

# **Modélisation méso-macro du frottement entre les fils en tenant compte de l'architecture des tissus**

## ***Meso-macro modeling of yarn-to-yarn friction taking into account the fabric architecture***

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### **Résumé**

Le préformage est la première étape de la fabrication de pièces composites complexes par le biais du processus de moulage de composites liquides. À cette étape, les défauts susceptibles d'être rencontrés dans la structure de la préforme peuvent réduire les propriétés mécaniques attendues du produit final. Le comportement du frottement de contact entre les fils détermine en grande partie le comportement de déformation du tissu. Par conséquent, une compréhension approfondie du frottement entre les fils est cruciale pour comprendre et prédire les propriétés mécaniques des renforts textiles pendant le processus de moulage. Un modèle théorique méso-macro a été développé pour prédire les caractéristiques du frottement. Les résultats du modèle théorique sont très cohérents avec les résultats expérimentaux pour les structures unies et en sergé. On constate que la précontrainte du fil est un paramètre clé qui augmente le frottement dans l'architecture testée et qui affecte directement les performances de frottement du fil.

### **Abstract**

Preforming is the first step in manufacturing complex composite parts through the liquid composite molding process. At this step, defects in the preform structure may reduce the expected mechanical properties of the final product. The contact friction behavior between yarns determines the deformation behavior of the fabric. Therefore, an in-depth understanding of the friction between yarns is crucial to predict the mechanical properties of textile reinforcements during the molding process. A meso-macro theoretical model was developed to predict the friction characteristics. The result of the theoretical model is very consistent with the experimental plain and twill structures. It can be found that yarn pretension is a key parameter which increases friction in tested architecture and directly affects the yarn friction performance.

**Mots Clés :** Textile composites, Mise en forme, Architecture, Friction, Modélisation.

**Keywords:** Textile composite, Forming, Architecture, Friction, Modelling

## **1. Introduction**

Textile composites are increasingly utilized as structural materials in aerospace, automotive, and sports equipment industries due to their exceptional mechanical properties, including high specific strength, high specific modulus, and design flexibility. During the manufacturing of composite parts with complex geometries, such as in resin transfer molding (RTM) processes, the reinforcements are pre-formed prior to the resin injection phase[1, 2]. This preforming process subjects the reinforcement to significant local and global deformations. These deformations alter the fiber orientation and fiber volume fraction, which can seriously reduce the mechanical performance of the final product. When fabrics are punched, their structural deformation occurs across multiple scales. The macroscopic behavior of the material is influenced by the mesoscopic interactions between yarns (yarn-yarn) and the microscopic interactions between yarns (fiber-yarn). Yarn friction, particularly between warp and weft yarns, plays a pivotal role in determining the shear properties of fabrics and their formability during processes such as punch forming. In the past, research related to yarn friction has been conducted at different scales. Cornelissen et.al.[3] have developed a contact mechanics model for predicting friction between sliding tows, which considers the difference in friction behavior between perpendicular and nearly parallel relative tow directions. Wang et.al.[4] developed a micro-meso analytical model based on Cornelissen's study. The realistic contact area was modeled under micro/meso scales considering the contact angle between the yarns and the orientation of the fibers influenced by the twist. Vu proposed an anisotropic friction model to capture the effects of the yarn angle, normal force and capillary effect observed in the experiment.[5]

To optimize the forming process, better control parameters, tool design to avoid higher production costs, numerical simulation has been widely used to study the feasibility of fabric preforming. Gatouillat[6] proposed a geometric model where each yarn is represented using shell elements in contact-friction interaction with neighboring yarns, emphasizing the importance of simulating significant slippage between warp and weft yarns. However, yarn friction is inherently dynamic during the forming process, with frictional forces varying based on the contact area and deformation state. Taking the coefficient of friction as a constant oversimplifies the complex interaction dynamics between yarns, leading to incomplete and less accurate predictions of contact friction behavior. Therefore, it is necessary to conduct a special study on the friction behavior of the mesoscopic model of yarns in fabrics.

In this paper, the contact friction model between yarns is established based on the geometric model of plain and twill fabrics, and its accuracy is experimentally verified, and the effect of different pre-tensions on the friction force is considered.

## **2. Materials and methods**

### **2.1 Materials**

The fiber material utilized for the experimental investigation was high-molecular-weight polyethylene yarns (HMWPE, Spectra®) with a twist, supplied by Honeywell Company, USA. The fabric thread density is 6 per centimeter for both warp and weft. The linear density of the yarn is 135( $\pm 2.3$ ) tex. The yarn has a circular cross-section with a radius of 0.9 ( $\pm 0.1$ ) mm.

### **2.2 Experiment setup**

In order to analyze the friction mechanisms resulting from the movement of yarns with different structures, a characterization device has been created using 3D printer technology to study the influence of the interweaving environment on the friction behavior using a UMT Tribolab machine (Bruker, USA) equipped with a 10 N load sensor ( $\pm 0.5$  % F.S.). The sensor has an accuracy of 1 mN, which ensures that even minor changes in force are accurately detected. In this study, the upper fixture is connected to a mechanical sensor, while the lower fixture is fixed to a base and performs a linear reciprocating motion according to the user settings. The motor of the friction gauge drives the fixture to simulate yarn movement during the preform process and the mechanical sensor measures the friction force during the process. During sample loading, the yarn is initially fixed at one side of the fixture (upper/lower fixture), given a constant pre-tension, and fixed to the opposite side of the fixture. The pre-tensions with uniform distribution (UD) for warp yarn were selected to explore the evolution of friction behavior with LVDT (Linear Variable Differential Transformer). LVDT is measured by a differential transformer of Tribolab, which can characterize the linear displacement of yarn. LVDT has a precision of 1  $\mu$ m. The measuring range for displacement sensors was 0 to 120 mm, sufficient to capture the full range of motion during the tests. To ensure reliability and accuracy, each experiment was repeated multiple times. Specifically, a minimum of 5 tests were conducted for each configuration to account for variability and to provide statistically significant results.

### **2.3 Theoretical model**

Yarn sliding occurs relatively frequently when performing a woven reinforcement, the textile preform consists of two sets of orthogonal yarns interwoven together. As a result of this interlacing, inter-yarn friction is generated at the intersection area between the two yarn groups. In the geometric model, the initial yarn is assumed to be an elongated cylinder with uniform circular cross-sections. After deformation, the contact area between yarns increases. The transition from a cylindrical shape to one with a larger contact area is essential for understanding the frictional behavior during weaving. The Pierce geometric model can be used to mathematically describe the arrangement of yarns in a

fabric. The waviness in the warp ( $e_p$ ) and weft ( $e_t$ ) directions can be characterised by the following equations:

$$\begin{cases} e_p = \frac{2h_p}{d_p + d_t} \\ e_t = \frac{2h_t}{d_p + d_t} \end{cases} \quad (1)$$

where  $d_p$  and  $d_t$  represent the effective diameters of individual yarns,  $h_p$  and  $h_t$  denote the wave heights of warp and weft yarns, respectively. Figure 1 illustrates the definition of the angle  $\alpha$  between the yarns from the perspective of the warp cross section. The figure shows that according to the difference in  $\alpha$ , the contact mode can be divided into two types, namely type 1 and type 2, which can be observed across diverse fabric architectures. Regarding contact type 1, the relationship between related parameters is illustrated in Fig. 2(a). The  $\alpha$  can be expressed through the geometric model as:

$$\alpha = \arctan \left( \frac{1 - \tan \beta \sqrt{\frac{e_t^2}{\sin^2 \beta} - 1}}{\sqrt{\frac{e_t^2}{\sin^2 \beta} - 1} + \tan \beta} \right) \quad (2)$$

where  $\beta$  is the angle related to  $\alpha$ , which meets the relationship “ $\alpha + \beta \neq \pi$ ” and the Eq. (2) can be employed to calculate  $\alpha$ :

$$\begin{cases} \sin \beta = \frac{e_p}{2} = \frac{h_p}{d_p + d_t} \\ \tan \beta = \frac{h_p (d_p + d_t)}{(d_p + d_t + h_p)(d_p + d_t - h_p)} \end{cases} \quad (3)$$

where  $h_p$  and  $h_t$  are calculated mathematically, see Fig. 2(a) and (b).

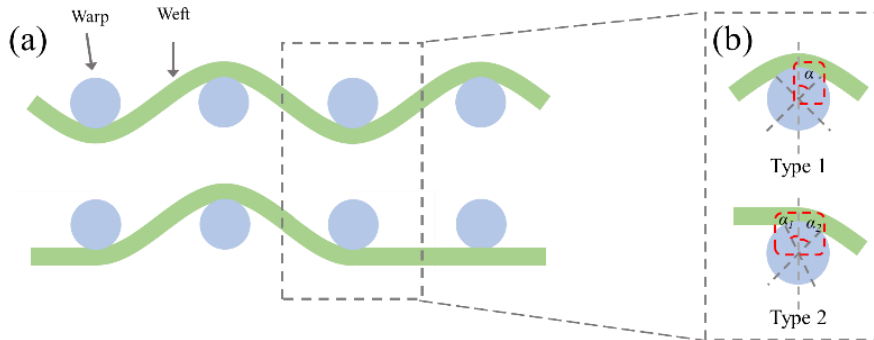


Fig.1 Geometric model of the cross-section of the interlacing of yarns in (a) plain and twill weave (b) Wrap angle.

Similarly,  $\alpha$  and  $\beta$  need to be met according to the following equations for contact type 2:

$$\begin{cases} \alpha + \beta = \pi \\ \sin \beta = \cos \alpha \end{cases} \quad (4)$$

According to the representative geometric shape, the contact arc length of the warp yarn  $l_p$  corresponding to  $\alpha$  can be calculated as:

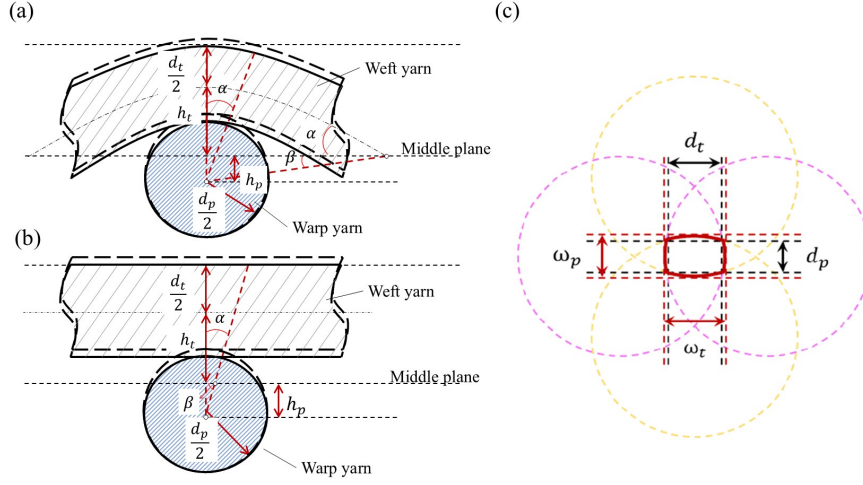


Fig.2. Geometric diagram of one interweaving point: (a) contact mode type 1, (b) contact mode type 2 and (c) top view for the contact zone.

$$l_p = d_p \cdot \alpha \quad (5)$$

Similarly, focusing on contact type 2, the arc length  $l_p$  or  $l_t$  corresponding to  $\alpha$ :

$$l_p = \frac{1}{2} d_p (\alpha_1 + \alpha_2) \quad (6)$$

The contact arc length of the weft yarn  $l_t$  can be obtained individually by the above equation. During the contact between warp and weft yarns, the fibers on the contact surface of the yarns are rearranged. In the calculation of the contact area, from the top view, the yarn expansion is considered. the width spread of the warp and weft yarns, considering the expansion  $\omega$  ( $\omega_p$  and  $\omega_t$ ) is calculated following the previous research [7]:

$$\omega = (12A_{trs}T_{hi})^{1/3} \quad (7)$$

where  $A_{trs}$  is the cross-section area of yarn and  $T_{hi}$  is the thickness of the contact surface. After deformation, the cross-section of yarn is elliptic. The  $A_{trs}$  can be obtained by approximate method [8]:

$$\begin{cases} A_{trs} \approx aE(2\alpha, e) \\ e = \sqrt{1 - (R_b^2 / R_a^2)} \end{cases} \quad (8)$$

where  $E(2\alpha, e)$  is the incomplete elliptic integral.  $e$  is the eccentricity, which can be shown by the semi-major axis  $R_a$  and semi-minor axis  $R_b$  of yarn cross-section deformed. The contact area increases due to the expanded behavior given by Gauss law:

$$\Delta A = \iiint_{\Omega} \left( \frac{x^2}{\omega_p/2} + \frac{y^2}{\omega_t/2} + \frac{z^2}{T_{hi}} \right) dv \quad (9)$$

where  $dv = dx dy dz$  and  $\Omega$  is defined as:

$$\Omega = \left\{ (x, y, z) \left| \frac{x^2}{\omega_p/2} + \frac{y^2}{\omega_t/2} + \frac{z^2}{T_{hi}} \right. \right\}, \frac{d_p}{2} \leq x \leq \frac{\omega_p}{2}, \frac{d_t}{2} \leq y \leq \frac{\omega_t}{2}, 0 \leq z \leq T_{hi} \quad (10)$$

Consequently, the contact area of one interweaving point should be calculated by:

$$A_r = l_p l_t + \Delta A \quad (11)$$

Finally, the contact area of the fabric  $A_{r,total}$  should be calculated by:

$$A_{r,total} = \sum_{i=1}^n A_{ri} \quad (12)$$

Secondly, when the warp and weft yarns are subjected to friction, it is necessary to confirm the dynamic identification process, that is, the relationship between the normal load and the wrapping angle and further analyze the friction behavior between the yarns. According to the friction adhesion theory:

$$F_f = A_{r,total} \cdot \tau \quad (13)$$

where  $A_{r,total}$  is the contact area of yarn and  $\tau$  is the specific shear strength, determined by calculating the ratio of the shear force applied to the yarn section to the area of the yarn section. The normal force applied  $F$ , related to the pre-tension  $F_p$ , can be projected in two directions (tangential and normal directions) shown in Fig.2 and equation (10):

$$\begin{pmatrix} F_t \\ F_n \end{pmatrix}_{(\vec{t}, \vec{n})} = \begin{pmatrix} F \cdot \sin \varphi \\ F \cdot \cos \varphi \end{pmatrix} \quad (14)$$

where  $F$  can be described using  $F_p$  with the following equation (15):

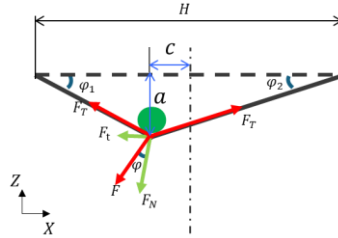


Fig. 3 The description of dimensional parameters during the friction process.

$$F = \left[ E_l A_{lrs} \left( \frac{H}{\sin \varphi_1} + \frac{H}{\sin \varphi_2} - 1 \right) + F_p \right] \cdot (\sin \varphi_1 + \sin \varphi_2) \quad (15)$$

Where  $E_l$  is the longitudinal modulus of warp yarn,  $\varphi_1$  and  $\varphi_2$  are angles between the warp and horizontal plane, and  $H$  is defined as distance under the action of  $F$ , which can have a relationship using  $\varphi_1$  and  $\varphi_2$ . All parameters in Eq. (15) can be calculated using the above equations according to previous research [9].

### 3. Results and discussion

In this paper, four warp yarns and one weft yarn are used as the configuration unit. The weft yarn moves back and forth in the interwoven structure of plain and twill, and its displacement is 5 cm per turn. During the full process, the warp yarn remains stretched due to the influence of pretension,

which will affect the friction. Figure 4 shows the friction results of two different structures. Generally, plain fabrics show greater friction relative to the two structures. This is mainly because the contact type 1 of plain fabric has larger contact area in the contact mode. Under the 0.5N pretension condition, the error range between the experimental and theoretical values of the friction is 4%. As shown in Figure 3, a comparative analysis of the results obtained under three pre-tensions of 0.25 N, 0.50 N and 1.2 N revealed that very satisfactory results were obtained. As the pre-tension increases, this difference gradually increases. The main reason is the  $F_p$  effect of the increase of  $F$ , and subsequently the increase of  $F_n$  leads to the expansion of the width  $\omega$  and the contact area, which leads to a nonlinear increase in the average friction force of the fabric.

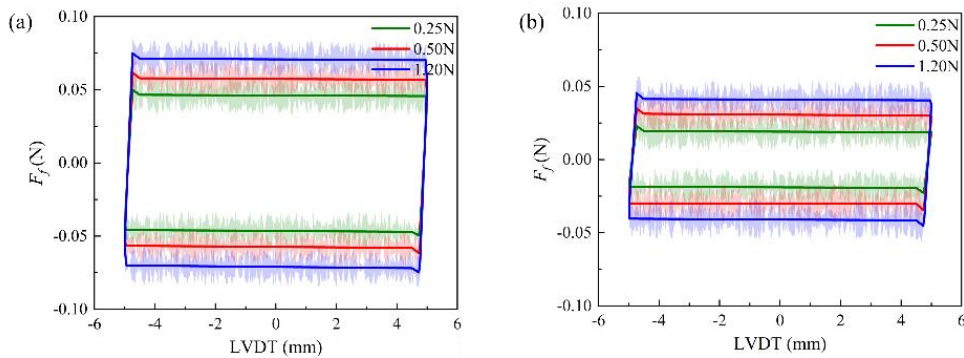


Fig. 4 Friction force under different pre-tensions: (a) plain weave and (b) twill weave.

#### 4. Conclusion

In this study, a contact friction model between yarns was developed to describe and predict the parameters involved in the friction process between yarns. The analytical model can predict the friction behavior under different pre-stretching conditions, and the accuracy of the model was experimentally verified. Under the 0.5N pre-tension condition the error range between the experimental value and the theoretical value of the average friction force of the two structures is 4%. The friction gradually increases under three pre-tension conditions: 0.25 N, 0.50 N, and 1.2 N.

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