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Geometrical model of 3D layer-to-layer angle-interlock woven preforms with oblique structure

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Abstract
The original configuration of 3D layer-to-layer angle-interlock (LLA) woven fibers cannot be maintained during matrix impregnation and is unstable when the composite is subjected to loading. The fibers in the yarn are susceptible to lateral sliding, resulting in deformation of the textile geometry. The initial modulus of the composite in the warp direction is smaller and can be inconsistent owing to the unstable geometry of the fabric. A stable 3D layer-to-layer angle-interlock (SLLA) fabric was devised by constructing a denser yarn arrangement, and the properties of this new structure were investigated in this study. The geometric parameters of this novel reinforcing structure were mathematically modeled, and the results were validated experimentally. The results showed that the SLLA structure was more stable than that of the LLA fabric. The experimentally determined structural parameters were in good agreement with the theoretically calculated values.

1. Introduction

Fiber-reinforced materials have been widely used in many fields, such as aerospace and transportation, as they are lightweight with high specific strength [1, 2]. Studies on structural textile composites have shown that they can replace metal materials in many fields owing to their excellent delamination resistance and high damage-tolerance [3, 4]. As one reinforced structure, 3D layer-to-layer angle-interlock (LLA) woven fabric has demonstrated higher interlaminar fracture toughness, high shear stiffness, and high damage-tolerance compared to 2D laminated composites because the binder used in this materials contains fibers in the thickness direction [5, 6]. Moreover, the manufacturing processes are highly automated and the cost is low [7]. 3D LLA fabric composites are better choices for specific structural components such as rocket nozzles and composite helmets [8], owing to their higher designability and lower manufacturing cost compared to those of 3D braided composites [9].

The relationship between the structure of the 3D angle-interlock fabric and the properties of the composites has been studied using prediction models and experiments. Li et al [10] presented a finite-element model based on the actual microstructure of 3D angle-interlock composites to predict the mesoscale mechanical response and effective elastic properties. Dau [11] and Ren [12] experimentally evaluated the in-plane and out-of-plane elastic properties of 3D angle-interlock composites. The compressive strength in the warp direction was found to be low owing to the waviness of the yarn in the thickness direction. Zheng et al [13] proposed a micro-unit model for analyzing the structure of woven composites, which reflects the fluctuation and deformation of the yarns. Guan et al [14] investigated the influence of the structural parameters of the yarn on the in-plane shear properties of 3D LLA woven fabrics during bias extension. The linear density of the yarn and number of yarn layers in the fabric were found to have a significant influence on the in-plane shear properties. Zhao et al [15] prepared angle-interlock woven composites and studied the influence of the fabric structure on the thermal conductivity of braided composites. Sun et al [16] fabricated different types of 3D angle-interlock fabrics.
Experimental study of the performance of the fabrics showed that the fabric density has a significant influence on the mechanical properties of the 3D angle interlock fabric.

However, it has been observed that the original configuration of the 3D LLA woven fabric cannot be maintained during impregnation due to sliding of the weft yarn, as shown in figure 1 [7]. Dai et al also suggested that changing the fabric geometry is more effective for improving the compressive strength than increasing the fiber volume fraction [17]. Moreover, the configuration is unstable when the composite is loaded, which compromises the deformation resistance of the fiber-reinforced composites. This instability limits the application of 3D LLA woven fabric, especially in the production of thick-wall preforms. Thus, 3D LLA woven fabric with a stable geometric configuration is required.

This study aims to explore the origin of the instability in the 3D LLA woven configuration using a mathematical model. Based on this analysis, a novel 3D woven fabric with a stable structure is developed. The effects of the weave parameters on the deformation behavior of the fabrics are evaluated using a prediction model. In addition, a 3D LLA structure and 3D SLLA structure are prepared to verify the results of the theoretical analysis. Accordingly, the results for the two fabrics are discussed and compared.

2. Analysis of geometric stability of 3D LLA preform

3D LLA woven fabric is the most widely used material in the composite industry because such weaving structures are readily processed using a traditional dobby loom or a Jacquard loom. The 3D LLA woven fabric consists of warp and weft yarns. The microstructures of the 3D LLA woven fabrics are shown in figure 2. The weft yarn path is slightly straight, whereas the path of the warp yarn is sinusoidal. Two layers of weft yarn are interlaced by warp yarns. This highly symmetrical structure reduces production costs and shortens the processing period. However, it has been reported that the fiber architecture of the 3D LLA preform is limited because the original configuration cannot be maintained during matrix impregnation and is unstable when the composite is loaded.

In the 3D LLA woven preform, the warp yarns are interlaced through different layers of the weft yarns, as shown in figure 3. The weft yarns are nearly straight, with no interlacements. The warp yarns form zigzag patterns in the thickness direction; thus, they bend at cross-over points. In the figure, \( \alpha \) represents the bending angle (also known as the crimp angle) depending on the number of layers the warp passes through and the arrangement of the weft yarns.
The outer surface of the warp yarn is pulled and the inner surface is pressed. Within the range of elastic deformation, the stress on the warp yarn increases as the curvature of the yarn increases.

The elongation percentage $\xi$ outside the warp yarn can be expressed as [18]:

$$\xi = \frac{L_{out} - L_{in}}{L_{in}} \times 100\%$$

$$\xi = \left(\frac{R + A}{R} - \frac{R}{R} \frac{\pi - \alpha}{\alpha}\right) \times 100\% = \frac{A}{R}$$

(1)

where $A$ is the width of the warp yarn cross-section, $R$ is the radius of the weft; $\alpha$ is the bending angle; $L_{out}$ and $L_{in}$ are the inner and outer arc lengths of the warp yarn at the cross-over point, respectively, as shown in figure 4.

The tensile stress $\sigma$ is obtained as:

$$\sigma = E \times \xi = E \times \frac{A}{R}$$

(2)

where, $E$ is the tensile modulus of the yarn.

The elongation percentage $\xi$ of the warp yarn and tensile stress decrease with increasing bending angle. Therefore, a specially designed structure for a layer-to-layer angle-interlock preform was developed to enhance the compressive deformation resistance by increasing the bending angle.

3. 3D SLLA woven preform

Figure 5 shows the microstructure of the stable layer-to-layer angle-interlock (SLLA) woven preform proposed in this study. In the 3D SLLA preform, which is different from the traditional 3D LLA, the weft yarns are arranged in oblique lines, resulting in a dense structure with potentially greater stability and compressive deformation resistance. The oblique lines of the SLLA were formed by the oblique arrangement of the warp system.

The bending angle $\alpha_{wt}$ can be defined as follows:

$$\alpha_{wt} = \pi - (\beta - \delta) - \theta$$

(3)
where $\beta$ is the angle between the two sides of the unit cell, $\delta$ is the angle between the side of the unit cell and the warp yarn, and $\theta$ is the angle between the straight part of the warp yarn and the fabric plane.

Figure 6 shows a front view of the unit cell. Some geometric parameters considered in this study are depicted in the figure, and the 3D SLLA structure can be observed more clearly.

### 3.1. Mathematical model of 3D SLLA woven preform

The following assumptions are made for formulation of the problem:

1. The yarn is untwisted and is regarded as a linear elastic material.
2. The cross-sections of the warp yarns are rectangular. Along the direction of the preform length, the axis of the warp yarn is a curve consisting of a straight line and an arc.
3. The cross-sections of weft yarns are rhomboid. Along the direction of the preform width, the axis of the weft yarn is a straight line.

Figure 7 shows the front and side views of the unit cell, where $2d$, $D$, and $B$ represent the width, length, and thickness of the unit cell, respectively. The relationship between the warp and weft yarns was determined from $\beta$ to $\varphi$. The dotted line in the figure represents the centerline of the warp yarn. The warp yarn consisted of a straight line and a circular arc, where $\varphi$ denotes the central angle of the arc; $\theta$ is the angle between the straight part of the warp yarn and fabric plane; $\delta$ is the angle between the side of the unit cell and the warp yarn. The angle between the dividing line of the arc, the straight line, and the side of the unit cell is $\gamma$. Here, $\beta$ is the interior angle of the unit cell ($\beta < 90^\circ$).

According to the position of each yarn in the unit cell, the angles in figure 7 can be defined using the following formulas:

\[
\begin{align*}
\sin \beta &= \frac{(r + A)}{d} \\
\cos \gamma &= \frac{(2r + A)}{d} \\
\cos \delta &= \frac{A}{d} \\
\sin(\beta - \delta) &= \frac{2(r + A)}{D} \\
\sin \theta &= \frac{2(2r + A)}{D} \\
\theta &= \frac{\pi}{2} - (\beta + \gamma) \\
\varphi &= \theta + \beta - \delta
\end{align*}
\]  

The cross-section of the weft yarn is shown in figure 8.
The area of the cross-section of the weft yarn $Q_d$ is expressed as:

$$ Q_d = 3r^2 \sin(\theta + \beta - \delta) + (\theta + \beta - \delta)r^2 $$

(5)

The cross-section of the warp yarn is shown in figure 9.

The area of the cross-section of the warp yarn $Q_l$ is expressed as:

$$ Q_l = AB = mB^2 $$

(6)

where $m$ is the deformation coefficient of the warp yarn ($m = A/B$).

Based on the geometry derived above, the length of the warp yarn, $L_1$, in the unit cell is obtained as follows:

$$ L_1 = \left( r + \frac{A}{2} \right) \left( 2\varphi + 2 \cot(\beta - \delta) - \cot \theta + \tan \gamma \right) $$

$$ + A \times \cot(\beta - \delta) + d \times \cos \delta + 2d \times \frac{\sin \beta}{\sin \theta} $$

(7)

The length of the waft yarn, $L_d$, in the unit cell is given by:

$$ L_d = 2B $$

(8)

As the fabrics investigated in this study are composed of warp and weft yarns, the volume of yarn, $V_f$, in the unit cell is obtained as follows:

$$ V_f = L_1 Q_l + L_d Q_d $$

(9)

The volume of fiber, $V_f$, in the unit cell can be derived as:

$$ V_f = \lambda V_f $$

(10)

where $\lambda$ is the yarn packing factor, which is determined by the fiber architecture and ranges from $\pi/2$ to $\sqrt{3}/6$.

The fiber volume fraction, $V_f$, in the unit cell is derived as:

$$ V = \frac{V_f}{V_E} \times 100\% $$

(11)

where the volume of the unit cell, $V_E$, is defined as:

$$ V_E = 2D(r + A)B $$

(12)

### 3.2. Influence of yarn parameters on structure of 3D SLLA preform

It is known from the above analysis that the fiber volume fraction, $V_f$, bending angle of the warp yarn, $\alpha$, and unit inclination angle, $\beta$, are basic modeling parameters of 3D SLLA preforms.

In fiber-reinforced composites, stresses are mainly carried by the fibers. Therefore, the higher the $V_f$, the higher the strength of the composites. As seen from equations (1) and (2), the smaller the bending angle $\alpha$, the
higher the elongation percentage of the warp yarn, the higher the stress on the yarn, and the more unstable the structure. The unit inclination angle, \( \beta \), affects the slip of the weft yarn. Figure 10 shows preform units with different values of \( \beta \). As shown in the figure, the smaller the value of \( \beta \), the higher the warp volume fraction in the unit. The warp and weft form an interlocking structure. The higher the warp density, the more stable the structure.

To investigate how the linear density of the yarn affects the mechanical properties and shape retention of the 3D SLLA fabric, septuple- and triple-ply yarns were used as the weft and warp, respectively, to make fabrics. The thickness \( (B) \) of the unit cell was set to 1 mm.

The fiber volume fraction \( V_f \) decreased with an increase in the linear density of the yarn (figure 11(a)). As demonstrated in figure 11, the fiber volume fraction decreased non-linearly with an increase in the linear density of the yarn. The linear density of the fiber increased by 1.7%, and the volume fraction of the fiber decreased by 0.05%. As the linear density of the yarn increased, the bending angle \( \alpha \) increased, as shown in figure 11(b). The inclination angle \( \beta \) of the unit cell increased with an increase in the linear density of the yarn (figure 11(c)). Figure 12 shows the relationship between the geometric parameters of the preform and deformation coefficient of the warp yarn. With an increase in the deformation coefficient, the fiber volume fraction \( V_f \) increased (figure 12(a)). The bending angle \( \alpha \) and inclination angle \( \beta \) also increased with an increase in the deformation coefficient (figures 12(b) and (c)).

4. Experiment

4.1. Specimen preparation

In traditional LLA weaving (figure 13), two sets of yarns, perpendicular to each other, interlace to form a fabric. The set of yarns that runs lengthwise along the weaving machine direction is called the warp. The new structure proposed in this study is produced by a process similar to that of the traditional angle interlock structure, involving shedding, weft insertion, and beat-up. As shown in figures 14(a), (b), the difference between the SLLA and LLA is that in the former, the warp is arranged in a parallelogram rather than a rectangle. In the cross-section of the warp direction, the circular shape is the weft yarn, and the wavy shape is the warp yarn. In the cross-section of the warp direction, the circular shape is the weft yarn, and the wavy shape is the warp yarn. Figure 14(b) is the same as (a), except that the cross-sectional shape of the yarn is different.

To validate the theoretical analysis, an SLLA preform (figure 15) was fabricated. The experimental specimens were fabricated using quartz fibers with an epoxy resin matrix (BP-251) using vacuum-assisted resin transfer molding (VARTM), as shown in figure 16. The linear densities of the warp and weft yarns were 190 tex \( \times \) 4 ply and 190 tex \( \times \) 7 ply, respectively. The numbers of warp and weft layers were 35 and 36, respectively. The traditional LLA preform was manufactured by Sinoma Science & Technology Co., Ltd. The size (length \( \times \) width \( \times \) thickness) of each sample was 200 \( \times \) 200 \( \times \) 30 mm\(^3\). The pitch was 3.75 and 4.28 mm, respectively.

5. Results and discussion

The following conclusions were obtained through the experiments and observations of the specimens:

The fiber volume fractions of the LLA and SLLA preforms were measured by the weighing method, and the following relationship was applied:

\[
\text{fiber volume fraction} = \frac{\text{weight of the fabric}}{\text{density of yarns} \times \text{volume of the fabric}}
\]

The fiber volume fractions obtained using the weighing method for LLA and SLLA were 47.25% and 47.50%, respectively. The predicted values calculated using equation (11) were 44.24 and 45.31%, respectively. The theoretically calculated fiber volume fraction of LLA and SLLA differed from the results obtained using the
weighing method by 3.01% and 2.19%, respectively. This discrepancy arises because the crimp-due yarn interlacement was not considered in the theoretical calculation of the fiber volume fraction.

The angle between the two sides ($\beta$) of the unit cell in the 3D LLA preform is $90^\circ$. The weft yarns slid laterally, causing deformation of the textile geometry. In the 3D SLLA structure, the angle between the two sides was approximately $37.5^\circ$, and the structure was stable without obvious deformation. When the fiber volume fraction was 47.50%, the predicted value of $\beta$ was $38.06^\circ$, which differs from the measured result ($37.5^\circ$) by 1.49%.

The fiber volume fraction, $V_f$, decreased with an increase in the linear density of the yarn. A single yarn consists of many fiber bundles. The linear density of the yarn is the diameter of the fiber. The cross-sectional area of the same yarn type was constant. As the linear density increased, the diameter of the fibers increased, resulting in a decrease in the number of fibers in the yarn. The decrease in the fiber quantity in the yarn further led to a decrease in the fiber volume fraction in the preform.

Figure 11. Relationships between geometry parameters of preform and yarn linear density. (a) Fiber volume fraction; (b) bending angle of warp yarn; (c) inclination angle $\beta$ of unit cell.
6. Conclusions

The stability of the 3D LLA fabric structure was discussed in this study. A novel type of 3D woven fabric with an anti-deformation structure was proposed based on a mathematical model. The influence of the linear density of the yarn and deformation coefficient of the warp yarn on the structural parameters was revealed. Comparison of the experimental and theoretical prediction results shows that the proposed unit cell model is effective for calculating the structural parameters of the layer-to-layer angle-interlock fabric. Accordingly, several key conclusions can be drawn.

In the novel structure, with a 1.7% increase in the linear density of the yarn, the fabric fiber volume fraction decreased by 0.05%. Simultaneously, the warp bending angle, inclination angle, and side length of the unit cell

Figure 12. Relationships between geometric parameters of preform and deformation coefficient of warp yarn. (a) Fiber volume fraction; (b) bending angle of warp yarn; (c) inclination angle $\beta$ of unit cell.
increased with an increase in the linear yarn density. LLA and SLLA preforms were prepared and analyzed for comparison. The SLLA preform proposed in this study has a 0.35% higher fiber volume fraction than LLA with the same volume and material. The differences between the theoretically calculated and actual measured values of the fiber volume fraction were 3.01% and 2.19%, respectively. After curing, the LLA yarns showed slippage and structural deformation, whereas the structure of SLLA did not show significant changes. In a future study, we will produce a sufficient amount of fabric for different tests.

Figure 13. Schematic view of 3D weaving loom.

Figure 14. Schematic view of processing and mesoscopic view of LLA (a) and SLLA (b).

Figure 15. 3D LLA woven preform (a) and SLLA woven preform (b).
Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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