1 Introduction

The draping of pre-impregnated plies (prepregs) is an important concern in the manufacturing of composite material products. Prepreg draping represents an interesting alternative to the LCM processes (Liquid Composites Molding) [1, 2] where a resin is injected/infused on a textile preform. The prepreg forming starts with semi-products where the matrix is already integrated into the continuous fibre textile reinforcement. This resin can be thermoset or thermoplastic. Thermoforming of thermoplastic prepregs is a fast manufacturing process in comparison to LCM process or thermoset prepreg draping that need a long polymerisation stage in an autoclave. In addition the composites with thermoplastic matrix are more easily recyclable than thermosetting material. The fibre volume fraction in the final composite part obtained by thermoplastic thermoforming can be high. The forming process must be performed at a temperature close to or higher than the melt temperature of the resin in order to render the textile reinforcement deformation possible.

Depending on the geometry of the final composite parts, on the reinforcement type (weaving, properties of fibres ...) and on manufacturing parameters (tool loads, blank holder, temperature ...), double-curved shape manufacturing may lead to defects (wrinkling, porosities, fibre fracture ...). Simulation software for composites forming has been developed to predict the conditions for the process feasibility and optimize the main forming parameters [3-7]. The present paper is based on the software developed in [8-10] and demonstrates the forming simulation analyses taken into account thermal and viscous effects.

These software packages need the mechanical behaviour of the composite ply during forming. As this ply is generally modelled by shell finite elements (or membrane elements if the bending stiffness is neglected), the mechanical behaviour of the prepreg ply during forming is given by the biaxial tensile properties [11-14], the in-plane shear properties [15-21] and the bending properties [22-24].

2 Mechanical modeling of thermoplastic composites during forming

2.1 Semi discrete approach for woven composites

Many research works about the numerical modelling of composite forming can be found in the literature [25-29]. These numerical simulations were realized on several scales, as the mechanical behaviours are very specific for the macroscopic scale, the mesoscopic scale and the microscopic scale.

As an alternative approach to the macroscopic approach and mesoscopic / microscopic approaches, a semi-discrete approach has been developed in [8, 9]. This semi-discrete shell finite element is comprised of unit woven cells with rotation free, which presents only displacements of nodal variables [30] (Fig. 1). The warp and weft directions of the woven fabric can be in an arbitrary direction with respect to the direction of the element side. Comparing to the discrete approach, the computational cost is reduced significantly due to the decrease in the number of DOF (degree of freedom).
freedom). Regarding the continuous approach, the semi-discrete approach avoids the use of stress tensors and defines directly the loading on a woven unit cell by the warp and weft tensions and by in-plane shear and bending moments. In this case, it does not need to determine and update the particular homogenous behaviour of textile materials to employ in a continuous model.

The virtual work theorem can be described as Eq. (1) to any virtual displacement field \( \mathbf{\eta} \) (\( \mathbf{\eta} \) is equal to zero on the boundary with prescribed displacements \( \Gamma_u \)). In our explicit numerical model the virtual internal work applies to all of woven element cells, which can be composed into three main terms (see Eq. (2)): the work connected to fibre biaxial tensions, the work due to in-plane shear presenting the variation of the angle between warp and weft directions, the work corresponding to bending effects during a flexion of the fabric (Fig. 1).

\[
\begin{align*}
W_{\text{ext}}(\mathbf{\eta}) - W_{\text{int}}(\mathbf{\eta}) &= W_{\text{acc}}(\mathbf{\eta}) \\
\forall \mathbf{\eta} / \mathbf{\eta} = 0 & \quad \text{on} \quad \Gamma_u
\end{align*}
\]

(1)

with

\[
W_{\text{int}}(\mathbf{\eta}) = W_{\text{int}}^t(\mathbf{\eta}) + W_{\text{int}}^s(\mathbf{\eta}) + W_{\text{int}}^b(\mathbf{\eta})
\]

(2)

where \( W_{\text{int}}^t(\mathbf{\eta}) \), \( W_{\text{int}}^s(\mathbf{\eta}) \) and \( W_{\text{int}}^b(\mathbf{\eta}) \) are the virtual internal works of tension, in-plane shear and bending respectively with:

\[
W_{\text{int}}^t(\mathbf{\eta}) = \sum_{P=1}^{n_{\text{cell}}} P \varepsilon_{11}(\mathbf{\eta}) \cdot P T_{11} \cdot P L_1 + P \varepsilon_{22}(\mathbf{\eta}) \cdot P T_{22} \cdot P L_2
\]

(3)

\[
W_{\text{int}}^s(\mathbf{\eta}) = \sum_{P=1}^{n_{\text{cell}}} P \gamma(\mathbf{\eta}) \cdot P M^s
\]

(4)

\[
W_{\text{int}}^b(\mathbf{\eta}) = \sum_{P=1}^{n_{\text{cell}}} P \chi_{11}(\mathbf{\eta}) \cdot P M_{11} \cdot P L_1 + P \chi_{22}(\mathbf{\eta}) \cdot P M_{22} \cdot P L_2
\]

(5)

where \( P \) is the woven cell number, \( n_{\text{cell}} \) is the total number of woven cells, \( \varepsilon_{11}(\mathbf{\eta}) \) and \( \varepsilon_{22}(\mathbf{\eta}) \) are the virtual biaxial strains, \( L_1 \) and \( L_2 \) are the length of unit woven cell in warp and weft directions, \( \gamma(\mathbf{\eta}) \) is the virtual angle between the warp and weft directions, \( M^s \) is the in-plane shear moment, \( \chi_{11}(\mathbf{\eta}) \) and \( \chi_{22}(\mathbf{\eta}) \) are the virtual curvatures of warp and weft direction, \( M_{11} \) and \( M_{22} \) are the bending moments on the woven cell following warp and weft directions.

Fig. 1. (a) Loads on a unit woven cell and resultants: (b) tensions, (c) in-plane shear moment, (d) bending moments.

2.2 Viscous friction modeling and implementation

As for the contact management in our semi-discrete model, the complex shell to shell contact problem is experienced during the numerical simulation of forming process. The surface contact type is composed in point / point, point / surface, point / segment and segment / segment cases.

The numerical modeling of contact behaviour during the forming process is accomplished using the algorithm of the forward increment Lagrange multipliers proposed by Carpenter [31]. This method could be introduced into the dynamical expression (Eq. (6)) as contact occurs.

\[
[M][\dot{\mathbf{u}}_n] + [F^\text{int}] + [G_{n+1}]^T \{ \lambda_n \} = \{ F^\text{ext} \}
\]

(6)

\[
[G_{n+1}](\{ u_{n+1} \} + \{ X_0 \}) = \{ 0 \}
\]

where \( \{ u \} \) is the vector of displacement degrees of freedom, \( \{ X_0 \} \) is the material co-ordinate vector, \( [M] \) is the mass matrix, \( \{ F^\text{int} \} \) and \( \{ F^\text{ext} \} \) are internal and external loads vectors of the system,
\[ \{ \lambda \} \text{ is Lagrange multiplier vector and its components are the surface contact forces, } n \text{ is an index of calculation step, } [G] \text{ is a surface contact displacement constraint matrix.} \]

In the case of "semi-implicit" integration, the total displacement of each node can be calculated according to equations (7) by a predictor \( \{ u^p \} \), determined from equation (6) under the condition without contact effect and a corrector \( \{ u^c \} \), determined computed as the contact loads present as shown in Fig. 2.

\[
\{ u_{n+1} \} = \{ u^p_{n+1} \} + \{ u^c_{n+1} \} \\
\{ u^p_{n+1} \} = \Delta t^2 \{ \lambda \} \text{ with } \Delta t \text{ a time step increment.} \\
\{ u^c_{n+1} \} = -\Delta t^2 \{ \lambda \} \text{ where } \{ \lambda \} = [G]^{-1} \{ \lambda \} \\
\{ u^c_{n+1} \} = -\Delta t^2 \{ \lambda \} \text{ with } \{ \lambda \} \text{ a surface contact force.}
\]

As one key problem, the viscous friction on tool / ply and ply / ply interfaces should be taken into account in the numerical modeling of thermoplastic composite forming. A lubricated friction (a Stribeck friction model) will be implemented as a fluid layer separates two solid surfaces. In this case, the effective friction coefficient can be described by Eq.(9).

\[
\mu_{eff} = C_1 \cdot He + C_2 \\
He = \frac{\eta \cdot V}{F_N}
\]

with \( He \) the Hersey Number, is dependent on resin viscosity (\( \eta \)), velocity between two contact surfaces \( V \) and normal load applied \( F_N \); \( C_1 \) and \( C_2 \) the two constants determined by pull-out experiments.

The relative velocity between the two contact surfaces can be known from the total displacement of the slave node contacting with a mistress surface. The vector of tangential contact force on one slave/mistress surface can be modelled (Eq. (10)).

\[
\{ F^T \} = -(C_1 \cdot \eta \cdot \| V \| + C_2 \cdot F^N_C) \cdot \frac{\{ V \}}{\| V \|}
\]

3 Numerical simulations

3.1 Single layer thermoforming

The first numerical application is performed for a cylindrical forming process at different temperatures. The punch diameter of 156 mm and a maximum displacement of 30 mm are proposed in this forming. The dimensions of a single woven layer are 400 mm × 400 mm× 0.35 mm and the fibre orientation is 0°/90°. Eight independent blank holders with cube geometry are employed and a homogenous pressure of 0.1 MPa is maintained during the whole forming stage (Fig.3a).

Figures 3b and 3c demonstrate two numerical simulation examples of a cylindrical forming for one carbon/PPS prepreg ply at 270°C and 310°C. We
can observe that the deformed shape is very distinct and a difference of about 11° of the maximum shear angle in two final pieces, as there is a significant difference of the in-plan shear behavior of carbon/PPS prepreg at 270°C and 310°C. Especially, this difference leads to a very distinct field of in-plan shear angle. The numerous wrinkles can be noted in the formability at 270°C. The prediction of numerical simulations points out the importance of thermal conditions during the thermoplastic composites forming.

3.2 Multilayer composite thermoforming simulation

The finite element simulation of the forming of 7 carbon/PEEK prepreg plies by a punch with a bowl shape is performed in Fig. 4. The dimensions of a single prepreg ply are 500 mm × 500 mm × 0.3 mm and the fibre orientation is 0°/90°. The figure 4 shows the forming tools and the shape of final composite part. The surrounding plates will be employed in the consolidation stage to obtain a homogenous thermal condition. prepreg ply are 500 mm × 500 mm × 0.3 mm and the fibre orientation is 0°/90°. Fig. 2 shows the geometric model and the mesh structure.

Regarding the temperature measurement, the forming temperature is not homogenous in the preform, but it remains almost constant during the forming stage. Consequently, it should calculate the temperature field of each ply at the beginning of the forming. As it presents in figure 5, the temperature distribution in preform stacking determined by numerical simulation is between 320°C and 375°C. This temperature field will be constant and taken into account in the flowing forming simulation.
Fig. 5. Temperature distribution of each ply before thermoforming.

Fig. 6a presents the final shape of the composite part obtained by numerical simulation. The agreement with the experiments is good (Fig. 7a). Furthermore, a correct correlation is obtained for the maximum shear angle in the corners on the ply 7 of the deformed plate between the numerical simulation (48°, Fig. 6b) and experiments (the angle between warp and weft yarns is 42°, Fig. 7b).

Wrinkling is one of the most common flaws that occur during textile composite forming processes [9]. The numerical and experimental analyses of wrinkling during this industrial thermoforming benchmark are presented in Fig. 8. Wrinkles can be observed in both numerical and experimental analyses at the beginning of the forming process, in the middle of the process (Figs. 8a and 8b), as well as in the final composite part (Fig. 8c). The correlation between the numerical simulation and experiments concerning the wrinkles is correct. Numerical simulations can highlight the wrinkle onsets and developments during a thermoforming process and consequently permit to optimize the process parameters to avoid these defects at least in the useful zone.

Fig. 5 shows a temperature gradient in the plies. The zone closed to the edges of the part have a temperature (320°C) that is lower than the melt temperature of PEEK resin (343°C). Consequently,
because of the strong dependence of the stiffness of the prepreg on the temperature, the edges of the plies are more rigid than the central region and wrinkles are created by in-plane shear during forming. The ideal thermoforming condition should be an isothermal field (in space). The prepreg stack would have a homogenous temperature, higher than the melt temperature of the matrix. The result of a simulation for a uniform temperature of 360°C is shown in Fig. 9. Contrary to the previous case, no wrinkling is observed in the forming simulation as the temperature has been assumed to be constant in the part. In practice, it is generally not the case and the simulation of a prepreg forming process is a thermo-mechanical phenomenon. Both the temperature and the displacement fields must be computed. This simulation example pointed out that the temperature strongly influences the results of the thermoforming simulation, in particular the wrinkle onset.

Fig. 8. Numerical / experiment comparison of wrinkling phenomena (a) at the beginning of forming, (b) at the middle of forming, (c) at the end of forming.

Fig. 9. Numerical simulation of isothermal forming with a temperature at 360°C.

4. Conclusion

A numerical simulation of the mono and multilayered CFRTP prepreg forming and the comparisons with experimental approach were described in this paper. The simulation takes into account thermal and viscous friction effects. A correct correlation was observed between numerical and experimental results. It is important to predict the feasibility conditions of the prepreg composite forming through numerical simulation analysis. The numerical simulation can improve the understanding of the forming process. On the other hand it gives some essential forming information, such as temperature, final shape of the laminate, direction of the fibres at all points of the different layers and possible wrinkling phenomena. The forming simulations have pointed out the significant importance of thermal conditions during the forming process. The temperature field must be taken into account in a very accurate manner in this simulation. In the approach presented in the paper, it is assumed that the forming process is fast enough to consider the temperature field constant in a given point during forming. Ideally the thermal and mechanical analyses should be fully coupled. Several other aspects of the modelling need also improvement. In particular the variation of the
bending properties with the temperature would probably be necessary in some thermoforming processes.

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References


