Sci Eng Compos Mater 19 (2012): 139–144 © 2012 by Walter de Gruyter • Berlin • Boston. DOI 10.1515/secm-2011-0121

Effect of shallow straight-joint braided fabric geometrical parameters on fiber volume fraction

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Abstract

This research paper establishes the relationship between fabric parameters and fiber volume fraction through analyzing the representative unit cell of the 2.5D shallow straight-joint preform. The effect of fabric parameters on the fiber volume fraction by theoretical study is also investigated. The 2.5D shallow straight-joint fabric was manufactured by quartz fiber to verify the fiber volume fraction by theoretical and experimental study. The errors between predicted and measured results is only 2.12% and 1.13%. It was also found that as warp density and linear yarn density of yarn decrease and fabric thickness increases, the overall fiber volume fraction and weft yarn fiber volume fraction increase, but warp yarn fiber volume fraction decreases. Weft yarn has greater influence on fiber volume fraction of fabric than warp yarn in the structure of shallow straight-joint.

Keywords: fabric parameter; fiber volume fraction; representative unit cell; 2.5D structure.

1. Introduction

Composites manufactured using textile techniques have received more attention in recent years, which is attributed to the ability of producing large volumes of textile preforms at a faster rate [1]. 2.5D (two-and-a-half-dimensional) braided composites have been identified as a class of material that have potential performance and manufacturing benefits compared to traditional 2D (two-dimensional) laminate composites for structural applications [2–6]. In this paper, shallow straight-joint braided structure is one type of 2.5D braided structure. 2.5D braided fabrics can be manufactured by a new technique, which combines a braiding and weaving process, reducing the manufacturing cost and cycle times. Owing to the characteristics of the 2.5D braided technique, 2.5D composites provide a unique opportunity of near-net-shape design and manufacturing of composite components, and thus minimize the need for cutting and joining parts [7]. The fiber volume fraction is an important parameter in designing composites, as it determines composite properties [8]. One of the aims in designing 2.5D fabric parameters is to meet the requirement of fiber volume fraction in engineering applications. Many parameters (e.g., fabric thickness, warp density and linear yarn densities of warp and weft yarn) are involved in determining the fiber volume fraction [9]. Hence, to fully realize influencing factors of the fiber volume fraction, it is important to understand these parameters.

The objectives of this work were to build the relationship between fabric geometry parameters and the fiber volume fraction through characterizing the unit cell geometry, and to study the effect of 2.5D shallow straight-joint braided parameters on the fiber volume fraction.

2. Fabric structure

2.5D braided fabrics are composed of warp, weft and sometimes binding yarns. Many variations in the geometry of 2.5D braided preforms are possible, depending on the number of weft threads interlaced, the pattern of repeat, and the presence of inlaid threads [10]. The fabric selected in this study was provided by Nanjing Institute of Glass Fiber (Figure 1C).

Figure 1 shows the 2.5D (shallow straight-joint) preform structure. This structure is a unique type of multilayer fabric. The preform is composed of layers of straight weft yarns and a set of sinusoidal warp yarns, with two layers of weft yarns interlaced together by warp yarns (Figure 1A,B). The preform is a symmetrical object. Firstly, the preform is symmetrical in the warp and weft directions with respect to their respective midplanes. Secondly, two adjacent layers of warp yarns are symmetric with respect to the symmetry center. This type of structure lowers manufacturing cost and shortens processing periods. In particular, this type of structure may be used to prepare dome-shaped components.

3. Unit cell geometry

Various researchers [11–15] developed different models to describe the microgeometry of 3D woven interlock composites at the unit cell level or representative volume element level. In this work, an appropriate representative unit cell (RUC) was chosen to describe the microgeometry of the 2.5D shallow straight-joint preform, and this approach of intercepting RUC is proposed [11, 16, 17].

Figure 2 shows the microstructure of the 2.5D shallow straight-joint structure and illustrates geometry parameters of the fabric and RUC. In this work, the unit cell is representative of one repeat of the 2.5D shallow straight-joint

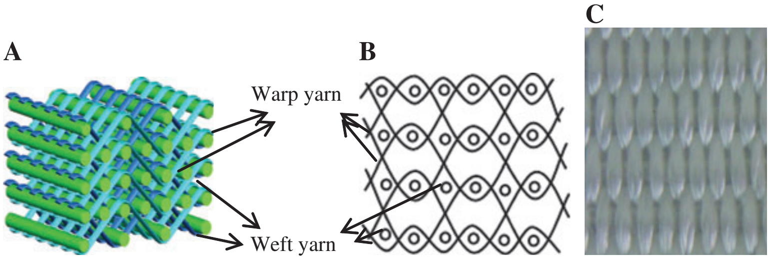


Figure 1 Photograph and structure of the 2.5D (shallow straight-joint) fabric. (A) Three-dimensional view of the fabric; (B) schematic diagram of the 2.5D shallow straight-joint fabric; (C) surface photography of the fabric.

architecture [18], and takes into account the actual geometry including the yarn cross-sectional area. It can be seen from Figure 2 that the spatial path of warp yarn is sinusoidal and the spatial path of weft yarn is straight, and the cross-sectional shape of weft yarn is lenticular and rhombus, respectively.

Figure 3 shows the front and side view of RUC. Many parameters involved in this work are depicted in picture and the 2.5D shallow straight-joint structure can be seen more clearly. The new modeling approach makes it easy to understand the fabric geometry, and accurate to calculate the fiber volume fraction.

Wu [11] categorized the geometric parameters of tow and preform into three groups: (i) input design and material parameters, also called manufacturer specified parameters; (ii) measurable parameters; and (iii) interim calculated parameters. The parameters involved in the description of geometric properties of the fabrics, modeling of yarns and preform, are listed in Tables 1 and 2, respectively, and illustrated in Figures 2 and 3, respectively.

4. Result and discussion

4.1. Fabric geometry parameters

4.1.1. Warp yarn The spatial path of warp yarn is sinusoidal [6], and the cross-sectional shape of warp yarn is rectangular (shown in Figure 4). The volume of warp yarn in RUC is calculated by Eq. (1).

$$U_w=L_w\times S_w \tag{1}$$

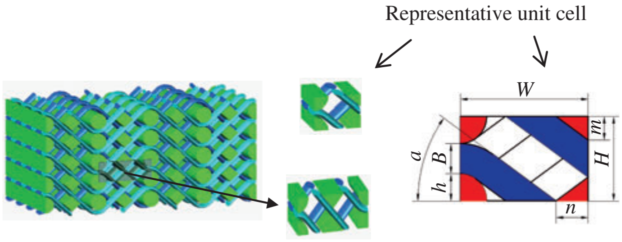


Figure 2 Microstructure of the 2.5D shallow straight-joint structure.

where L_w is the total length of warp yarn in RUC and S_w is the theoretical cross-sectional area of warp yarn. S_w can be calculated from manufacturer specifications data by Eq. (2) [11, 19].

$$S_w=B\times L=T_w\times 10^{-6}/\rho_w \tag{2}$$

4.1.2. Weft yarn Figure 5 shows the lenticular weft yarn cross-section. The spatial path of weft yarn A is straight, and the cross-sectional shape of weft yarn is lenticular.

Similarly, the volume of weft yarn in RUC and cross-sectional area of weft yarn A are given by Eqs. (3) and (4), respectively.

$$U_f=L_f\times S_f \tag{3}$$

$$\begin{aligned} S_f&=T_f\times 10^{-6}/\rho_f\\ &=2\times\arccos((R-H/2)/R)\times R^2-2\times R\times(R-H/2)\\ &\quad\times\sqrt{1-(R-H/2)^2/R^2} \end{aligned} \tag{4}$$

where L_f is the total length of weft yarn in RUC. L_f is given by Eq. (5):

$$L_f=2L \tag{5}$$

The spatial path of weft yarn B is straight, and the cross-sectional shape of weft yarn is rhombus (Figure 6). Thus, the cross-sectional area of weft yarn B can be calculated by:

$$S_f=4\times m\times p \tag{6}$$

Sizes of weft yarn are:

$$\tan\alpha=m/p \tag{7}$$

$$m=1/2\times\sqrt{S_f\tan\alpha} \tag{8}$$

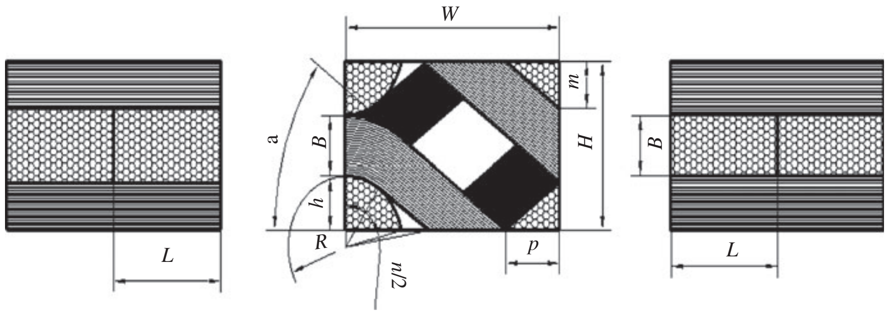
$$p=1/2\times\sqrt{S_f/\tan\alpha} \tag{9}$$

$$H=(K-C_w\times B)/(C_f) \tag{10}$$

$$n=2\times\arccos[(R-H/2)/R] \tag{11}$$

$$Q=2\times R\times\sin(n/2) \tag{12}$$

4.1.3. Representative unit cell Figure 2 shows a three-dimensional view of RUC. The volume of RUC can be calculated by Eq. (13):



Side view Front view Side view

Figure 3 Representative unit cell for the 2.5D shallow straight-joint structure.

$$U=2\times W\times L\times(2\times m+B/\cos\alpha) \tag{13}$$

where W is the length of RUC as depicted in Figure 3. W is calculated by Eq. (14):

$$W=B/\sin\alpha+(R-H/2)\times\tan\alpha+(R-(R-H/2)/\cos\alpha)/\sin\alpha)+(S_f/2\tan\alpha)^{1/2} \tag{14}$$

In RUC, the total length of warp yarn can be calculated by:

$$L_j=\frac{((S_w\times\tan\alpha)^{1/2}/2+B/2\cos\alpha)}{\sin\alpha}+\frac{(R\text{-(R-H/2)/cos}\alpha+B/2)}{\tan\alpha}+(R+B/2)\times\alpha \tag{15}$$

As the fabrics studied in this paper are composed of warp and weft yarns, we have

$$U_y=U_j+U_w \tag{16}$$

4.2. Relationship between fabric geometry parameters and fiber volume fraction

The relationship between fabric geometry parameters and the fiber volume fraction of warp and weft yarn in RUC can be calculated by Eqs. (17) and (18):

$$V_w=\frac{U_w}{U}\times100\%=\frac{L_w\times S_w}{2\times W\times L\times(2m+B/\cos\alpha)}\times100\% \tag{17}$$

$$V_f=\frac{U_f}{U}\times100\%=\frac{2\times L\times S_f}{2\times W\times L\times(2m+B/\cos\alpha)}\times100\%$$
$$=\frac{S_f}{W\times(2m+B/\cos\alpha)}\times100\% \tag{18}$$

The overall fiber volume fraction, V_y, is a very important parameter for manufacturers and users. Its value can be obtained from:

$$V_y=U_y/U\times100\% \tag{19}$$

which can also be calculated by total of fiber volume fraction of warp and weft yarn:

$$V_y=V_w+V_f \tag{20}$$

To check the accuracy, two fabrics of the 2.5D shallow straight-joint structure were provided by Nanjing Institute of Glass Fiber. The design parameters of the 2.5D shallow straight-joint structure preform in this paper, which is made up of quartz fibers, are listed in Table 3. The linear yarn densities of warp and weft yarn are both 195Tex×2 [9]. The numbers of warp and weft layers are 8 and 7, respectively. The

Table 1 Yarn parameters.

Input design and material parameters (manufacturer specified parameters)	
T_w, T_f	Tex no. of warp and weft yarns (g/km)
ρ_w, ρ_f	Density of warp and weft yarns (g/cm^3)
Measurable parameters	
B	Height of warp yarn
L	Width of warp yarn
H	Chord height of weft yarn A
Q	Chord length of weft yarn A
m, p	Diagonal of weft yarn B
Interim calculated parameters	
S_w, S_f	Cross-sectional area of warp and weft yarns
n	Central angle of weft yarn A
R	Radius of weft yarn A

Table 2 Preform parameters.

Input design and material parameters (manufacturer specified parameters)	
C_W, C_f	Number of warp and weft layers
P_w	Ends/cm per warp layer along fill direction
K	Preform thickness
ρ	Fiber density
Measurable parameters	
α	Fiber orientation angle
L_w, L_f	Length of warp and weft yarn in RUC
Interim calculated parameters	
U	Volume of RUC
U_y	Volume of all the yarns in RUC
U_w, U_f	Volume of warp and weft yarn in RUC

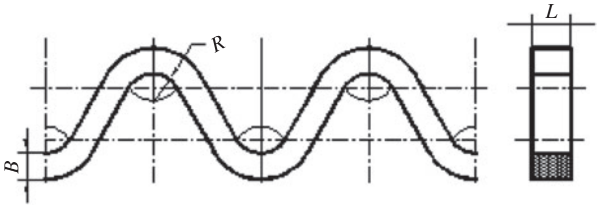


Figure 4 Schematic diagram of warp yarn.

calculated result of fiber volume fraction is 46.4%, which is calculated by MATLAB software (MathWorks, USA). However, the measured result can be obtained from:

$$\text{fiber volume fraction}=\frac{\text{weight of the fabric}}{\rho\times\text{volume of the fabric}}$$

The measured results are 47.5% and 47.9%, respectively. The errors between predicted and measured results are only 2.12% and 1.13%. Therefore, the prediction result is very close to the actual value and the proposed RUC can exactly describe inner yarn of the fabric. However, there are tiny differences between the prediction result and experimental result. One of the obvious reasons is that the twist of yarn is not taken into account when analyzing RUC of the fabric.

4.3. Effect of design parameters on fiber volume fraction

Figures 7–9 show the different influence factors on fiber volume fraction. From Figures 7–9, it can be seen that variations of weft yarn fiber volume fraction with parameters P_w, T and K are similar to fabric fiber volume fraction. However, variations of warp yarn fiber volume fraction with these parameters are approximately opposite to overall fiber volume fraction. Thus, we can deduce that weft yarn has greater influence on fiber volume fraction of fabric than warp yarn in structure of shallow straight-joint. Parameter α is one of important parameters to affect fiber volume fraction. In Figures 7–9, the overall fiber volume fraction is also increasing with increasing parameter α.

From Figure 3, it can be concluded that the width of warp yarn (L) has a direct relationship with warp density (P_w), as described in Eq. (21):

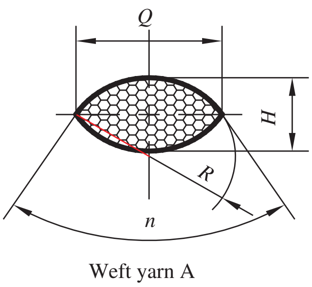


Figure 5 Lenticular weft yarn cross-section.

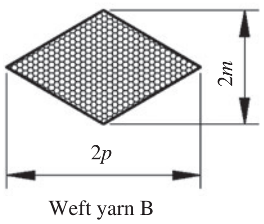


Figure 6 Rhombus weft yarn cross-section.

$$L=\frac{10}{P_w} \tag{21}$$

Hence, the variation of V_i (i=y, f, m) with design parameter P_w can be shown through width of warp yarn (L) (shown in Figure 7). In Figure 7, as the width of warp yarn increases with a decrease in P_w, fiber volume fraction of the fabric and warp yarn decrease and weft yarn fiber volume fraction increases. It can also be seen from Figure 7 that when L goes up to nearly 2 mm, that is to say, P_w decreases to 5 threads/cm, variation of fiber volume fraction is slowly and quasi-linearly. Thus, the decrease of P_w leads to the decrease of overall fiber volume fraction. The reason is that fabrics become more and more loosened when P_w is decreasing. Thus, fiber volume fraction of the RUC decreases and the overall fiber volume fraction also decrease.

Figure 8 shows the effect of linear density of yarn on the fiber volume fraction. As the linear density of yarn increases,

Table 3 Manufacturer specified parameters of the fabric used in this study.

T_w	ρ_w (g/cm^3)	C_w	P_w (ends/cm)	T_f	ρ_f (g/cm^3)	C_f	K (mm)
195×2	2.2	8	10	195×2	2.2	7	3.5

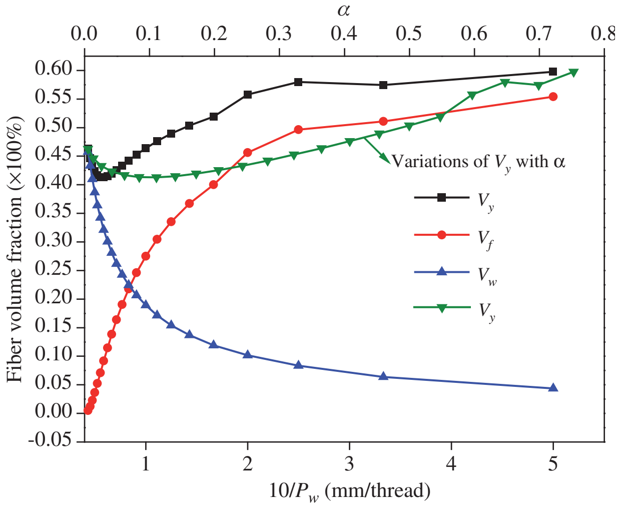


Figure 7 Effect of width of warp yarn on the fiber volume fraction.

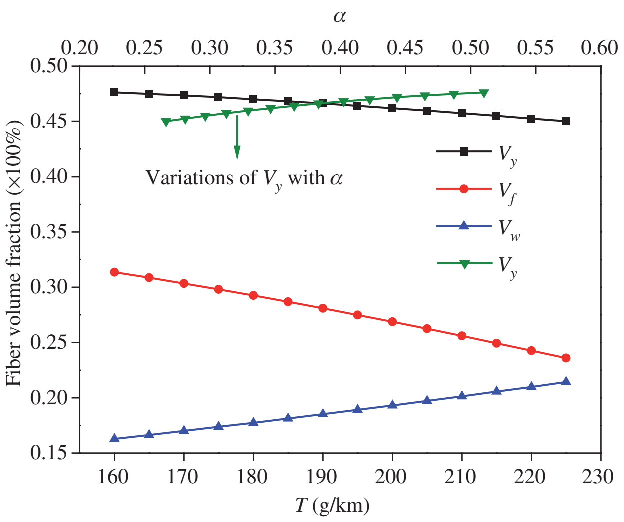


Figure 8 Effect of linear density of yarn on the fiber volume fraction.

overall fiber volume fraction and weft yarn fiber volume fraction predicted decrease quasi-nearly and warp yarn fiber volume fraction increases quasi-nearly. The reason for these variations is that as linear density of yarn increase and other geometric parameters remain constant [14], the thickness of warp yarn increases and the fabric becomes more and more loosened. Thus, the more loosen the fabric is, the lower the overall fiber volume fraction is.

Figure 9 describes the influencing factor K on fiber volume fraction. As the thickness of fabric increases and layers of warp yarn remain constant, overall fiber volume fraction increases as well as fiber volume fraction of weft yarn. From Figure 9, we can see that warp and weft yarn fiber volume fraction decrease when fabric thickness is approximately >3.5 mm. Hence, it can be concluded that reducing the thickness of fabric properly in less than a 3.5-mm region can contribute to increasing overall fiber volume fraction.

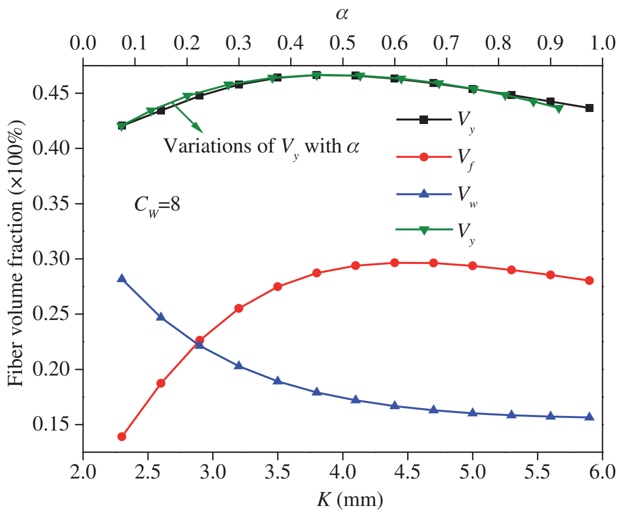


Figure 9 Effect of fabric thickness on the fiber volume fraction.

5. Conclusions

- A comparison of theoretical prediction and experimental results demonstrated the validity of the proposed RUC in predicting fiber volume fraction. However, there are tiny differences between prediction and experimental results. The errors are 2.12% and 1.13%. The reason is that the twist of yarn was not taken into account when analyzing RUC of the fabric.
- The fabric exhibits a rise in fiber volume fraction (both overall fiber volume fraction and weft yarn fiber volume fraction) with decreasing linear yarn density of yarn and warp density and increasing fabric thickness, a behavior that is opposite to that observed generally in the case of warp yarn fiber volume fraction. Weft yarn has greater influence on fiber volume fraction of fabric than warp yarn in structure of shallow straight-joint. We can obtain a good result in fiber volume fraction when fabric thickness is in a 3.5-mm region and other geometric parameters remain constant. These can be attributed to meeting the requirement of fiber volume fraction in parameters designing 2.5D shallow straight-joint fabric.

Acknowledgments

The authors wish to thank the basic research project of Science and Technology of Jiangsu Province (No. BK2009002).

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