

Research on the Permeability of 3D Full Five-Directional Braided Preforms

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Abstract—Based on the micro-structure of the 3D full five-directional braided composites inner unit cell model and the dual-scale characteristics of braided preform porosity, this paper established a model for calculating the permeability of 3D full five-directional braided preforms. By applying periodic boundary condition, the axial and vertical filling processes of 3D full five-directional braided preforms are simulated using the two-phase model in Fluent, and the axial and vertical unsaturated permeability of the preforms with different braiding angles are obtained. The simulation results shows the regular pattern that how the permeability responds to the change of the braiding angle: the axial permeability of 3D full five-directional braided preform is larger than the vertical one, and with the increase of braiding angle the axial permeability increases while vertical one decreases. Furthermore, the permeability of preform is much larger than the permeability of fiber bundles, which leads that the macro speed of resin is much larger than the speed of infiltration. So the resin filling time should be extended to realize the completely infiltration of the fiber bundles.

Keywords-3D braiding; full five-directional preform; permeability; RTM; radial flow techniques

I. INTRODUCTION

As an a kind of advanced composite materials, 3D braided composites overcome the shortcoming of laminated composite materials that their performance interlayer is poor and improve the impact strength and damage tolerance, for their spatial interwoven fiber structure^[1,2]. Meanwhile, the 3D braided composites can play a role in the complex load conditions, because the fiber structure of 3D braided preforms is designable^[3]. In recent years, the composite structure parts produced by 3D braiding technology, have been applied widely in aerospace and other fields.

3D full five-directional braided composites are different with other kind of 3D braided composites in the microstructure. The former increase the proportion of axial

yarn which enhance the axial properties of the material, so that they can play a better role in the structure^[4].

Resin transfer molding(RTM) process is one of the most commonly used molding methods for 3D braided composites. RTM process has the advantages that it costs less, pollutes less and products with higher precision. But the RTM process may generate dry spots and other process defects^[5]. In order to reduce process defects, improve part quality, it is necessary to conduct a scientific design for the RTM filling program. The common approach is to simulate the RTM resin flow field inside the mold, find the locations of defects that may occur depending on the resin flow front, then improve the RTM filling program based on the locations^[6-8]. And obtaining the permeability parameters according to the microscopic structural characteristics is the basis of carrying out this task^[9,10]. But the experimental measurement of the permeability often requires a large number of carefully controlled experiments which cost much money and time. So it is necessary to find a way to conduct the numerical prediction of the permeability.

II. THEORETICAL BASIS

The resin flow process in the preform can be seen as a Newtonian fluid flow in porous media, that follow the Darcy's law^[11-13]:

$$\mathbf{V} = -\frac{\mathbf{K}}{\mu} \nabla P \quad (1)$$

Meanwhile, the resin flow satisfies the continuity equation:

$$\nabla \cdot \mathbf{V} = 0 \quad (2)$$

Where \mathbf{V} is the volume averaged velocity vector of the resin, μ is the Newtonian viscosity of fluid, ∇P is the pressure gradient vector, and \mathbf{K} is the permeability tensor of porous medium.

III. GEOMETRIC MODELING

Section and polish the 3D full five-directional braided composite with internal braiding angle of 45° which is braided with 12K carbon fibers, and enlarge 50 times in the optical microscope, then this can be see: the contact between yarns is intimate, the axial yarns cross-section is extruded into approximately square, the flat braiding yarns and the resin are distributed around the axial yarns periodically. The section macrophotograph of 3D full five-directional braided composites is shown in Fig. 1.



Figure 1. Section macrophotograph of 3D full five-directional braided composites

Because the internal microstructure of 3D full five-directional braided composites is cyclical, a unit cell model can show the microstructure characteristics. In order to facilitate the modelling process, this paper made the following assumptions:

- The braiding process remains stable.
- Because the effect of adjacent yarn extrusion, the cross-section of the internal braiding yarn remains hexagonal, and the cross-section shape remains unchanged along the yarn axis direction.
- Because the effect of adjacent yarn extrusion, the cross-section of the internal axial yarn remains square, and the cross-section area remains unchanged along the yarn axis direction.
- The adjacent fiber bundles are closely contact.
- The characteristics of all fiber bundles are same, and the fiber bundle is not distorted.

Thus, according to the section observations, and considering the other existing geometric models of 3D braided composites inner unit cell^[14-16], establish a geometric model of inner unit cell to calculate the permeability of the preform. The unit cell model is shown in Fig.2, and Fig.3-5 respectively represent the braiding yarns, axial yarns and resin.

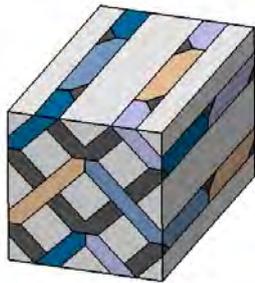


Figure 2. 3D full five-directional braided composites unit cell model

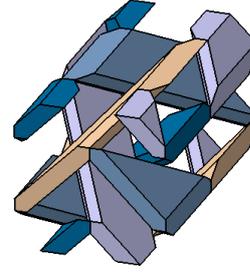


Figure 3. Braiding yarns of 3D full five-directional braided composites

unit cell model

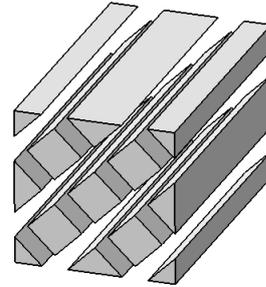


Figure 4. Axial yarns 3D full five-directional braided composites unit

cell model

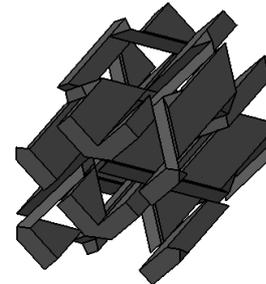


Figure 5. Resin of 3D full five-directional braided composites Unit cell

model

In this model, the packing fraction of the fiber bundle is set to 0.6. For Toray T700 carbon fiber which the composites are made of, the fiber filament diameter is 7 μ m, the unit cell specifications of different braiding angle is shown in Table 1. Where γ is the internal braiding angle, ϵ is the fiber bundle packing fraction, l is the length of a unit cell, w is the width of a unit cell, V_0 is the volume of the resin zone in a unit cell.

TABLE I. SPECIFICATIONS OF THE UNIT CELL MODELS

$\gamma/^\circ$	ϵ	l/mm	w/mm	V_0/mm^3
25	0.6	10.684	3.523	30.5
35	0.6	7.292	3.611	22.8
45	0.6	5.303	3.750	18.8

It can be seen from the internal microstructure of the 3D full five-directional braided preform that the pores

inter-fiber are in micron level while the pores inter-tow in millimeter level. When the fiber filament diameter is 7 μm and the fiber bundle packing fraction is 0.6, the axial permeability of the fiber bundles is approximately $4 \times 10^{-11} \text{m}^2$ and the vertical one is $4 \times 10^{-12} \text{m}^2$ ^[17].

IV. NUMERICAL SIMULATION

Because the scale difference of the pores inter-tow and inter-fiber, the velocities of resin flow inter-tow and inter-fiber are different^[18]. On the basis of whether the resin is completely infiltrate the fiber tow, permeability can be respectively defined as saturated or unsaturated one.

Meanwhile, due to the periodicity of the 3-D full five-directional braided composites microstructure, the macroscopic resin flow in the preform is symmetrical. Therefore, the one primary direction (the axial direction) of permeability is parallel to the axial yarns, the other two primary directions (the vertical directions) are perpendicular to each other and both perpendicular to the axial yarns. And the permeability of the two vertical directions are equal to each other.

Simulate the resin filling process in both axial and vertical directions of the unit cells with braiding angle with 25°, 35° and 45°. The resin inflows from one side of the unit cell and flows out from the opposite side at a constant volumetric flow rate during simulation, besides periodic boundary conditions are applied to the boundaries which are perpendicular to the flow direction. Considering the influence of capillary pressure, use the Fluent User-Defined Functions to set the capillary pressure at 400Pa which acting on the interface between the resin and air inside the fiber bundle and perpendicular to the interface pointing at the dry fiber region. Setting resin viscosity of 0.1Pa·s, density of 1200kg/m³. Initially, the unit cell is filled with air. For the unsaturated one-way resin flow, the following equation is obtained:

$$u = \frac{V_{fr}}{V_o} L \quad (3)$$

Where μ is apparent resin flow velocity, V_{fr} is resin volume flowing through the unit cell per second, L is the length of unit cell in the direction of resin flow.

On inserting (3) into (1), we obtain:

$$K = -\frac{V_{fr}}{V_o} \frac{L^2 \mu}{\Delta P} \quad (4)$$

Where K is unsaturated permeability, ΔP is the difference in pressure between the outlets and inlets.

The resin filling processes of unit cells are simulated using the two-phase model in Fluent. When the resin flows through the entire unit cell, record the volume flow rate and the pressure difference between the inlets and outlets. Then take the data into (4) and calculate the unsaturated permeability.

V. RESULTS AND DISCUSSION

Resin volume fraction contours of the unit cell section during the resin filling process are shown in Fig.6 and Fig.7. Those contours show that the resin flow into the unit cell, gradually fill the inter-tow region while only a little resin infiltrates the fiber bundles. The velocities of resin flow inter-tow and inter-fiber are different, because the scale difference of the pores inter-tow and inter-fiber.

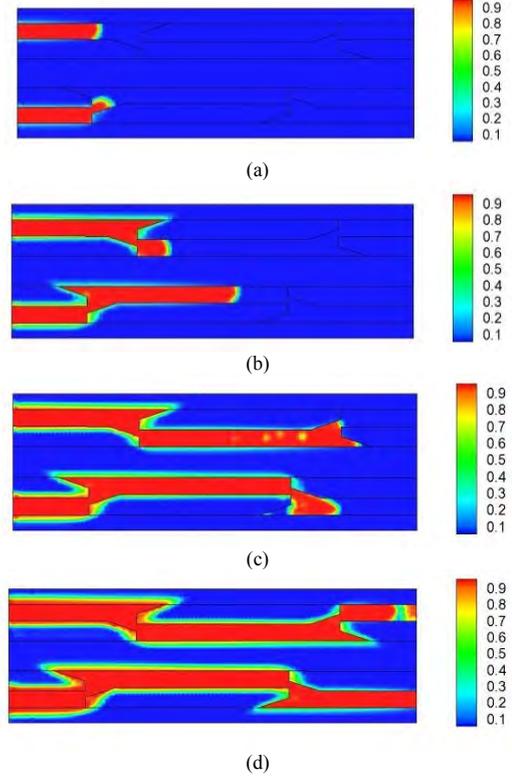


Figure 6. Volume fraction contours of the axial filling process

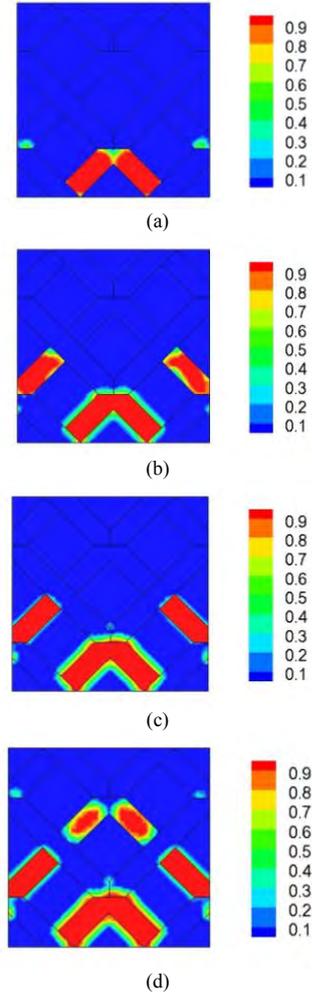


Figure 7. Volume fraction contours of the vertical filling process

Fig.8 shows the vertical permeability calculation results of the preforms with different braiding angles and Fig.9 shows the axial permeability calculation results.

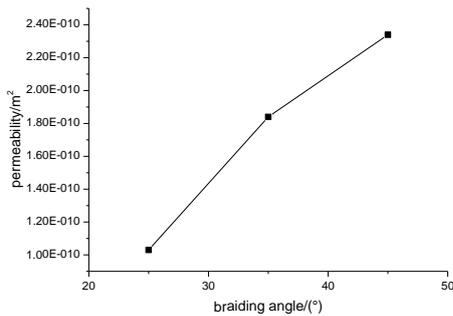


Figure 8. Vertical permeability with different braiding angles

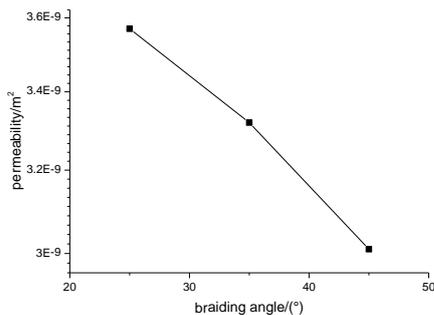


Figure 9. Axial permeability with different braiding angles

Calculation results show that the axial permeability of 3D full five-directional braided preform is larger than the vertical one, and with the increase of braiding angle the axial permeability increases while vertical one decreases. The reason for this may be that the shape of resin region is different for the preforms with different braiding angle and the flow channel changes with the shape of resin region. So when designing RTM process, it is important to make the resin flow along the axial fiber bundle as much as possible. And the dry spot defects may generate where the vertical resin flow happens.

Furthermore, the calculation results show that the permeability of preform is much larger than the permeability of fiber bundles, which leads that the macro speed of resin is much larger than the speed of infiltration. And when resin has been through the whole unit cell, only a little of the fiber bundle is infiltrated by resin. So in order to realize the completely infiltration of fiber bundles, the resin filling time should be extended.

VI. SUMMARY AND CONCLUSIONS

Based on the unit cell model of 3D full five-directional braided composites and the dual-scale characteristic of the preform pores, a model for simulate the resin filling process is established. And by simulating the axial and vertical resin filling process, the permeability of the 3D full five-directional braided preform with different braiding angles is obtained. Thus, the regular pattern that how the permeability responds to the change of the braiding angle is shown. At the same time, because the

permeability of preform is much larger than the one of fiber bundles, the process of resin infiltrating the fiber bundles is much slower than the resin macroscopic flow in the preform. Combined with the volume fraction contours of filling process, it is known that the resin filling time should be extended to realize the completely infiltration of the fiber bundles.

REFERENCES

- [1] Shen J, Xie H Q. Development of research and application of the advanced composite materials in the aerospace engineering[J]. *Materials Science and Technology*, 2008, 16(5): 737-740. (in Chinese)
- [2] Du S Y. Advanced composite materials and aerospace engineering[J]. *Acta Materiae Compositae Sinica*, 2007, 24(1): 1-12. (in Chinese)
- [3] Lu Z X, Yang Z Y, Li Z P. Development of investigation into mechanical behavior of three dimensional braded composites[J]. *Acta Materiae Compositae Sinica*, 2004, 21(2): 1-7. (in Chinese)
- [4] Liu Z G. Concept of three-dimensional all five-directional braided preforms[J]. *Journal of Materials Engineering*, 2008, (z1): 305-312. (in Chinese)
- [5] Qi Y Y, Liu Y Q, Zhang Y J. The research develop-ment of major defects in RTM process[J]. *Engineering Plastic Application*, 2006, 34(12): 72-75. (in Chinese)
- [6] Dai H F, Zhang B M, Du S Y, Wu Z J. Simulation of mould-filling in RTM process for 3D complex shape thin shell parts[J]. *Acta Materiae Compositae Sinica*, 2004, 21(2): 87-91. (in Chinese)
- [7] Li H C, Wang B, Zhou Z G. Numerical simulation of resin flow during multiple port injection process in resin transfer molding[J]. *Engineering Mechanics*, 2002, 19(2): 119-124. (in Chinese)
- [8] Qin W, Li H C, Zhang Z Q, Wu X H. Comparison be-tween numerical simulation and experimental result of resin flow in RTM[J]. *Acta Materiae Compositae Sinica*, 2003, 20(4): 77-80. (in Chinese)
- [9] Dong S H, Wang C G, Jia Y X, Jiao X J. Research pro-gress on permeability of fiber composite preforms with structural dependence[J]. *Journal of Materials Engineering*, 2013, (5): 94-100. (in Chinese)
- [10] Li H C, Zhang M F, Wang B. Method on measuring fibre permeabilities in resin transfer molding[J]. *Journal of Aeronautical Materials*, 2001, 21(1): 51-54. (in Chinese)
- [11] Lam Y C, Joshi S C, Liu X L. Numerical simulation of the mould-filling process in resin-transfer moulding[J]. *Composites Science and Technology*, 2000, 60(6): 845-855.
- [12] Maier R S, Rohaly T F, Advani S G. A fast numerical method for isothermal resin transfer mold filling[J]. *International Journal for Numerical Methods in Engineering*, 1996, 39(8): 1405-1417.
- [13] L Tong, A P Mouritz, M K Bannster. 3D fiber reinforced polymer composites, 1st ed, vol 1. Oxford, 2008, pp.117-125.
- [14] Zhang F, Liu Z G, Wu Z, Tao G Q. A new scheme and microstructural model for 3D full 5-directional braided composites[J]. *Chinese Journal of Aeronautics*, 2010, 23(1): 61-67.
- [15] Zheng X T, Ye T Q. Microstructure analysis of 4-step three-dimensional braided composite[J]. *Chinese Journal of Aeronautics*, 2003, 16(3): 142-150.
- [16] Liu Z G, Zhang H G, Lu Z X, Li D S. Investigation on the thermal conductivity of 3-dimensional and 4-directional braided composites[J]. *Chinese Journal of Aeronautics*, 2007, 20(4): 327-331.
- [17] C DeValve, R Pitchumani. Simulation of void formation in liquid composite molding processes[J]. *Composites: Part A*, 2013, 51: 22-32.
- [18] Hua Tan, Krishna M Pillai. Multiscale modeling of unsaturated flow in dual-scale fiber preforms of liquid composite molding I: Isothermal flows[J]. *Composites: Part A*, 2012, 43: 1-13.