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A New Scheme and Microstructural Model for 3D Full 5-directional Braided Composites

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Abstract

Three-dimensional (3D) braided composites are a kind of advanced ones and are used in the aeronautical and astronautical fields more widely. The advantages, usages, shortages and disadvantages of 3D braided composites are analyzed, and the possible approach of improving the properties of the materials is presented, that is, a new type of 3D full 5-directional braided composites is developed. The methods of making this type of preform are proposed. It is pointed out that the four-step braiding which is the most possible to realize industrialized production almost has no effect on the composites' properties. By analyzing the simulation model, the advantages of the material compared with the 3D 4-directional and 5-directional materials are presented. Finally, a microstructural model is analyzed to lay the foundation for the future theoretical analysis of these composites.

Keywords: 3D braided fabrics; four-step braiding; 3D full 5-directional braided composites preform; microstructure

1. Introduction

Three-dimensional (3D) braided composites have been studied for decades since the 1970s'-1980s'. The developed countries have invested considerable financial, material and human resources to conduct the relevant researches, and acquired plentiful fruits. 3D braided composites are becoming the primary representative of the solid composite structures because of their special features and advantages. The main features and advantages are as follows[1-8]:

(1) The yarns are solidly interlaced with each other in the space and arrayed in a beeline interiorly.

(2) It may be preformed in a close complete section[2].

(3) It can fabricate components with complex sections one time, and has no use for cementation or needlework[3].

(4) It can resist delamination, damage, impact and endure ablation[4-7].

(5) The low cost processes such as resin transfer modeling (RTM) and vacuum assisted resin transfer modeling (VARTM) are used, it dispenses with the complicated technology and expensive equipment such as prepreg and hot-press pot[8].

(6) It may realize sewing connection and common curing process/cementing curing process with other plane (two-dimensional) composites components.

In recent years, 3D braided composites have been widely used in thermal protection nose cone, brake block, the hot-end guard tile or other parts of the motor, rocket engine throat lining, rocket nozzle, truss joint and so on. With the technological advancement and the enlargement of industrial need, the resin-base, carbon-base, ceramic (quartz ceramic) -base and metal-base 3D braided composites will be widely used for the 3D structures in the future. Their range of application will be extended from aerospace to vessel, automobile and other engineering industries.

Although the 3D braided composites have superior performance and numerous researches have been carried out, many positive results have not been put into application on large scale. It is mainly because that there are still some obvious shortcomings and deficiencies which are restraining their development[8-16]:

(1) The cost is expensive such as the factory cost, labor cost and piece-production cost owing to back-

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ward automatization.

(2) The item size is restricted in the braider competence, so the parts are mostly small size or section ones.

(3) The manufacturing period is too long because of the premature braiding technology and specification within the backward automatization and the low productivity.

(4) The 3D braided composites' in-plane properties are inferior to that of the 2D layer composites' owing to the 3D braided method[9-11]. We can utilize the high properties of the fibers to design their properties according to the needs. Therefore, every directions' properties almost have certain restriction, they cannot achieve the same strength level. Some directions' properties are upgraded at the expense of the others' properties.

(5) On the material's stiffness and strength side, the compressive resistance is obviously inferior to the tensile resistance[10-13].

(6) The processing quality is difficult to be controlled, and the consistency is not good enough. The fiber volume fraction usually does not meet the design requirement.

(7) The material properties are dispersive.

In a word, some of the above-mentioned shortages and disadvantages are enslaved to the actual technological level and processing capacity. They can be solved by means of increasing the research investment and improving the existing technology. The others cannot be realized by the present 3D braided technology such as above-mentioned key points (4)-(5) .

In Ref.[10], Z. G. Liu put forward a new type of 3D full 5-directional braided composites which can evidently improve the above-mentioned problems. Based on the study, the implementation techniques of 3D full 5-directional braided composites preform are introduced, and a manually braided practicality is offered in this article. The internal structure of the 3D full 5-directional braided composites is analyzed, and the calculation model used for the finite element analysis is built. It provides a basis for the following quantitative analysis of the mechanical property.

2. Realization of 3D Full 5-directional Braided Composites Preform

3D full 5-directional braided composites preform is obtained based on 3D 4-directional[12] or 5-directional ones[17].

2.1. Scheme for 3D full 5-directional composites preform

3D 5-directional preform consists of $m\times n+m+n$ braiding yarns and $m\times n$ axial yarns, and the numbers of braiding and axial yarns are almost equal. Fig.1 shows the paths of the preform yarns[17]. The lines which are slanting and turning back to the inside of textile are the yarns' direction. In the region surrounded by the intersected yarns, "●" stands for axial yarn and "○" stands for cavity without axial yarn. When the preform is compounded with base, the cavity positions form rich resin districts. On the one hand, the cavities degrade the composites' uniformity. On the other hand, the rich resin districts are the areas with poorer property, and it is easy to produce deficiencies and affect the property of composites.

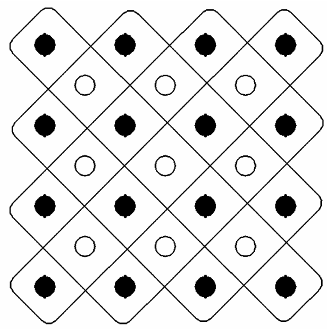


Fig.1 Yarns path of 3D 5-directional preform.

In view of lacking bridging effect, the tiny flaws (such as crack) within the composites are easy to be spread in the rich resin districts. When the cracks arrive at the surface of the fibers, the spiry high-stress easily induces the fiber rupture or spreads along the interface between fiber and base bringing about the further expansion of the damage.

The braided preform will generate inward stress and be distorted because of the cavities and the braiding yarns' straining effect during braiding. In addition, being short of the transverse supports at the cavities, the vicinal braiding yarns and axial yarns incline towards the cavities so that the fibers axes are bent, the section shapes are changed, and the direction of the monofil space of the fasciculus shows wavelike patterns. Therefore, when this type of the composites' fibers endure tensile loads, they will tend to be straightened, and the load direction is not completely the same as the fiber. Otherwise, the common fiber with high property (such as carbon fiber) has strong tension resistance and compression resistance along the axial direction, as well as weak shearing resistance along the transverse orientation, so the bent fasciculus initiate shear failure and interface sticky point failure due to cross constraint in the process of straightening out, and the macroscopic tensile property is degraded. However, when the fasciculus endure compressive loads, they will be buckled to degrade the compression property[11-13].

The ultimate method which solves the above-mentioned problems is the 3D full 5-directional braided composites preform which is gotten by infilling axial yarns in the cavities marked with "○".

2. 2. *Detailed technique*

Slender puncture braiding The hollow needle tubes in which fasciculus are drawn in are infixed into the cavities along the axial direction. After the tubes go through the other side, the fasciculus in the tubes are fixed. Then, the tubes are drawn out. In this way, the fasciculus are retained in the cavities and the lead-in axial yarns have no damage. But the braiding yarns may be damaged in the process of inserting the tubes. Therefore, the tube head should be smooth enough, and having no skewness should be assured when they are inserted. In addition, the length of the punctured fasciculus is restricted.

Down-leading method A thinner probe is used to puncture the cavity and go through the opposite side, and it is to be assured that the probe must only pass through the cavity and does not go through the braiding yarns. Then, the fasciculus are carried through by the barb or eyelet at the tail end of the probe forming axial yarns. In this way, it should pay attention that the braiding yarns are not be damnified. The yarns may be broken because of the friction between the yarns when the axial yarns are drawn out.

Four-step braiding Simulating the movement of four-step braiding yarns, all axial yarns are arranged at the beginning of the braiding, and then the shuttles of the braiding yarns are moved manually according to the rule of four-step braiding. The braiding yarns go round the adjacent axial yarns and wrap around the axial ones, and then the 3D full 5-directional braided composites preform is formed. It demands very deep-going comprehension and understanding of the principle of four-step braiding[18]. Fig.2 is the 3D full 5-directional braided composites preform formed by four-step braiding, where $m=n=4$, and the yarns path is shown in Fig.3. It has $m\times n+m+n=24$ braiding yarns and $m\times n+(m-1)\times(n-1)=25$ axial yarns, and there are 9 more axial yarns than 3D 5-directional braided preform's 16 axial yarns. When the preform's section is larger, the number of 3D full 5-directional composites preform's axial yarns is two times as great as that of 3D 5-directional composites preform.

For observing conveniently, the material is pellucid plastic tubes. The axial yarns are substituted by thicker plastic tubes, while the braiding yarns are substituted by thinner plastic tubes. It is obvious by Fig.2 that the braiding yarns are separated from each other in the axial direction. It is because that the substitution of the plastic tubes cannot be flattened and

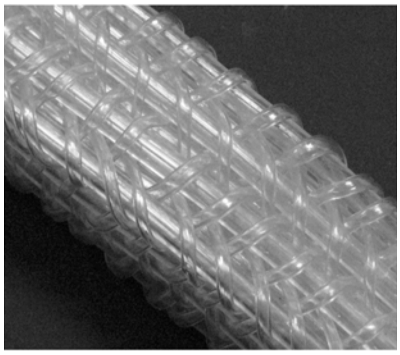


Fig.2 Preform of 3D full 5-directional braided composites.

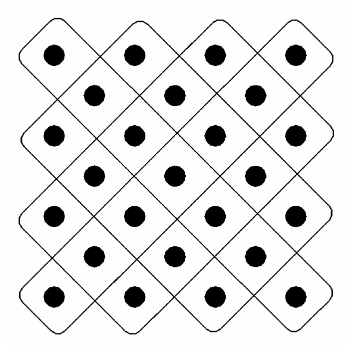


Fig.3 Yarns path of 3D full 5-directional composites preform.

dispersed like the fasciculus. This phenomenon may be eliminated by fasciculus braiding. According to Fig.2, the surface braiding angle of the preform obviously exceeds 45°, and it is about 70° by measuring. The former preforms cannot reach that extent. In a sense, the big surface braiding angle can degrade the axial property of 3D braided composites, however, the number of axial yarns of 3D full 5-directional braided composites is almost increased by one time, at $m\times n+(m-1)\times(n-1)$. In each interior unit cell, the number of axial yarns is twice greater than the braiding ones, so the total axial property can be improved owing to the increase of the axial yarns. Meanwhile, with the increase of the braiding angle, the braiding yarns can bear more transverse loads and have an enhanced effect on transverse property. For 3D full 5-directional braided composites, the ways by which the transverse property can be improved are as follows. On the one hand, the braiding yarns should be arranged along the transverse direction as far as possible, that is to say, the braiding angle should be as big as possible. On the other, the density of the braiding yarns should be increased along the axial direction, namely shortening the section length. In fact, when the surface braiding angle approaches 90°, the composites' property will be similar to that of the 3D orthogonal braided composites.

In addition, the braiding yarns and the axial yarns are supporting each other because the axial yarns are uniformly arranged and the cavities do not exist. Not only it is advantageous for the yarns to straighten out, but also the phenomenon of uneven sections due to the uneven yarns' tension does not appear. That is to say, the stability of the preforms size is better.

3. Microstructural Model of 3D Full 5-directional Braided Composites

Fig.4 is the ideal yarns' structure of the 3D full 5-directional body unit cell simulated by computer, where h is the height of the unit cell, a the half length of the unit cell's undersides, and γ the interior braiding angle. It is obvious that the configuration of the yarns within the body cell is very regular. As being viewed along some axial yarns or braiding yarns, there are other axial and braiding yarns passing by, and all yarns' center lines are nearly straight. In fact, the yarns sections are deformed under the transverse pressing. So the section shapes of the yarns and the axial directions are changed, when the preform is braided by real fibers. However, the center lines are still close to the straight lines.

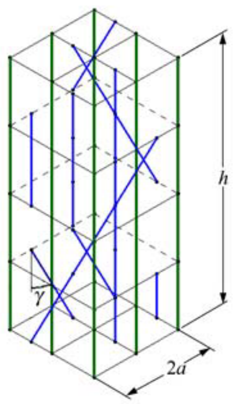


Fig.4 Interior yarns structure of 3D full 5-directional unit cell.

For laying the foundation for the finite element analysis of 3D full 5-directional braided composites, this article puts forward a new element analysis model for 3D full 5-directional rectangle braided composites which is shown in Fig.4. As being viewed along the axial yarns direction (planform), there are only the braiding yarns along the 45° direction passing through their upper, lower, left and right sides. Moreover, their relative position is invariable in the different cycle lengths. Thus, the sections of axial yarns may be regarded as square section. As being viewed along the axial direction of the braiding yarn, there are two axial yarns and four braiding yarns passing by its side. When these braiding yarns touch the square axial yarns and other braiding yarns, the volume fraction of the 3D full 5-directional braided composites reaches its maximum value theoretically. At this time the shape of the unit cell is shown in Fig. 5, and the section of the braiding yarn is assumed being hexagon.

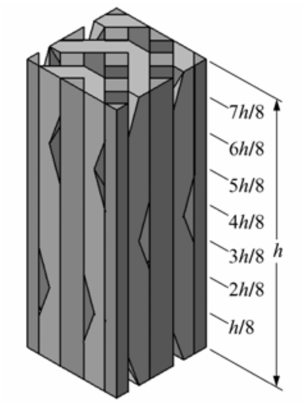


Fig.5 Microstructural model of 3D full 5-directional unit cell.

The model is parted into eight sections along the section length in order to comprehend the full microstructure of the unit cell model. The microstructure models of the section positions are shown in Fig.6.

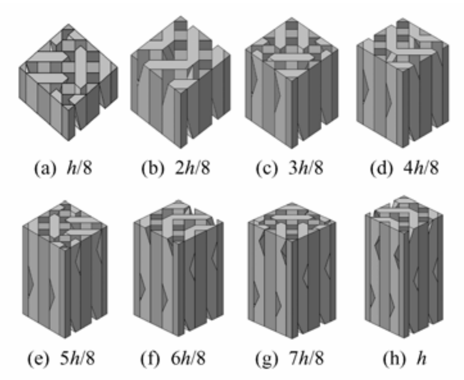
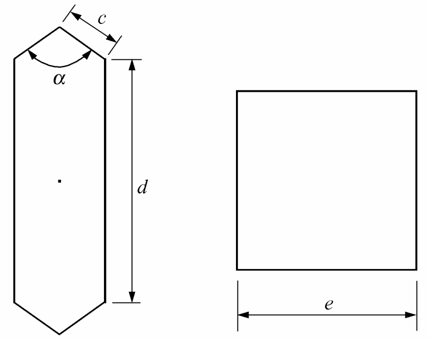


Fig.6 Microstructural models of 3D full 5-directional unit cell in different section positions.

It is supposed that the axial yarns contain N_1 pieces of fasciculus and the braiding yarns contain N_2 pieces of fasciculus, of which section collection rates are ε_1 and ε_2 separately. The diameter of the monofil is d_f. The length of side of the axial yarns is e, the length of the braiding yarns' straight segment d, and the length of oblique line c, as shown in Fig.7.



(a) Cross section of braiding yarn (b) Cross section of axial yarn

Fig.7 Yarn's cross sections of 3D full 5-directional unit cell.

According to the interspace contacting rela-tion-ship between the braiding yarns and the axial yarns, and the relationship between the cell shape and the braiding craftwork parameter, the following relational expression can be deduced.

$$\tan\gamma = \frac{2\sqrt{2}A}{h} \tag{1}$$

The planform of at the quarter model of the 3D full 5-directional unit cell is shown in Fig.8, which displays the contacting condition between the braiding yarns and the axial yarns. The surface 2-3-7-6 is the projection of the braiding yarn and the surface 1-2-3 is the projection of axial yarn. The line 2-3 is the intersection's projection of the braiding yarn and the axial yarn.

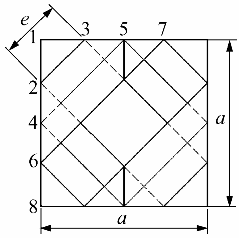


Fig.8 Contacting relationship between braiding yarns and axial yarns.

By the contacting relationship between the axial yarns and the braiding yarns, the following equation is obtained:

$$\sqrt{2}\left(2c\sin\frac{\alpha}{2}+e\right)=a \tag{2}$$

Fig.9 is the contacting condition among the braiding yarns, in which the central lines are non-uniplanar lines. The distance between the two non-uniplanar lines is expressed as L.

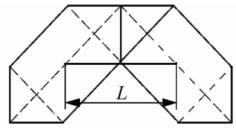


Fig.9 Contacting condition among braiding yarns.

By the contacting condition among the braiding yarns, the distance between the center lines of the braiding yarns is written as

$$L = 2\left(c\cos\frac{\alpha}{2}+\frac{d}{2}\right)\sin\frac{\alpha}{2} \tag{3}$$

Withal, Eq.(4)is derived by the formula of the distance between the two non-uniplanar lines.

$$L = \frac{a}{\sqrt{\frac{\tan^2\gamma}{2}+1}} \tag{4}$$

From the geometric relationship in the space, we can deduce

$$\alpha = 2\arcsin\frac{1}{\sqrt{1+\cos^2\gamma}} \tag{5}$$

The cross-section area of the axial yarn is

$$S_1 = e^2 = N_1\pi\left(d_f/2\right)^2/\varepsilon_1 \tag{6}$$

The cross-section area of the braiding yarn is

$$S_2 = c^2\sin\alpha + 2dc\sin\left(\alpha/2\right) = N_2\pi\left(d_f/2\right)^2/\varepsilon_2 \tag{7}$$

Withal

$$S_2 = c^2\sin\alpha + 2dc\sin\frac{\alpha}{2} = \frac{3a^2-2\sqrt{2}ae-2e^2}{4}\cos\gamma \tag{8}$$

So the yarn volume content is

$$V_y = \frac{V_1}{V} = \frac{8S_1h+4S_2\frac{h}{\cos\gamma}}{(2a)^2h} = \frac{3}{4}-\frac{\sqrt{2}e}{2a}+\frac{3e^2}{2a^2} \tag{9}$$

where V_1 and V are the volumes of the yarn and the unit cell.

So the fiber volume fraction is

$$V_f = \frac{V_2}{V} = \frac{8S_1h\varepsilon_1+4S_2\frac{h}{\cos\gamma}\varepsilon_2}{(2a)^2h} = \frac{8N_1\pi\left(\frac{d_f}{2}\right)^2+4N_2\pi\left(\frac{d_f}{2}\right)^2\frac{1}{\cos\gamma}}{4a^2} \tag{10}$$

where V_2 is the volume of the fiber.

By considering the geometric relationship, it iss ascertained that the fiber volume fraction of the unit cell will be maximum when ε is 1.00. The relationship is shown in Table 1, where K denotes one thousand pieces of monofilament.

Table 1 Fiber volume fraction of unit cell for 3D full 5-directional braided composites

Serial number	Axial yarns/K	Braiding yarn/K	γ /(°)	ε_1	ε_2	V_f /%
1	12	12	45	1.00	1.00	69.51
2	12	12	45	0.75	1.00	64.83
3	12	12	45	1.00	0.80	66.57
4	12	12	45	0.75	0.80	61.89
5	12	12	40	1.00	1.00	69.58
6	12	12	40	0.75	0.80	62.17
7	12	9	40	0.75	0.80	62.73
8	9	12	40	0.75	0.80	62.50
9	9	12	30	0.75	0.80	62.94

Therefore, the fiber volume fractions of the 3D full 5-directional braided composites for most of the braiding angles can reach about 60%, which is higher than 40%-55%[19-20] of the general 3D 4-directional or 5-directional braided composites, and close to 60%-70% of the laminates. Because of the higher fiber volume fraction, the 3D braided configuration and the straight trend of the fibers, the global property of the 3D full 5-directional braided composites can be greatly enhanced. As a result, they can play an important role in the engineering application as a kind of new advanced structural material.

4. Conclusions

The inherent shortages of the traditional 3D 4-directional and 5-directional braided composites are analyzed, and a new scheme for 3D full 5-directional braided composite is presented. The preform is successfully achieved by four-step braiding method. It charts the path for the future research and development of the composites.

In terms of the microstructure of the 3D full 5- directional braided composites, the advantages of their property are analyzed. It is pointed out that this type of composites may become a new high-performance composites with high level property.

According to the micro-analysis of the 3D braided composites preform, a unit cell model used for the finite element analysis is proposed to lay the foundation for the future theoretical analysis of these composites.

References

[1] Crane R M, Macander A B. Multidimensionally braided fiber reinforced composite material characterization. Naval Engineers Journal 1984; 96(6): 552-560.

[2] Li J L. Three dimensional braiding composites for structural components. Journal of Spacecraft Recovery & Remote Sensing 2007; 28(2): 53-58. [in Chinese]

[3] Reese E D, Majidi A P, Pipes R B. Friction and wear behavior of fiber FP/aluminum composites. Journal of Reinforced Plastics and Composites 1988; 7(11): 500-514.

[4] Florentine R A. Characterization of 3D braided composites-status of structure-property design data for magnaweave-reinforced carbon-epoxy aircraft composites. SAMPE. 1989; 433-443.

[5] Gause L W, Alper J. Structural properties of braided graphite/epoxy composites. ASTM Journal of Composites Technology Research 1987; 9(4): 141-150.

[6] Macander A B, Crane R M, Camponeschi E T, Jr. Fabrication and mechanical properties of multidimensionally (X-D) braided composite materials. Seventh Conference of Composite Materials Testing and Design. 1986; 422-443.

[7] Ko F K, Hartman D. Impact behavior on 2-D and 3-D glass/epoxy composites. SAMPE Journal 1986; 22(4): 26-30.

[8] Sun H Y. RTM process and mechanical properties of 3D braided composite materials. Journal of Materials Engineering 1998(5): 34-40. [in Chinese]

[9] Wu E, Wang J. Behavior of stitched laminates under in-plane tensile and transverse impact loading. Journal of Composite Materials 1995; 29(17): 2254-2279.

[10] Liu Z G. Concept of three-dimensional full five-direction braided preforms. Journal of Materials Engineering 2008 (Supplement): 305-308. [in Chinese]

[11] Yang C K. Experimental investigation on mechanical properties of 3-D braided composites. Journal of Materials Engineering 2002(7): 33-35, 39. [in Chinese]

[12] Lu Z X, Feng Z H, Kou C H. Studies on tensile properties of braided structural composite materials. Acta Materiae Compositae Sinica 1999; 16(3): 129-134. [in Chinese]

[13] Chen L, Liang Z Q, Ma Z J. Experimental investigation on longitudinal properties of 3-D 5-directional braided composites. Journal of Materials Engineering 2005(8): 3-6. [in Chinese]

[14] Tarnopolškii Y M, Roze A V, Portnoy G G. Some negative characteristics of fiber-reinforced materials. Polymer Mechanics 1969; 5(1): 115-123.

[15] Tang Z X, Postle R. Mechanics of three-dimensional braided structures for composite materials. Composite Structures 2001; 51(4): 451-457.

[16] Wang Y G, Wang Y L. Preparation and mechanical properties of 3-D braided carbon composites. Journal of Materials Science & Engineering 2004; 22(3): 344-346. [in Chinese]

[17] Chen L. Experimental analysis on the yarn's section of three-dimensional five-directional braided composites. Acta Materiae Compositae Sinica 2007; 24(4): 128-132. [in Chinese]
[18] Xu K. Microstructure model of 3D 5-directional rectangular braided composites. Journal of Nanjing University of Aeronautics and Astronautics 2008;40(2): 168-173. [in Chinese]
[19] Lu Z X, Yang Z Y, Liu Z G. Geometrical characteristics of structural model for 3D braided composites. Journal of Beijing University of Aeronautics and Astronautics 2006; 32(1): 38-59. [in Chinese]
[20] Li D S, Chen L, Li J L. Microstructure analysis of 3-dimensional 5-directional braided composites. Journal of Tianjin Polytechnic University 2003; 22(6): 7-11. [in Chinese]

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