STUDY OF INTERPLY SLIP DURING THERMOFORMING OF CONTINOUS FIBER COMPOSITE MATERIALS

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1 General Introduction

Continuous fiber thermoplastic composites have been introduced as structural materials for aerospace and automotive applications [1, 2, 3].
Thermoplastics are characterized by their plasticity at high temperature and their rigidity after forming.

In recent years, a large number of manufacturing processes have been developed while existing ones were modified in order to obtain a high quality process. The stamp forming process is generally chosen to process consolidated composite plates [4], consolidation, including void reduction and elimination, appears to be an important step before forming.

During forming of a pre-consolidated laminate, the individual plies slide over each other to avoid wrinkling [4 ,5, 6, 7, 8, 9].
The constraints imposed by friction between subsequent plies and between the laminate and the tools are major factor in the laminate deformations generated during composite forming.

In this work, a model was developed that predicts the friction between subsequent plies. The model is based on the Reynolds' equation for thin film lubrication and assumes hydrodynamic lubrication on a meso-mechanical level.

1.1 Review

Various studies have been performed on interply friction of woven-fabric composites [6, 10]. Some studies showed that the friction coefficient is related to the Hersey number, H, which is function of viscosity, η, velocity, U, and normal force, N.

$$H = \frac{\eta U}{N} \quad (1)$$

Another approach was presented by Akkerman and al. [9] that predicts friction between thermoplastic laminates and a rigid tool by assuming hydrodynamic lubrication on a meso-mechanical level.

The film thickness was derived iteratively from the Reynolds' equation for thin film lubrication. The fabric geometry and the matrix materials were used as the input parameters.

2 Friction model

A new model was developed to simulate the ply-ply friction. Fig.1 presents a schematic representation of to plies separated by a matrix film.

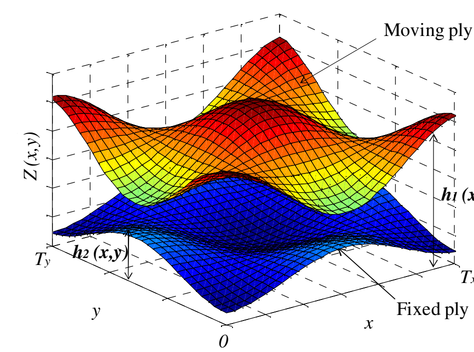

Fig.1. Schematic representation of two subsequent plies

It is assumed that the equation governing the flow between those plies is the incompressible, stationary Reynolds equation which for the two dimensional state reads:

$$div\left[\frac{\left(h_1^3 - h_2^3 - 3h_1^2 h_2 + 3h_2^2 h_1\right)}{12\eta}\overrightarrow{grad}\,P - \frac{(h_1+h_2)}{2}\vec{V}\right] = 0, \quad (2)$$

P is the pressure, $(h_1$-$h_2)$ the local film thickness, η the viscosity and V is the slip velocity.

This equation describes the relation between the pressure and thickness distribution of a Newtonian fluid matrix.

The resolution of (equ. 2) is usually made using a finite element method. In our case and considering a periodic profile for $h_1(x,y)$ and $h_2(x,y)$, a pseudo spectral method could be used. One boundary condition is needed.

$$P(0,0)=0 \tag{3}$$

It's important to notice through the writing of the Reynolds equation that the pressure depends linearly on velocity. For this reason, we will try first, and using method described above to solve the Reynolds equation for two different cases where in the first one, the moving ply slips in the x direction, whereas in second case the same ply slips this time in the y direction. The respective solutions will be called $P_1(x,y)$ and $P_2(x,y)$.
The linear solution could be written like:

$$\vec{P}=\eta(V_x.\vec{P_1}(x,y)+V_y.\vec{P_2}(x,y)), \tag{4}$$

Where $V= (V_x, V_y)$ is the velocity vector,

The pressure gradient is calculated:

$$\begin{aligned}\overrightarrow{grad}P &= \eta.V_x.\overrightarrow{grad}P_1+\eta.V_y.\overrightarrow{grad}P_2\\ &=\eta.\left[\overrightarrow{grad}P_1\otimes\vec{e_x}+\overrightarrow{grad}P_2\otimes\vec{e_y}\right]\cdot\vec{V}\\ &=\eta\cdot\overline{\overline{M}}\cdot\vec{V},\end{aligned} \tag{5}$$

Where, $\overline{\overline{M}}=\overrightarrow{grad}P_1\otimes\vec{e_x}+\overrightarrow{grad}P_2\otimes\vec{e_y}$

Integrating the shear stress over the sliding surface allows calculating the friction force:

$$\begin{aligned}\vec{F} &= \int_x\int_y \tau(x,y)dxdy\\ &=\iint_{x,y} -\frac{(h_1+h_2)}{2}\overrightarrow{grad}\,P+\eta\frac{\vec{V}}{h_1-h_2}dxdy\\ &=\iint_{x,y}\left[-\frac{(h_1+h_2)}{2}\overline{\overline{M}}+\frac{\eta}{h_1-h_2}\overline{\overline{I}}\right]dxdy\cdot\overline{V}\\ &=\overline{\overline{C_f}}.\overline{V}\end{aligned} \tag{6}$$

This model predicts the friction force F_f as a function of the friction matrix C_f and velocity V.

The friction matrix C_f depends on both plies geometries, described by h_1 and h_2, and on the pressure gradient.

2.1 Model Analyses

The previous model shows that the coefficient of friction is not scalar according to the velocity.
After calculating Eigen values λ_1, λ_2 and their corresponding Eigen vectors u_1 and u_2, of matrix C_f, we deduced that friction force is only collinear to velocity when this one is collinear to u_1 or u_2 vectors.

$$\begin{aligned}\overrightarrow{F_1}&=\lambda_1.(\beta.\overrightarrow{u_1})\\ \overrightarrow{F_2}&=\lambda_2.(\beta.\overrightarrow{u_2})\end{aligned} \tag{7}$$

λ_1, λ_2, u_1 and u_2 depend on the film thickness, distribution and regularity.

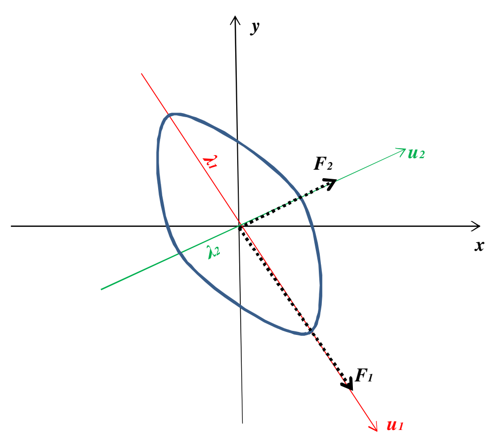

Fig.2. Schematic representation of friction force when velocity is collinear with u_1 or u_2

3 Numerical results and discussion

The previously presented model (equ.6) was applied to calculate friction parameters between two 3×3 Twill plies as shown in (Fig. 2).

Geometric equations of both plies are given by:

$$\begin{aligned}h_1(x,y)&=h_1^*\left[1+\varepsilon_1\cos\left(\frac{2\pi x}{T_x}\right)\cdot\cos\left(\frac{2\pi y}{T_y}\right)\right]\\ h_2(x,y)&=h_2^*\left[1-\varepsilon_2\cos\left(\frac{2\pi x}{T_x}\right)\cdot\cos\left(\frac{2\pi y}{T_y}\right)\right]\end{aligned} \tag{8}$$

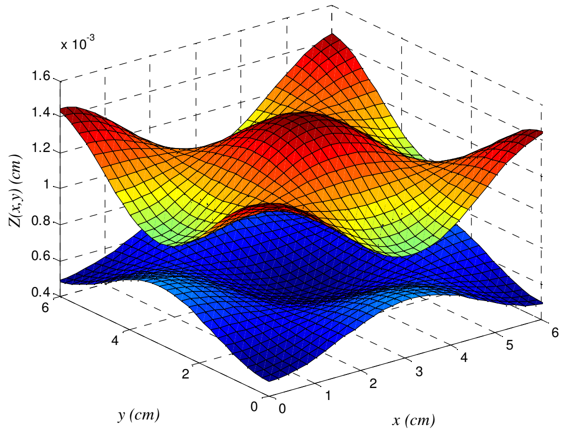

Fig.3. Inter-ply slip between two 3x3 Twill plies

The maximum and the minimum film thicknesses are equal to:

$$e_{\max} = h_1^*(1+\varepsilon_1) - h_2^*(1-\varepsilon_2)$$
$$e_{\min} = h_1^*(1-\varepsilon_1) + h_2^*(1+\varepsilon_2) \quad (9)$$

As h_1^*, h_2^*, ε_1, ε_2, T_x, T_y and N, the number of collocation points, are the imposed values (Table 1), $P_1(x,y)$, $P_2(x,y)$, and their respective gradients could now be calculated using the pseudo-spectral Fourier method. Profiles are shown in (Fig. 4).

Table 1. Example Parameters

Parameter	Value	Unit
h_1^*	12.10^{-6}	m
h_2^*	6.10^{-6}	m
ε_1	0.2	
ε_2	0.2	
T_x	0.06	m
T_y	0.06	m
η	100	Pa.s
N	15	

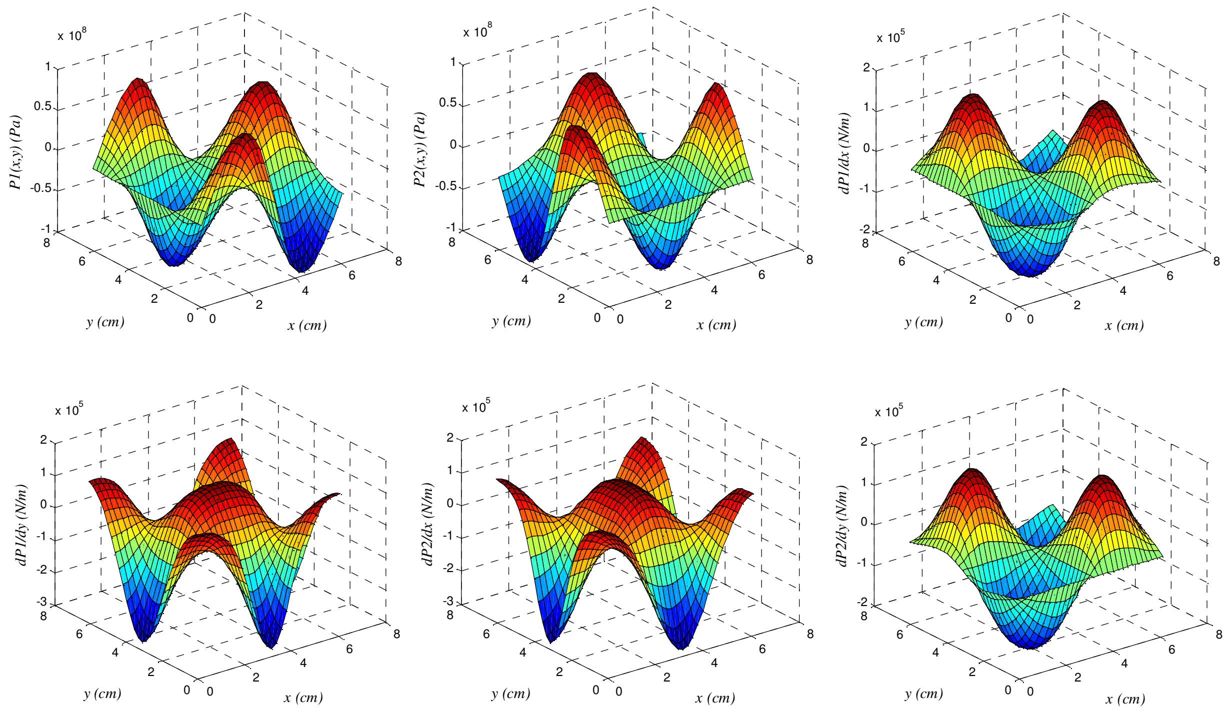

Fig.4. Different pressure and gradient of pressure profiles

3.1 Influence of film thickness on friction behavior

As demonstrated before, the friction matrix C_f, which characterize the relation between friction force and velocity, is dependant from both plies geometries h_1 and h_2. Or in other terms, the thickness of resin film layer formed between both plies will play an important role in the variation of the components of C_f.

To evaluate this influence, we calculated C_f for different (e_{min}/e_{max}) values.
Fig.5 shows that changing film thickness did not affect the Eigen vectors. In our case, when the velocity vector is deflected by a ±45° angle with *x*-axis, friction force is collinear to this vector whatever the film thickness variation is.

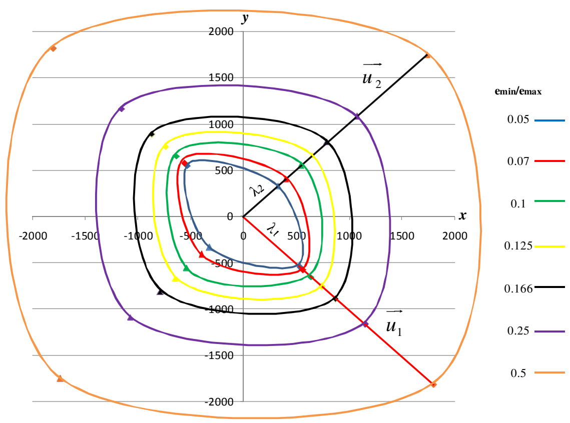

Fig.5. Eigen values and Eigen vectors of C_f function of (e_{min}/e_{max})

On the other hand, the irregularity of film thickness has a significant effect on λ_1 and λ_2. With the increase of (e_{min}/e_{max}) values λ_1 and λ_2 will finish by being equal (Fig. 6).

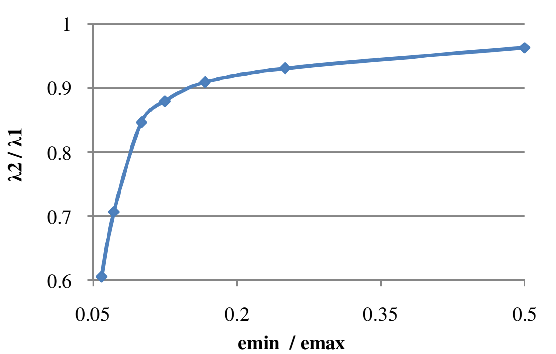

Fig.6. Variation of anisotropy factor with film irregularity

4 Conclusions

The inter-ply slip is very variable, and plays an important role in forming processes of thermoplastic laminates. Modeling this phenomenon shows that the coefficient of friction is not scalar according to the velocity. Variation in film thickness has a significant effect on relation between friction force and velocity.

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