are spatial curves [7]. In Zhang's work, the 3D yarn paths inside the preform were determined based on the least-squares method [11]. Owing to the continuity in the braiding process, the straight line inside the preform is tangent to the spatial curves of the surface and corner. Considering the motion of the carrier, the spatial curve is regarded as a helix, which satisfies the helix equation,

$$\begin{cases} R = \mu \dfrac{\sqrt{2}}{2} d \\ H = \dfrac{3p}{\pi} \theta \end{cases},\quad 0 < \mu \le 1 \tag{12}$$

where *d* is the distance between adjoining carriers, μ is a coefficient of yarn tension, *p* is the pitch length and θ is the angle displacement for coordinates of the yarn positions. $0 \le \theta \le \frac{\pi}{4}$ and $0 \le \theta \le \frac{\pi}{2}$ are satisfied in the surface and corner regions, respectively. As a result, the spatial distribution of yarn units can be determined.

Preform Boundary Reflection (PBR) Method

Although the geometric structure of the rectangular preform can be effectively simulated by traditional least-squares method, the coordinates of the yarn positions after every step must be calculated, hence the simulation process is time consuming. Many hours or even days could be used for designing the structure of one preform. In fact, more information can be extracted from the braiding process to simplify the motion model of the yarns. Thus an efficient method, namely preform boundary reflection (REF) method, is proposed.

Principle of the PBR Method

In the PBR method, the yarn path for one unit model can be separated into two types of basic structure:

(1) Straight line inside the preform.

(2) Surfaces and corners on the boundary of the preform.

Taking yarn #12 in *Figure 5* as an example, in one cycle of the step motion, the yarn moves from the upper boundary through the internal structure to the left boundary, then goes to the lower boundary. After that, it goes to the right boundary, and finally back to upper boundary to form a yarn unit, as shown in *Figure 5*.

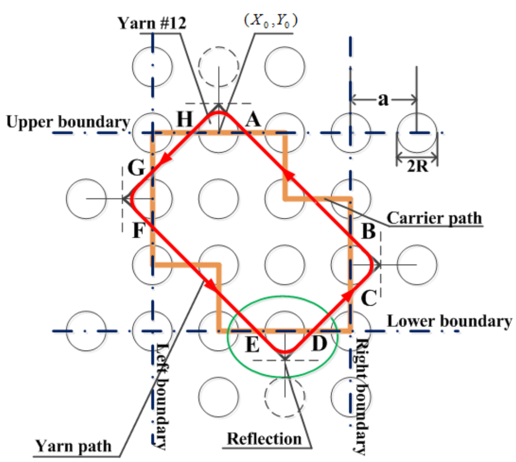


FIGURE 5. The unit model for yarn #12.

Whenever the yarn reaches the surface of the structure, it turns back into the interior of the preform, so the slope of the straight line will be changed as shown in *Figure 6*.

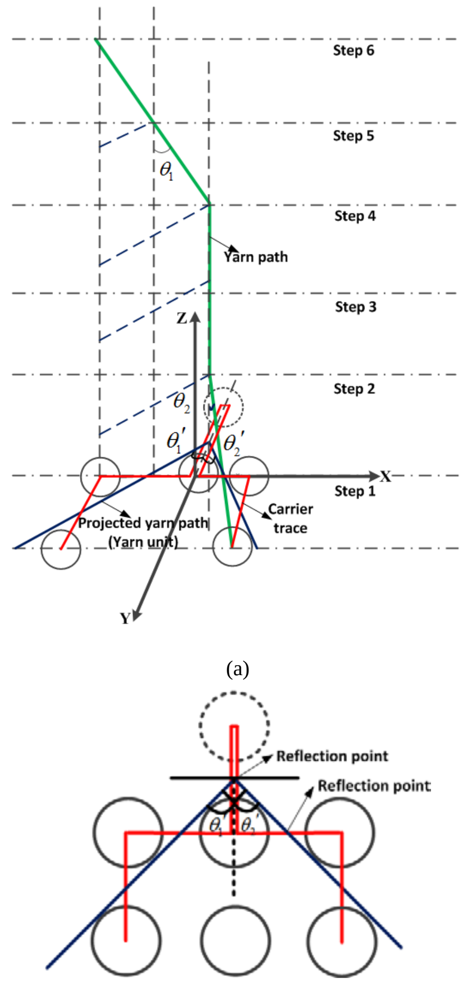


FIGURE 6. The yarn path near the surface region. (a) 3D model. (b) Projected yarn path.

From *Figure 6*, one angle is formed in the surface region. According to Yang's work [13], the spatial orientation of yarn segment for each step is defined by its orientation angle with respect to the braiding axis (z-axis) as

$$\theta = \tan^{-1}\frac{\sqrt{P_b^2 + P_c^2}}{P_a} \tag{13}$$

where P_b and P_c is related to the distance between adjoining carriers on rows and columns, respectively. P_a is the pitch length of the preform.

Two conditions are satisfied:

(1) 1:1 rectangular braiding is assumed i.e. the distance between every two adjoining carriers, both in columns and rows, is the same.

(2) The braiding process is stable, so that the braided structure is uniform and consistent. All yarn paths pass through the center between adjoining carriers, i.e. the midpoint of the carrier trace for each step, as shown in *Figure 7*.

These assumptions lead to

$$P_b = P_c = a/2 \tag{14}$$

Furthermore, the pitch length remains the same for each step, i.e. $P_a = p$ is satisfied for all the regions.

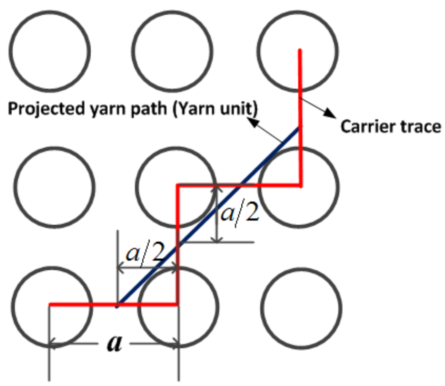


FIGURE. 7 The relationship between carrier trace and yarn path.

For the surface region, the yarn moves from the preform interior to the surface, stops one for step, then goes back to the inside. According to Eq. (13),

$$\tan\theta_1 = \tan\theta_2 = \frac{\sqrt{P_b^2 + P_c^2}}{P_a} = \frac{\sqrt{2}a}{P_a} \tag{15}$$

θ_1' and θ_2', the projections of θ_1 and θ_2 on the X-Y space can now be calculated,

$$\tan\theta_1' = \tan\theta_2' = {}^{a/2}\!\big/_{a/2} = 1 \tag{16}$$

i.e. $$\theta_1' = \theta_2' = 45^\circ \tag{17}$$

Since the yarn paths near the surface are symmetric according to the carrier trace on the surface, each yarn path will reflect at the same angle, i.e. 45°, as it hits the surface. That means the yarn yields a ‘reflection’ of the motion direction on the surface region, with the carrier trace normal to the reflection. According to reflection theory, when the yarn reaches surface, it will be reflected into the interior of the preform and the slope of the straight line will be changed from 1 to -1, or vice versa.

For the corner regions, the yarn moves from preform interior to the surface, the yarn path reflects twice and then goes back to the inside. It can be considered to consist of two surface structures, as shown in *Figure 8*.

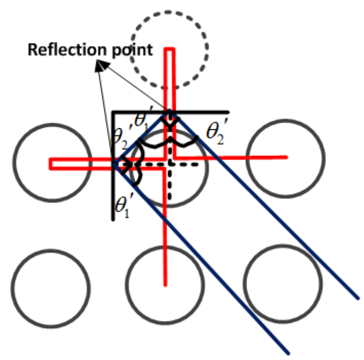


FIGURE. 8 The yarn unit model for corner region.

The initial motion direction and linear equation is obtained after the yarn carrier moves two steps. When the yarn path reaches the boundary of the main part, its direction rotates by 90° into the preform, according to the characteristics of ‘reflection’. For the slope of the reflected yarn path and the reflection point outside the boundary, another linear equation representing the yarn path inside the main part can be determined. The process is repeated until the initial point is included in the yarn path, the projection of yarn path inside the preform, i.e. the structure of straight a line in a yarn unit, can be obtained. Then surface and corner regions are constructed with spatial curves between adjacent boundaries, and finally complete the continuous 3D yarn path by moving via straight line inside the preform on the Z direction tangent to the spatial curve in the preform surface and corner.

Procedures for the PBR Method

Assuming the initial axis of the yarn #12 in *Figure 5* is (X_0, Y_0), the yarn's radius is *R*, and the distance between the adjoining carrier is *a*, the method consists of 5 steps:

(1) Definition of the boundaries of the main part. The boundaries determine the scope of the yarn's movement for each part in one yarn unit:

Upper boundary:

$$y = Y_0 + r\cos\frac{\pi}{4} \quad (18)$$

Left boundary:

$$x = X_0 - a - r\cos\frac{\pi}{4} \quad (19)$$

Lower boundary:

$$y = Y_0 - 3a - r\cos\frac{\pi}{4} \quad (20)$$

Right boundary:

$$x = X_0 + 2a + r\cos\frac{\pi}{4} \quad (21)$$

(2) Determination of the yarn's initial motion direction. After the yarn carriers move two steps, the initial two positions of the yarn path are determined. Using yarn #12 as an example, the initial direction is determined by line *AB*, i.e. from the upper boundary to the left boundary of the preform. It can be shown that the slope of line *AB*, i.e. the initial path direction is 1.

(3) Determine the linear equation of the yarn's path inside the preform. For the example of yarn #12, the linear equation for *AB* is:

$$y = x - X_0 + Y_0 + \frac{a}{2}, \quad X_{\min} \le x \le X_{\max} \quad (22)$$

where $X_{\min}$ is the left boundary of the main part and $X_{\max}$ is the *x* coordinate of intersection between line *AB* and the upper boundary of the main part.

Then the yarn path is 'reflected' to the lower boundary, i.e. line *CD*. Since the yarn is moved from the surface to the interior of the preform, the slope of line *CD* is changed from 1 to -1. With the aid of the reflection point, the path of yarn on line *CD* can be expressed as,

$$y = -x + X_0 + Y_0 - \frac{5a}{2}, \quad X_{\min} \le x \le X_{\max} \quad (23)$$

where $X_{\min}$ is the left boundary of the main part and $X_{\max}$ is the *x* coordinate of intersection between line *CD* and lower boundary of main part.

Similarly, the other two linear equations in one yarn unit can be obtained:

Line *EF*:

$$y = x - X_0 + Y_0 - \frac{9a}{2}, \quad X_{\min} \le x \le X_{\max} \quad (24)$$

where $X_{\min}$ is the *x* coordinate of intersection between line *EF* and the lower boundary of main part and $X_{\max}$ is the right boundary of main part.

Line *GH*:

$$y = -x + X_0 + Y_0 - \frac{a}{2}, \quad X_{\min} \le x \le X_{\max} \quad (25)$$

where $X_{\min}$ is the *x* coordinate of intersection between line *GH* and upper boundary of the main part and $X_{\max}$ is the right boundary of the main part.

(4) Define a spatial curve representing the corner and surface. According to the braiding pattern, the yarn's motion direction changes in the surface and corner regions. Owing to the softness of the yarn, square corners in the yarn unit are replaced with smooth curves (see *Figure 9*), which are simulated by circular arcs. The start or end point of the arc is the intersection point between the yarn path inside the preform and the boundary of the main part. Given the coordinates of the two points $S_1(X_1, Y_1)$, $S_2(X_2, Y_2)$ ($X_1 < X_2$), the scan angle θ of the arc, and the braiding steps in the surface or corner region, the corresponding coordinates of the yarn unit model can be obtained.

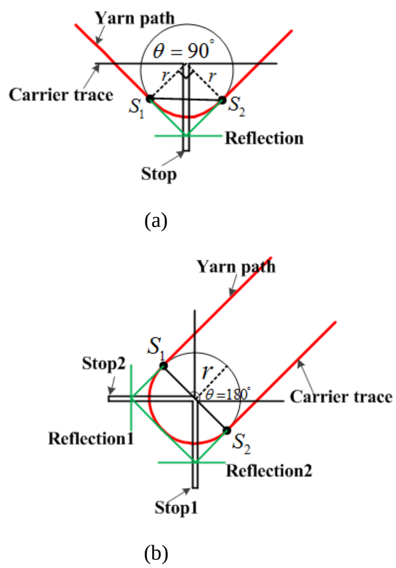


FIGURE. 9 Surface and corner regions represented by arcs in one yarn unit. (a) Surface region. (b) Corner region.

The distance between S_1 and S_2 is:

$$S_1S_2 = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2} \tag{26}$$

Then the radius of the arc is,

$$r = \frac{1/2 S_1 S_2}{\sin(1/2\theta)} \tag{27}$$

It is possible to define

$$\theta_{12} = \arctan\frac{Y_1 - Y_2}{X_1 - X_2} \tag{28}$$

given initial points

$$\begin{cases} X_0 = X_1 + r\cos\theta_{01} \\ Y_0 = Y_1 + r\sin\theta_{01} \end{cases} \tag{29}$$

where θ_{01} is initial angle

$$\theta_{01} = \begin{cases} -\dfrac{\pi}{2} + \theta_{12} + \dfrac{\theta}{2}, & \text{counter-clockwise arc} \\ \dfrac{\pi}{2} + \theta_{12} - \dfrac{\theta}{2}, & \text{clockwise arc} \end{cases} \tag{30}$$

The coordinates of the yarn positions can be expressed as,

$$X_i = \begin{cases} x_0 + \cos(\pi + \theta_{01} - a), & \text{counter-clockwise arc} \\ x_0 + \cos(\theta_{01} + a - \pi), & \text{clockwise arc} \end{cases} \tag{31}$$

$$Y_i = \begin{cases} y_0 + \sin(\pi + \theta_{01} - a), & \text{counter-clockwise arc} \\ y_0 + \sin(\theta_{01} + a - \pi), & \text{clockwise arc} \end{cases} \tag{32}$$

where $a = \frac{\theta}{T} i, \quad i = 0,1,2,\cdots,T-1$. T is the number of yarn steps on the arc.

For the surface region, the angle displacement of the yarn position is $\theta = \frac{\pi}{2}$. In this process, the yarn carrier moves four steps, i.e. T = 4. When the carrier moves one step, the yarn moves $1/4$ pitch length in Z direction, and rotates $\frac{\pi}{8}$ in braiding direction.

The corner region can be considered as two surface structures. The angle of displacement of the yarn position is $\theta = \pi$. Similar to the surface region, the yarn carrier moves seven steps, i.e. T = 7, in this process. When the carrier moves one step, the yarn moves $1/4$ pitch length in the Z direction, and rotates $\frac{\pi}{7}$ in the braiding direction.

(5) Complete the unit model of one yarn. If the yarn path doesn't reach initial position, continue the 3rd and 4th steps.

(6) If one yarn unit is finished, steps 1 to 5 are repeated in order to calculate the motion model for the other yarns of the preform.

(7) Complete the continuous 3D yarn paths. Move the straight line of the yarn unit in the direction of the Z axis to be tangent with the spatial curve in the perform surface and corner.

Using these procedures, the unit model of each yarn can be obtained using only two initial steps of carrier motion, so the calculation time is effectively reduced. The design time of the traditional and new methods will be compared quantitatively in the results and discussion section.

PREFORM GEOMETRY AND CAD SYSTEM

With the help of VC++ and SolidWorks API, a program with a user-friendly interface can be according to the motion model and braiding parameters. The motion model is programmed and tested by Matlab and invoked as Dynamic Linking Library (DLL) in VC++. Inputting the number of rows and columns in the main part, the distance between adjoining carriers, the pitch length, and the corresponding preform entity can be automatically generated.

Figure 10 shows the simulated preforms with different braiding parameters, which are shown in *Table* Ⅰ.

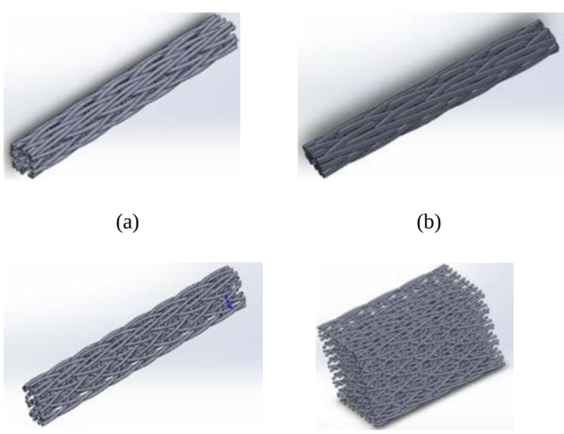


FIGURE. 10 Simulated performs with different braiding parameters. (a) Preform [2×4]. (b) Preform [3×5]. (c) Preform [4×4]. (d) Preform [10×10].

TABLE I. Braiding parameters for different preforms in *Figure 10* (mm).

Size of main part ($m\times n$)	Distance between adjoining shuttle (d)	Pitch length (p)	Yarn radius (R)
2×4	5	6	1.2
3×5	5	6	1
4×4	5	7	1.2
10×10	8	8	1

Figure 10 shows that the structure of the simulated preforms are close to the actual ones, even after the motion model has been simplified. Furthermore, the mesoscopic geometric structures such as intersection, buckling and kinking at surface, corner and interior regions can be observed and studied by cross-section during simulation.

RESULTS AND DISCUSSION

In order to evaluate the proposed model, the PBR method is compared with traditional methods. Since the geometric structure of the 3D braided preform can be effectively simulated by the least squares method [11], the simulation results of the PBR method are compared to those generated by the least-squares method in *Table I.* The braiding parameters of the preforms are the same as those in *Figure 10*. In order to compare the two methods under the same conditions, ten-step braiding is adopted for each simulation process. All of the computations and simulations were carried out on a 2.6 GHz 2-core AMD Opteron (TM) PC, with 16G RAM running SolidWorks 2012 on a Microsoft Windows 7 platform.

TABLE II. Braiding parameters for different performs.

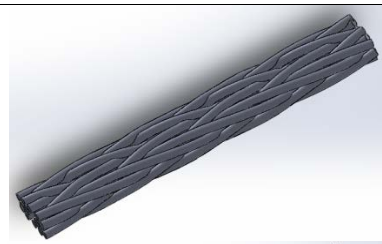
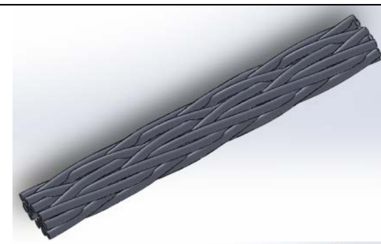
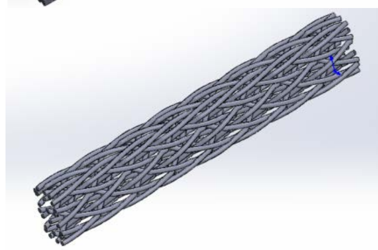
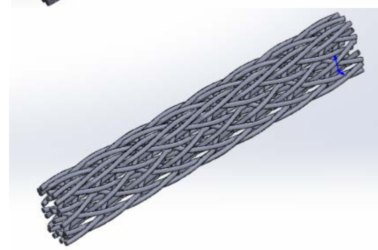
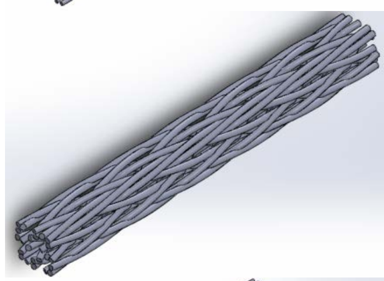
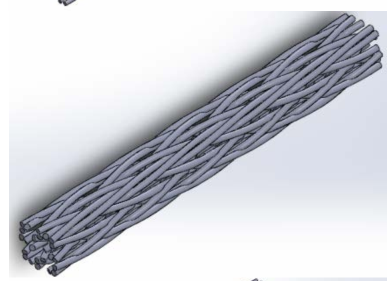
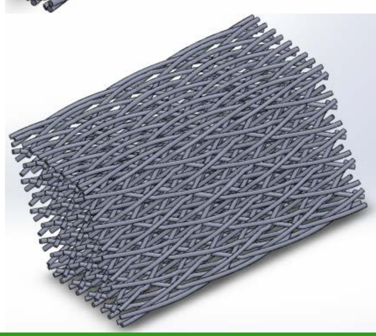
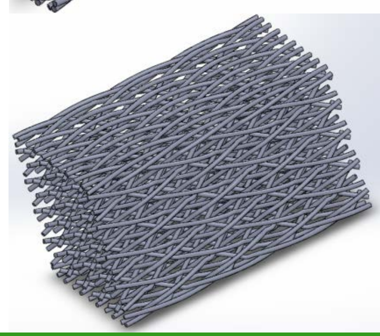
Size of main part ($m \times n$)	Least square method	PBR method
2×4		
3×5		
4×4		
10×10		

TABLE III. Time required for preform simulation (ten-step braiding for the same preform).

Size of main part	Time Required (s)					
	Least square method			PBR method		
	Motion model	Geometry formation	Total time	Motion model	Geometry formation	Total time
2×4	4.55	18.67	23.22	3.17	9.88	**13.05**
3×5	9.73	177.21	186.94	5.32	63.11	**68.43**
4×4	11.82	200.59	212.41	4.47	67.61	**72.08**
10×10	65.58	2134.79	2200.37	20.56	581.96	**602.52**

It should be noted that the PBR method and the traditional least-square method yield the same topological structure for the same braiding parameters. The real time performance is another important parameter in geometric modeling. The time required for generation of the motion model, geometry formation and the entire simulation process for PBR and traditional least-squared methods were calculated and compared in *Table III*.

The time required for preform entity construction can be divided into two parts. One part is the motion model construction of the topology structure in Matlab DLL, the other part is preform geometry formation in the CAD system. From *Table III*, the construction of the CAD model makes up the majority of the total time required. Compared to the traditional method, the simulation time required by the PBR method is effectively reduced. Furthermore, the acceleration of the design process will be greater as the size of the part being designed increases. This is due to increased level of multi-point connection inside the preform, which is replaced with a straight line during CAD model construction.

As a result, the PBR method makes the motion model simpler without affecting the precision of the geometric structure.

CONCLUSION

A CAD system for analysis of 3D rectangular braided performs was developed based on an efficient method, the preform boundary reflection (PBR) method. The motion model of the yarns was simplified based on yarn motion and the real braiding patterns. With the motion models simplified, the SolidWorks software was redeveloped using VC++ for geometric structure simulation. The simulation time based on the PBR method and the least-square method were calculated and compared. The motion model based on the PBR method can significantly reduce the computation time, especially for complex or large size parts.

The geometric models established in this paper were all depended upon some assumptions and the real geometric shape of the braid yarn within 3D braided composites is not fully considered. As a result, the true structures still have some differences from the simulated ones, which will reduce the precision of mechanical property estimations. In future work, the variation of cross-section, undulation and distortion within textile composites because of yarn jamming and crimp during the external loading will be considered in the motion model construction in order to improve the precision of the model in estimating mechanical properties of the 3D braided composite.

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