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Processing of plate 3D braided material based on space group $P\bar{3}$ symmetry

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ABSTRACT

3D braided material based on space group $P\bar{3}$ symmetry has not been used in industrial production although the braided fabric has been proved to have excellent properties. Considering that plate 3D braided fabric is widely used in some fields, the processing of plate 3D braided material based on space group $P\bar{3}$ is first proposed. Based on the novel geometry structure of space group $P\bar{3}$ symmetry, the yarn arrangement and motion law of the carriers of plate 3D braided material are studied. The fiber volume percentage and its variation tendency of the plate 3D braided material are predicted by establishing mathematical model. Plate 3D braided material based on space group $P\bar{3}$ symmetry has excellent properties and lays the foundation for industrial applications.

KEYWORDS

Space group $P\bar{3}$;
Plate 3D braided material;
Braided processing.

INTRODUCTION

3D braided composites are widely used in aerospace, automobiles and weaponry industry because of its light weight, high intensity and excellent performance. The performance of braided fabric is restricted by 3D geometry structure which is achieved by braided processing. Most researches still focused on 2-step and 4-step braiding method whose processing is relatively simple, and the yarn only move in the *x* and *y* direction[1]. The microstructures of these braided fabrics are established and yarn orientation and fiber volume fraction are analysed[1-3]. Based on the research of microstructure of the braided fabrics, mechanical properties and other properties are studied[4-5]. Braided performs with various cross sections can be obtained by certain processing[6-7]. The reducing yarn processing is widely used when braiding irregular shape of 3D braided fabrics[8-10]. Braiding angle is a key factor to many properties of braided composites[11-12].

The braided processing based on space group $P\bar{3}$ symmetry can make the yarn run through in every braided direction when the carriers move in each layer[13]. When the braided fabric reaches a certain thickness, a whole structure can be obtained while need not to adopt adding yarn, reducing yarn or transforming braided direction like 4-step braiding method.

The symmetry of the braiding geometric structure is described using crystal symmetric group theoretical methods in 2005, and then a series of novel geometry structure is deduced[14-15]. The geometry structure which has the symmetry of the space group corresponds to space group $P\bar{3}$. A novel geometry structure of unit cell is deduced by using the point group *S*6 corresponding to symmetry operations[15]. A novel geometry structure can be obtained by transforming the new cell symmetrically according to the symmetry described by space group $P\bar{3}$.

PROCESSING BASED ON SPACE GROUP $P\bar{3}$ SYMMETRY

The laws of the carriers' arrangement

In the novel braided processing, all of the yarns are divided into two groups: one is braided yarn that moves in the carrier plane according to certain rules, and the other is enhanced yarn that does not move. The array of the two groups of yarn is shown as Figure 1.

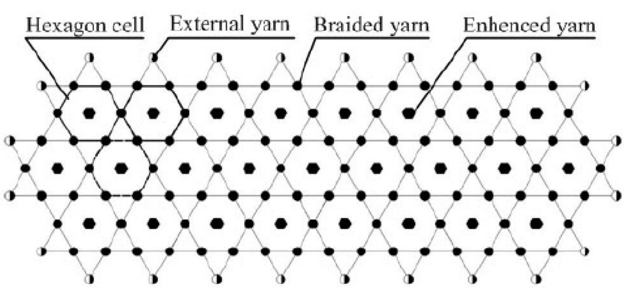


Figure 1 : Carrier array in the carrier plane.

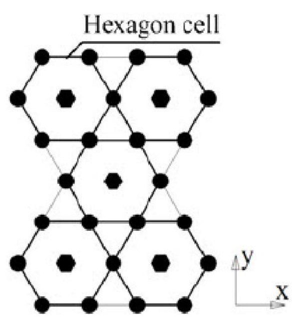


Figure 2 : Hexagon cell array.

As shown in Figure 1, the carrier plane can be seen as a number of hexagon cells arranged according to certain rules which are provided in Figure 2, and external yarns are arranged around the outer edges of the hexagon cells. The rules of hexagon cell array are given by Figure 2. Every hexagon cell shares one vertex with adjacent hexagon cell in *x* direction and their geometric centers are in a straight line. Hexagon cell in *y* direction is translated horizontally for a radius value of circumscribed circle of itself, so one hexagon cell joins with four hexagon cells and shares one vertex with each of them.

Interior yarns are arranged in every vertex of the hexagon cells (the black dot in Figure 1). Motionless enhanced yarns are arranged in the geometric centers of hexagon cells for enhancing the axial mechanical properties (the black hexagon in Figure 1). External yarns are arranged around the outer edges of the hexagon cells in order to constitute equilateral triangle with both ends of the edges.

The motion laws of the carriers

The motion laws of the carriers are studied according to the structural features of the new 3D yarn-cross structure. The shape of the carrier driver is designed as shown in Figure 3.

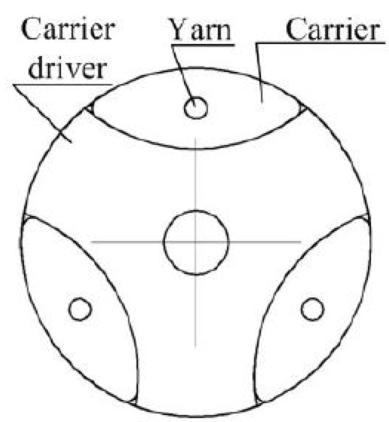


Figure 3 : The array of carriers and its driver.

As shown in Figure 3, the yarn is arranged in the center of the carrier, and the carrier is arranged arround the carrier driver. Three carriers are drove by one carrier driver. The carriers are drove by carrier driver which turns 120° every step. Three carriers and one carrier are defined as a driver group.

The circles with arrows in Figure 4 are defined as driver groups and the direction of the arrows means its movement direction. The geometrical centre lines of driver groups are numbered in Arabic as shown in Figure 4.

- Every three carrier, which consist of two carriers at the end of every edge of the hexagon cells and one carrier that can constitutes equilateral triangle with both ends of the edges, is drove by one carrier driver. All of the driver groups can be divided into two groups: anticlockwise group whose serial number of geometrical centre line is odd and clockwise group whose serial number of geometrical centre line is even. Different driver group move intermittently but synchronously in the same group.

- Six driver groups also make up a hexagon cell as shown in Figure 5. The movement direction of adjacent driver group is opposite. The specific movement rules are shown in Figure 6.

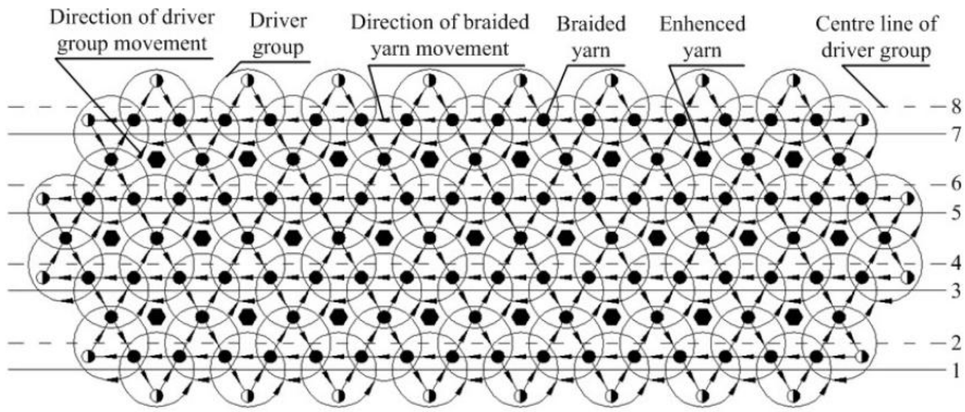


Figure 4 : The array of carrier drivers and the movement rules of carriers.

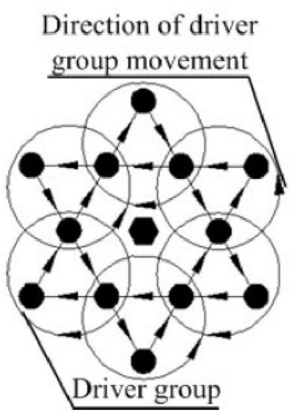


Figure 5 : Hexagon cell of the driver group.

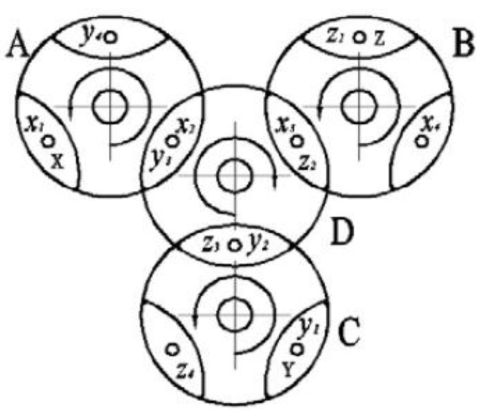


Figure 6 : Movement rules of carriers and its driver.

As shown in Figure 5, six driver groups compose one hexagon cell. A, B, C and D in Figure 6 are defined as carrier drivers and *x*, *y* and *z* mean coordinate points that carriers passed by.

The movement of three carriers named as 'X', 'Y' and 'Z' is studied for obtaining the movement rules of carriers easily in Figure 6. Driver A, B and C run counterclockwise while driver D runs clockwise. The new braided processing depends on the intermittent and circular movement of the two groups of drivers in the specified direction. First, driver A, B and C run counterclockwise for 120°. Carrier X moves from x_1 to x_2, Y moves from y_2 to y_2 and Z moves from z_1 to z_1. Second, driver D runs clockwise for 120°. Carrier X moves from x_2 to x_3, Y moves from y_2 to y_3 and Z moves from z_2 to z_3.

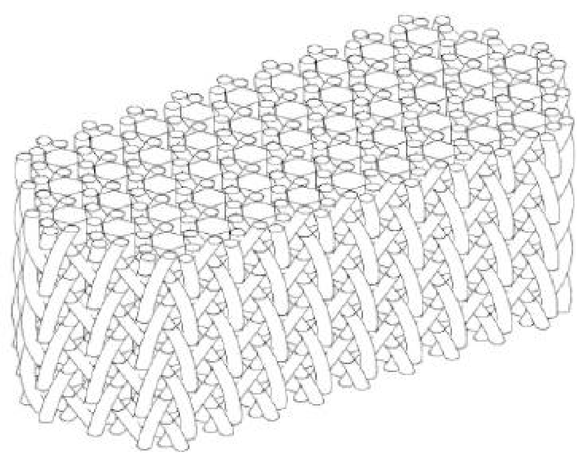
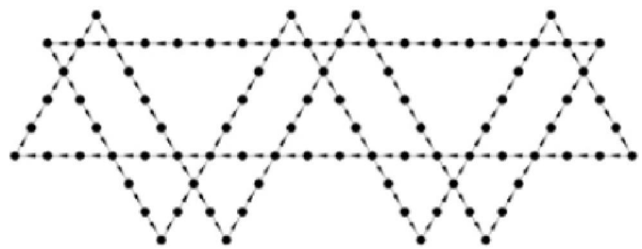


Figure 7 : Emulation model based on the new braided processing[13].

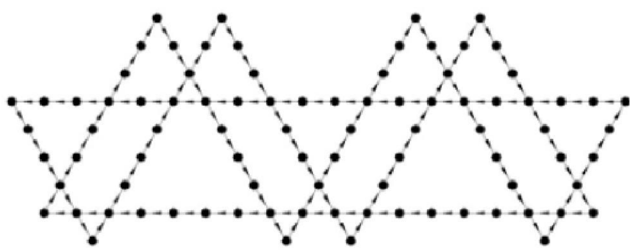
As shown in Figure 7, plate 3D braided material can be obtained by repeating the two steps.

THE MOVEMENT TRAJECTORIES OF THE CARRIERS BASED ON BRAIDEDPROCESSING OF SPACE GROUP $P\bar{3}$ SYMMETRY

The movement trajectories of the carriers in the carrier plane can be deduced by analyzing the movement of carriers in different positions according to the movement rules, as shown in Figure 8.



(a)



(b)

Figure 8 : Movement trajectories of the carriers in the carrier plane[13].

These black dots in Figure 8 indicate carriers' position; the straight lines mean movement trajectories and the arrows express movement direction. All of the carriers can return to their point of origin along the trajectories in the movement direction, and the processing is defined as a movement cycle. The resulted movement track of a carrier is shown as Figure 8 (a) or Figure 8 (b) depending on the movement order of the two groups of drivers.

THE CALCULATION OF THE FIBER VOLUME PERCENTAGE

The unit cells of the plate 3D braided material

3D braided fabrics are divided into interior region with no external yarn, surface region with one external yarn and corner region with two external yarns as shown in Figure 9.

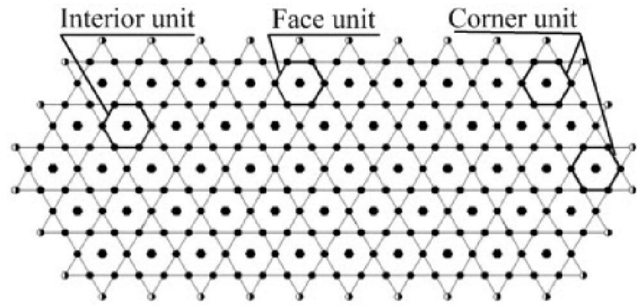
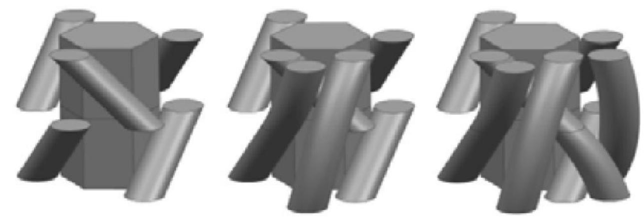


Figure 9 : Unit cells of the plate 3D braided fabric.



(a) Interior unit (b) Face unit (c)Corner unit.

Figure 10 : Fabric units.

The unit cell models are given in Figure 10. Interior unit, face unit and corner unit are respectively shown in Figure 10 (a), Figure 10 (b) and Figure 10 (c).

Basic hypotheses

- The section of the yarn is assumed to be elliptical, and the two axes of ellipse are 2a and 2b. The section of the enhanced yarn is assumed to be equilateral hexagon, and the length of its edge is R.
- The ratio of projected area in a certain direction of one layer fabric and one unit's projected area in the same direction is big enough.
- The length of the single external yarn in the face unit and in the corner unit is equal to the length of the single yarn in interior unit in a braid pitch.

Geometric parameters used for describing 3D braided fabric

(a) Number of braided fabric unit-cells

The number of unit cells in the outermost layer is assumed as n, and the row number is m. The number of interior, corner and face unit-cell can be expressed separately as N_i, N_c and N_f. Numbers of braided fabric unit-cells are

$$N = mn + \frac{(m-1)^2}{4} \quad (1)$$

$$N_c = 6 \quad (2)$$

$$N_f = 2(m+n) - 10 \quad (3)$$

$$N_i = N - N_f - N_c \tag{4}$$

(b) Braiding angle

There are two kinds of braiding angle: face braiding angle α, interior braiding angle β. They are given as follows:

$$\tan\alpha = (R + 2\sqrt{3}b)/3t \tag{5}$$

$$\tan\beta = (R + \frac{2b}{\sqrt{3}})\Big/t \tag{6}$$

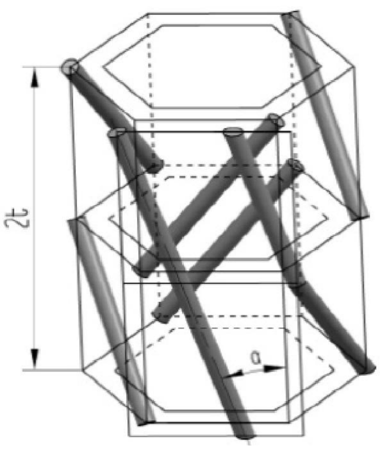


Figure 11 : Face braiding angle α**.**

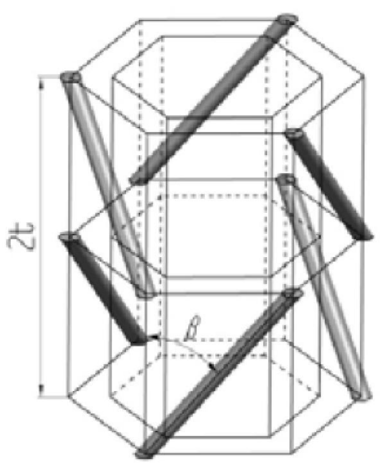


Figure 12 : Interior braiding angle β**.**

The face braiding angle α and interior braiding angle β are respectively expressed in Figure 11 and Figure 12.

(c) The cross-sectional area of the fabric A and the total volume of the fabric U

They are given as follows:

$$A = (3\sqrt{3}R + 8b)(25R + \frac{38\sqrt{3}}{3}b) \tag{7}$$

$$U = 2At = 2t(3\sqrt{3}R + 8b)(25R + \frac{38\sqrt{3}}{3}b) \tag{8}$$

(d) The total volume of the yarn in the fabric U_y

It can be expressed as:

$$U_y = 168\pi ab(R + 2b/\sqrt{3})/\sin\beta + 24\pi ab\sqrt{9t^2 + (R + 2\sqrt{3}b)^2 + (75\sqrt{3}R^3 + 150R^2 b)/\tan\beta} \tag{9}$$

(e) The fiber volume percentage V_f

It can be expressed as:

$$V_f = \frac{U_y}{U} \times 100\% \tag{10}$$

(f) The relation between the fiber volume percentage V_f and the yarn packing factor λ

The yarn packing factor, the original cross-sectional area of braided yarn and the original cross-sectional area of enhanced yarn can be assumed as λ, S_1 and S_2.

$$\lambda = \frac{b}{b}(\lambda \le 1) \tag{11}$$

$$\lambda S_1 = \pi ab \tag{12}$$

$$\lambda S_2 = \frac{3\sqrt{3}}{2}R^2 \tag{13}$$

Fiber volume percentage of the 3D braided fabric can be derived as

$$V_f = f(\lambda, \beta) \tag{14}$$

The variation tendency of V_f can be expressed as Figure 13.

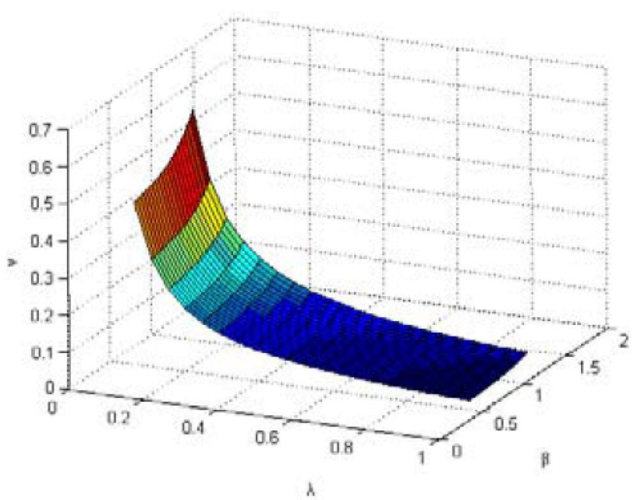


Figure 13 : Tendency of 3D braided fabric fiber volume percentage.

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As shown in Figure 13, the fiber volume percentage V_f decreases with the increase of the yarn packing factor λ, while increases with the increase of braiding angle β. Suitable braiding angle and yarn packing factor can be selected in the certain braided processing according to Figure 13.

CONCLUSION

Plate 3D braided processing based on space group $P\bar{3}$ symmetry is first proposed, including carriers arrangement, movement rules of the drivers and movement trajectories of the carriers of the braided material. Plate 3D braided material fiber volume percentage and its variation tendency are predicted by establishing geometric model. The fiber volume percentage of plate 3D braided material is mainly affected by the yarn packing factor and braiding angle. The braided processing based on space group $P\bar{3}$ symmetry is more convenient when braiding irregular fabric and the fabric has better properties and structural integrity. The variety of 3D braided material is enriched by researching plate 3D braided processing based on space group symmetry and the research lays the foundation for industrial applications.

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