

MODELING THE FIBER SLIPPAGE DURING PREFORMING OF WOVEN FABRICS

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SUMMARY: In prediction of preforming shape for woven fabrics, the pin-jointed net model has the advantage of simple for using the geometric data only, and is a widely used method. However, it only deals with pure shear and neglects other possible deformation modes. In some cases, there is evidence showing that other deformation modes have certain relevance and effectiveness to the final forming shape. A model considering only the shear mode will not have an adequate prediction. In this study, a slippage model is developed to modify the pin-jointed net model. Macrostructure of the fabrics is included in the slippage model in order to capture more deformation modes. As in pin-jointed net model, the fabric is represented by a number of line segments, and four segments form a unit cell. The length of the unit cell of the fabric is allowed to change due to the slippage of the fiber yarn. Comparisons of experimental and simulation results are presented. As it can be seen that the numerical prediction using the slippage model has better agreement with experimental measurements.

KEYWORDS: resin transfer molding, fiber preform, woven fiber, molding

INTRODUCTION

In the fabrication of polymer composites, an important step is to homogeneously bring together the resin matrix and fiber reinforcements. Several manufacturing processes accomplish this step by injecting the fluid resin into the dry fiber reinforcements inside a closed cavity. Among these processes, resin transfer molding (RTM) and structural reaction injection molding (SRIM) are becoming increasingly popular because of their short cycle times, low labor requirements, and low equipment costs. In the RTM process, a fiber preform is cut into the desired shape and preplaced in the mold cavity using either automated process or hand lay-up. In forming the complex shape of the fiber preform, the configuration of the

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fiber mats should deform in order to conform to the mold surface. Several deformation modes may occur during a forming process. It can be characterized by factors such as the local surface curvature of the mold, the loading condition and the type of the reinforcements. For woven fabrics, the simple shear is considered as the major deformation mode in the forming process [1,13]. Pin-jointed net model is the most popular one among these methods. In this model the fabric is treated as a fisherman's net with yarns that have an infinite stiffness and crossover points that are fixed. The fabric is represented by a number of flexible line elements having fixed length and joints having three rotational degrees of freedom. This representative model implies that the only available mode of deformation is the in-plane shear (or trellising) and no relative slip occurs at the joints. Another approach to model the forming of fabrics was presented by Gelin *et al.* [12]. A finite element approximation considering the deformation energy is used. However, due to the highly dependence on the mechanical properties of the fiber, it is difficult to apply.

As stated above, the pin-jointed net model only deals with pure trellising (or shear) and neglects the other possible deformation modes. Bergsma[13] proposed that fiber deformation modes including fiber stretching, fiber straightening, shear slip, shear, and buckling can be observed during preforming. In some cases, there is evidence showing that deformation modes other than shear have certain relevance and effectiveness to the final forming shape. Neglecting these deformation modes from the simulation model will fail to have an adequate prediction. In this study, a slippage model is developed to modify the pin-jointed net model. Macrostructure of the fabrics is included in the slippage model in order to capture more deformation modes. Although the structural loading and mechanical properties of the fabrics are not taken into account in the slippage model, this geometrical approach has its benefits. No test on the mechanical property of the fabrics is needed for the performing simulation. Only some geometry properties of the undeformed fabrics must be measured beforehand. From the comparisons of experimental measurements and simulation, it has been shown that this model is simple and gives a satisfied fiber preforming prediction.

BASIC CONCEPTS

Most woven fabrics are basically two-dimensional. The shape of the yarn cross-section can be considered as an ellipse. The warp and weft yarns are woven together without adhesives. This allows the yarns to slip against each other. Generally, the motion of one yarn can be classified into three modes, as shown in Fig. 1. The rotation about the X-axis corresponds to the twisting mode, while bending and turning are the rotations about the Y and Z axes. Due to the two-dimensional assumption, the twisting mode is often neglected. The turning and bending modes are the main deformation modes of one yarn. For a preforming process, the turning mode is the major motion that results in fiber slippage.

For the turning mode, one yarn along the X-direction is considered first. The top view of a yarn is illustrated in Fig. 2. When the yarn is subjected to a force to turn an angle θ with respect to the pivot point P , one side of the yarn is under compression and the other side is under tension. If the intra-tow slippage is not allowed to occur, the two ends of the yarn will remain perpendicular to the neutral line, as shown in Fig. 2. Since the fiber is not extensible, filament on the side under tension will move away from its original location as shown in Fig. 2 in order to keep the length unchanged. These phenomena may cause the yarns to slip against each other and change the shape of the yarn cross-section. As discussed latter that

when the turning angle is larger than a critical angle, the filaments of a yarn start to aggregate and the width is reduced. As we shall see that the turning mode is related to the fiber slippage.

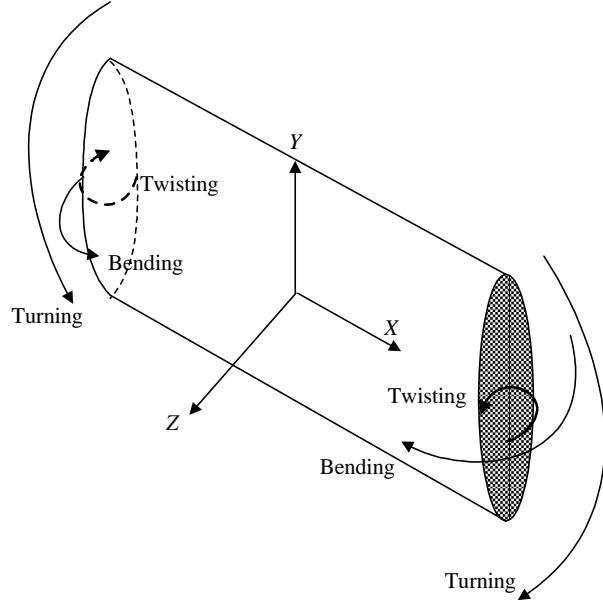


Fig. 1: Illustration of yarn deformation

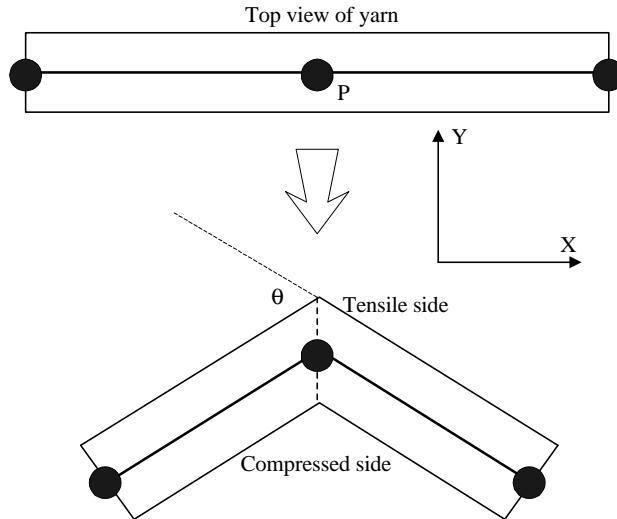


Fig. 2: Schematic of a yarn as it is turning

DESCRIPTION OF THE SLIPPAGE MODEL

In a woven roving fiber mat or a fiber cloth, the fiber yarns are woven together. Thus, each yarn goes as a weave form. From experimental observation, as a yarn is turning, the tensile side will be straightened first and the compressed side will be more undulated. When filament near the tensile side is straightened, its length is equal to the original length in undulated form. The straightened length of the filament can be approximated by a sinusoidal curve presented by McBride *et al.* [14]. Let the undulated length of a yarn segment in the unit cell be UL , such that

$$UL = S + \frac{h^2\pi^2}{16S} \quad (1)$$

where h is the undulated amplitude of the yarn and S is the yarn spacing. When a yarn is completely straightened, the length ratio per unit cell can be expressed as

$$LRc = 1 + \frac{h^2\pi^2}{16S^2} \quad (2)$$

For partially straightened, a factor k is introduced to represent the percentage of fiber straightening, and $k=1$ for fully straightened. The corresponding length ratio per unit cell is defined as:

$$LRp = 1 + k \cdot \frac{h^2\pi^2}{16S^2} \quad (3)$$

Since the fibers are restrained by each other within the tow, the intra-tow slippage is not likely to occur during the turning. As we keep on increasing the turning angle, the tensile side may be stretched and slip in the direction directing to the neutral line of the yarn. Obviously, the tensile side forms the main shape of the turning yarn. At the same time, the compressed side of the yarn will be more undulated or buckling. It is assumed that the tensile side is smooth and has a constant curvature. Let the radius of the tensile side be R and yarn width be equal to W . Furthermore, let the number of yarn segments included within this deformed region be $2 \cdot EN$. And EN represents one half of the effective number of yarn segments. From the configuration shown in Fig. 3, EN is approximated to be

$$EN \approx \frac{(R-W) \cdot \tan \frac{\theta}{2}}{S} \quad (4)$$

If the effects from the yarn along the Y -direction are neglected, only one half of the deformed yarn is taken into account by the assumption of symmetry. Also, let the boundary effect be ΔL and fiber stretching of the tensile side be $\Delta\epsilon$. The length balance Equ within $\theta/2$ can be expressed as

$$(R-W) \cdot \tan \frac{\theta}{2} + S \cdot (LRp - 1) \cdot EN - \frac{\Delta L}{2} + \Delta\epsilon = R \frac{\theta}{2} \quad (5)$$

where the boundary effect refers to the non-fixed condition in the two ends of the yarn. As shown in Fig. 3, if the woven force in the two ends of the yarn is not sufficient to fix the yarn, the yarn will slip against each other.

Usually, the fiber stretching is small compared to the other deformation modes and can be neglected. If the fiber preform is sufficiently large, the boundary effect ΔL can be neglected. It means that beyond the effective region the nodes are fixed without slippage. The length balance Equ within $\theta/2$ is then reduced to

$$(R - W) \cdot \tan \frac{\theta}{2} + S \cdot (LRp - 1) \cdot EN = R \frac{\theta}{2} \quad (6)$$

or

$$(R - W) \cdot \tan \frac{\theta}{2} \cdot LRp = R \frac{\theta}{2} \quad (7)$$

The radius of tensile side of the yarn, which comprises only one variable, θ , is found to be

$$R = \frac{W \cdot \tan \frac{\theta}{2} \cdot LRp}{\tan \frac{\theta}{2} \cdot LRp - \frac{\theta}{2}} \quad (8)$$

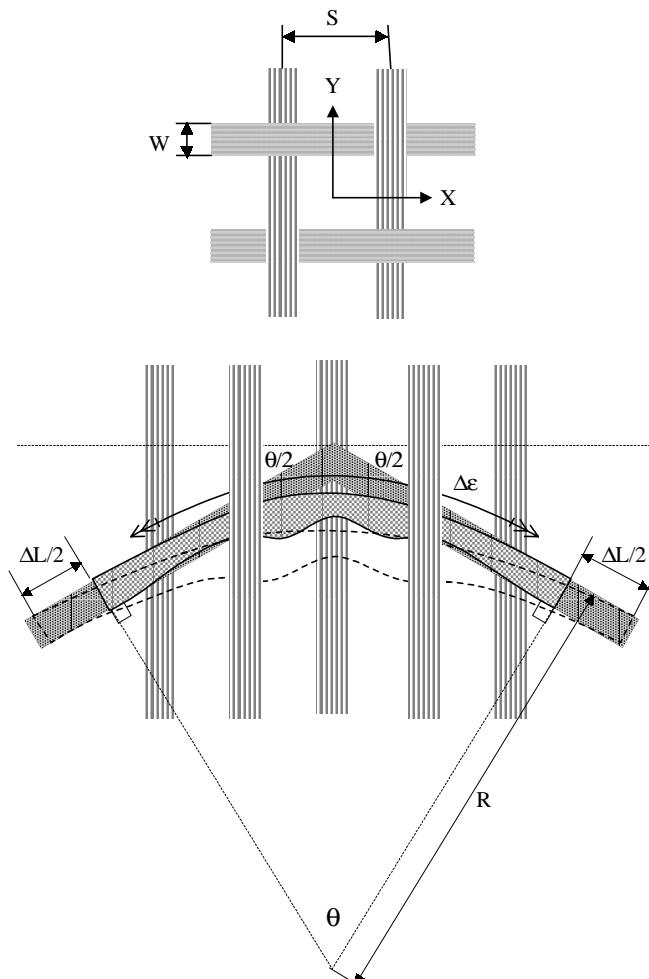


Fig. 3: Description of the slippage model

When the turning angle is approaching zero,

$$R|_{\theta \rightarrow 0} = W \cdot \left(1 + \frac{16S^2}{k \cdot h^2 \pi^2} \right) \quad (9)$$

If the fiber straightening is neglected (it corresponds to $k=0$ or $h=0$), Equs 8 and 9 are reduced to

$$\bar{R} = \frac{W \cdot \tan \frac{\theta}{2}}{\tan \frac{\theta}{2} - \frac{\theta}{2}} \quad (10)$$

and

$$\bar{R}|_{\theta \rightarrow 0} \rightarrow \infty \quad (11)$$

The tensile side of the yarn forms a part of a circle. The nodes within the effective region will slip to the new positions. The amount of slippage of each node is different as shown in Fig. 3. It means that turning at one node will affect the neighborhood. The effectiveness will vanish as far away from the turning point. For the bi-directional woven roving glass TGFW-600, the macrostructure of warp direction is listed in Table 1.

Table 1: Macrostructure of the bi-directional woven fabrics TGFW-600.

Property		Value
Industrial Reference		TGFW-600
Surface density (kg/m^2)		0.6
Density (kg/m^3)		2550
Warp direction	Yarn spacing (cm)	0.36286
	Yarn width (cm)	0.31
	Yarn thickness (cm)	0.03
Weft direction	Yarn spacing (cm)	0.42333
	Yarn width (cm)	0.31
	Yarn thickness (cm)	0.03

NUMERICAL IMPLEMENT

A circular shape is assumed for the tensile side of a yarn. The amount of slippage at each node due to the turning can be easily calculated from the deformed configuration. Although the pivot point is defined at the neutralization of the yarn instead of the tensile side, this small difference is neglected. The pin-jointed net model is used first to estimate the turning angle of each node in the preform. Assume that a finite element represented surface is used. A definition of \vec{N} , the normal vector of each point located on the represented surface, is given below.

$$\vec{N} = \frac{(\vec{v}_1 + \vec{v}_2 + \cdots + \vec{v}_m)}{m} \quad (12)$$

where \vec{v}_i is the normal vector of an element, $m=1$ for a point located within an element, $m=2$ for a point located on the boundary of two elements, and m is the number of the surrounding elements for a point located on a node.

From the plane constructed by the vector from $(i-1, j)$ to (i, j) and the mean vector of pivots $(i-1, j)$ and $(i+1, j)$, the turning angle is defined by the perpendicular distance D from $(i+1, j)$ to (i, j) , as shown in Fig. 4.

$$\theta = \sin^{-1}\left(\frac{D}{S}\right) \quad (13)$$

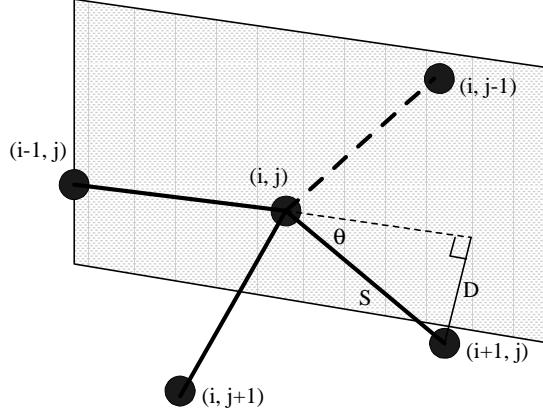


Fig. 4: Estimation of the turning angle

For every turning angle of a yarn, nodes affected by the turning will slip to new positions, and the displacements for each node must be determined. A step angle τ is introduced to define the position of the slipped node. Because of the circular shape assumption and the equal distance between adjacent pivots, the pivots within the arc should be equally separated. It implies the equal difference of slope between adjacent pivots. The step angle τ is defined as

$$\tau = \frac{\theta}{2EN} \quad (14)$$

If the effective number, EN , is not an integer, an amendment is proposed to maintain a total turning angle θ . For $n < EN \leq n + 1$, the distribution of the turning angles of the pivots within the effective region is

$$\left\{ \frac{\tau_b}{2}, \frac{\tau_b + \tau}{2}, \tau, \tau \cdots, \tau, \cdots \tau, \tau, \frac{\tau + \tau_b}{2}, \frac{\tau_b}{2} \right\} \quad (15)$$

where

$$\tau_b = (EN - \text{int}[EN]) \cdot \tau = \frac{\theta}{2EN} (EN - n) \quad (16)$$

Including the center pivot where slippage occurs first, there are $2n+3$ pivots within the effective region. It contains $2n-1$ of τ , two $(\tau_b + \tau)/2$, and two $\tau_b/2$ step angles. Total summation of turning angle is equal to θ . When n equals zero, the distribution is reduced to

$$\left\{ \frac{\tau_b}{2}, \tau_b, \frac{\tau_b}{2} \right\} \quad (17)$$

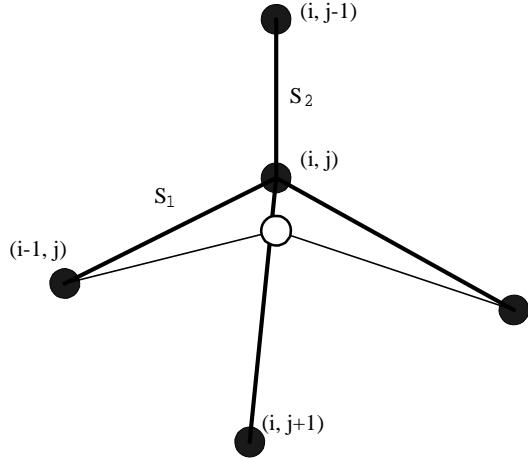


Fig. 5: The strategy of the fiber slippage

For a yarn to turn an angle θ , every pivot within the effective region has its own theoretical turning step angle. If the estimated turning angle calculated by the pin-jointed net model is less or more than the theoretical prediction, adjustment is done by either increasing or decreasing the yarn length. The turning angle at (i, j) is greater than the theoretical prediction, as shown in Fig. 5. The pivot (i, j) slips from the solid to hallow point by increasing the yarn length S_2 . The pivot (i, j) is unique determined by the pivots $(i-1, j)$ and $(i, j-1)$, and different yarn length will get different solution. Iterations are performed until the turning angle satisfies the theoretical prediction.

However, the model described in the above is only suitable for one turning angle without mutual coupling. To model the situations containing several turning angles with mutual coupling, it will be very difficult to find an analytical solution. The addition of step angles is an easy way to find an approximation of the forming shape. The method then can be applied step by step.

1. Use the pin-jointed net model to get the initial forming shape.
2. For each pivot point, estimate the turning angle θ by Equ 13, where θ can be applied into warp and weft directions.
3. Apply Equs 4, 8, and 14 to get R , EN , τ of each pivot.
4. Use the addition of step angles to get the new theoretical turning angle at each pivot.
5. Apply the slipping strategy shown in Fig. 5 to get the new position of every pivot by iterations.

EXAMPLE OF APPLICATION

The finite element mesh of an example is shown in Fig. 6. The simulation and experimental

forming shapes are presented in Fig. 7. From the comparisons of the forming shape, it is clear that the slippage model has a better prediction than the pin-jointed net model.

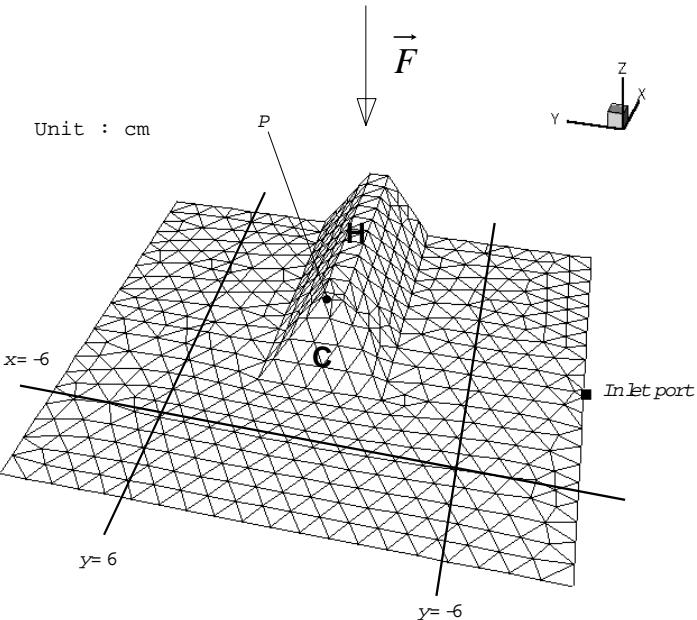


Fig. 6: FEM geometry of example of application

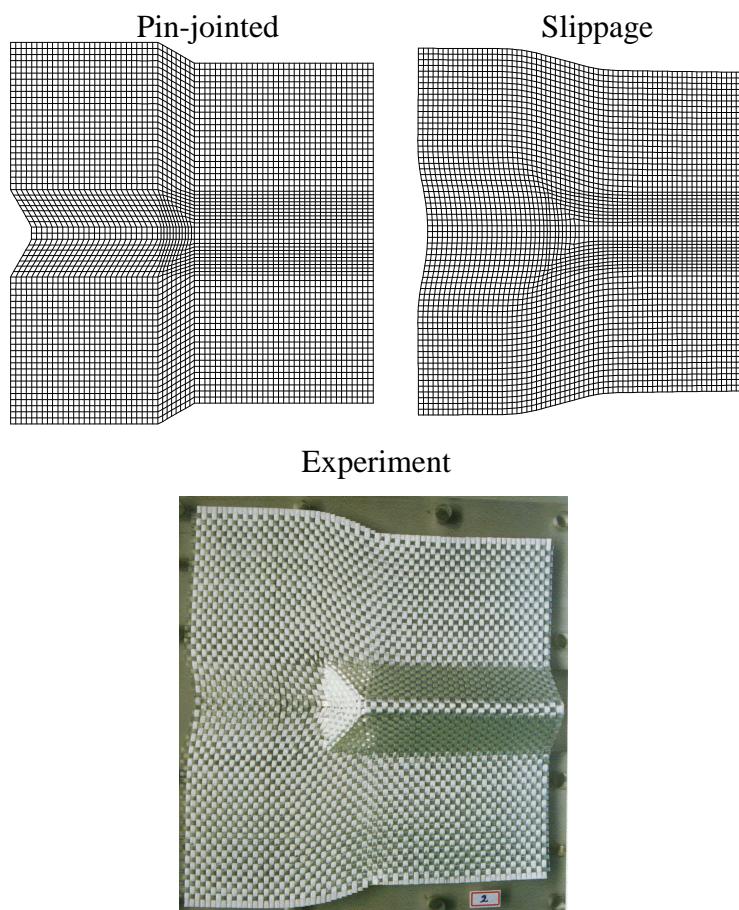


Fig. 7: Simulation and experimental forming shapes

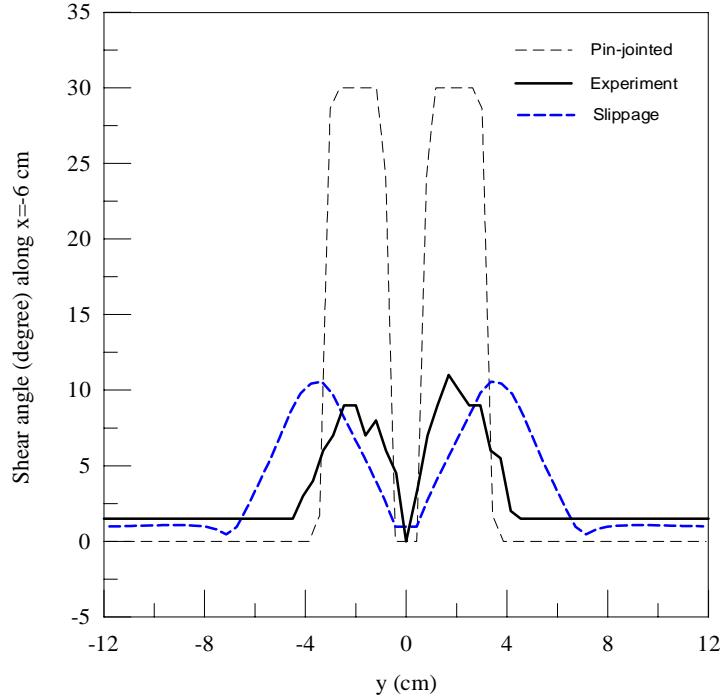


Fig.8: Comparison of shear angle along $x=-6$ cm

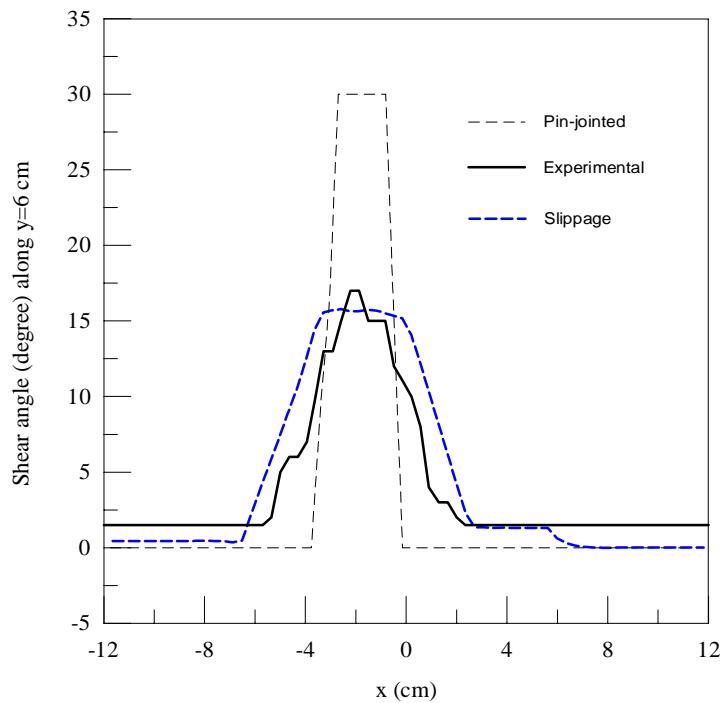


Fig. 9: Comparison of shear angle along $y=6$ or $y=-6$ cm

In addition, the comparisons of the pin-jointed net model, the slippage model, and experimental measurements are conducted at lines $x=-6$ and $y=\pm 6$ cm, provided in Figs. 8 and 9. The shear angle distribution of the slippage model is very close to the experimental measurements compared to the pin-jointed net model. This improvement is found to be quite acceptable. The distribution of shear angles at line $x=-6$ has been found to be more spread than the experimental results. It might be due to the assumption of addition of step angles. But the predictions at line $y=\pm 6$ seem to be in good agreement with experiment. Here, we may ask that what the shear angles in other places are. Up to now, there is still no comparison

method especially for preform shapes because of the difficulties to measure the shear angles at every locations. In the future, a quantitative analysis may be presented for shaping comparison. But now, the comparison of shear angles in our experiment is only performed in some special regions, i.e. lines $x=-6$ and $y=\pm 6$ cm.

Another example is the hemisphere shape with a diameter of 18.6 cm. A comparison along the diagonal direction is performed. Boundary effect is also discussed. For smaller size of fiber preform, the boundary effect is large, as shown in Fig. 10. When the size of fiber preform is enlarged, the distribution of shear angles is approaching the predictions of the slippage model. This slippage model is suitable for the fiber preform which is large enough. It is still difficult to estimate the boundary effect because of the numerous shape of fiber preform.

As we can see from Fig. 10, when the mold surface is smooth and has no sharp corner, the pin-joint net model is adequate. When there is any sharp corner, the induced angle change between adjacent unit cells may be too large. The pin-jointed net model is not appropriate in this case.

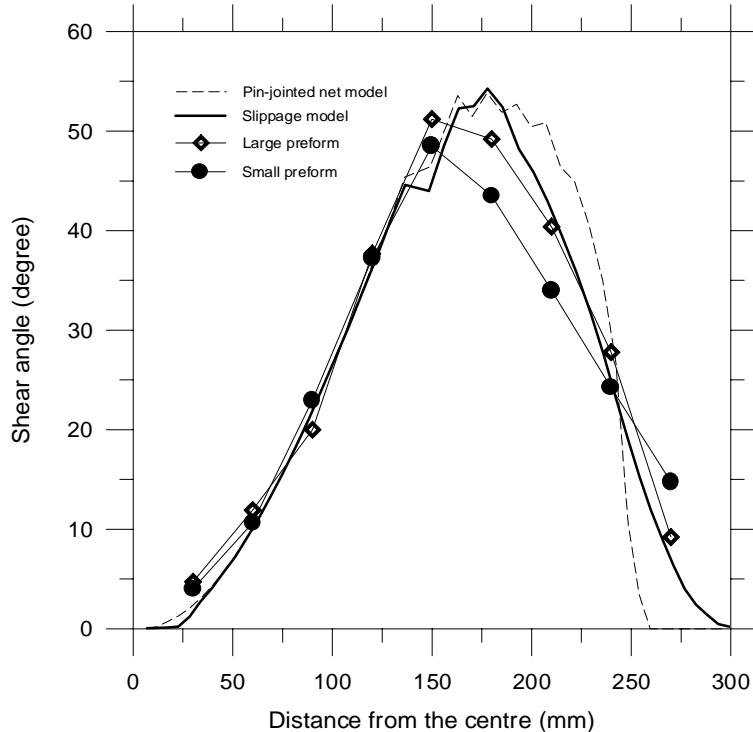


Fig. 10: Comparison of model prediction and experimental measurements along diagonal direction

CONCLUSIONS

A slippage model is developed to modify the pin-jointed net model. Macrostructure of the fabrics is considered in the present model in order to capture more deformation modes. In this study, no test on the mechanical property of the fabrics is needed for the performing simulation. Only some geometry properties of the undeformed fabrics must be measured beforehand. The turning model is used to characterize the fiber slippage. Comparisons of experimental results and simulation predictions are performed. It has been shown that better

predictions can be found when applying this slippage model. Fiber slip and shear deformation are found to be the main deformation modes which dominate most of the fiber deformations during preforming process. To have a more adequate preforming prediction, both fiber slip and shear must be considered into the forming calculations.

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