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SIMULATION OF THE THERMOFORMING PROCESS OF THERMOPLASTIC COMPOSITE PARTS

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ABSTRACT

In this paper, the numerical solution for the simulation of the thermoforming process built with the SAMCEF finite element code is presented. The draping is first simulated. This can be done based on a kinematic or a finite element approach. An original kinematic method for the draping is presented. It is based on an adaptation of the Fast Marching Method, which is commonly used to simulate the propagation of interfaces in different fields of the Physics. The thermal analysis is conducted, in order to determine the history of the temperatures during the cooling of the composite part. This temperature history is then used for the modeling of the crystallization. At this stage, specific material laws are used. The paper discusses the assumptions made in the analysis chain, the relevance of the different draping methods and of the material parameters of the crystallization laws. Applications demonstrate the ability of the computational chain to identify the final distortion of the composite part, as well as the residual stresses resulting from the manufacturing process.

1. INTRODUCTION

The finite element method has been used to simulate the manufacturing process of composites, either for thermosets [1,2] or for thermoplastics [3-5]. In this paper, some results of the research project PROTON (ZIM, Germany), which addresses the simulation of the thermoforming process of composites, are presented. As illustrated in Figure 1, the thermoforming process includes several steps. First, the thermoplastic pre-preg made of woven fabric is heated. It is then draped onto the mold. The compaction is carried out in the closed mold and the subsequent cooling allows the matrix to crystallize and consequently to reach the solid state. The part is then removed from the mold. At that stage, distortion usually appears in the resulting composite part due to thermal contraction and chemical shrinkage.

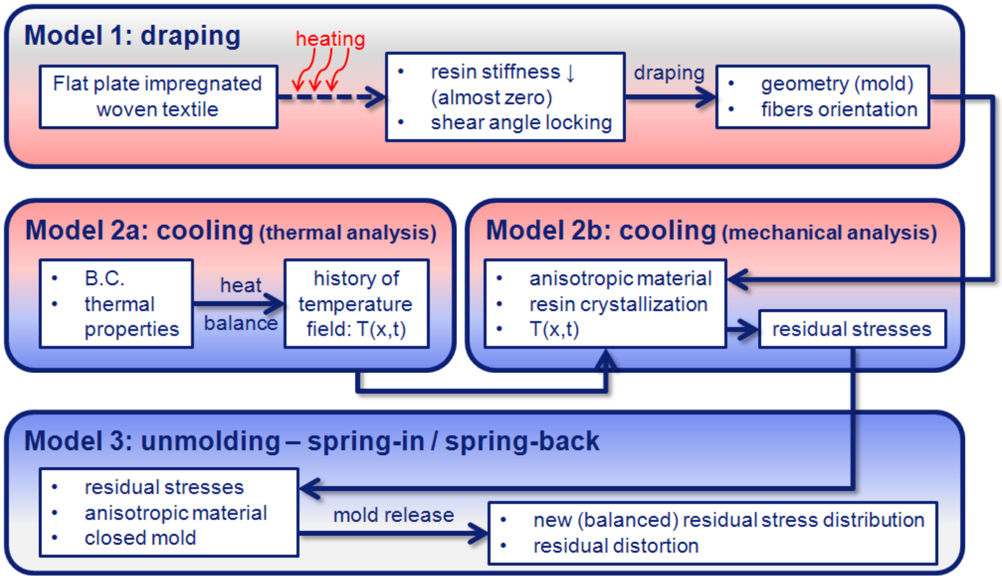


Figure 1; Steps of the thermo-forming process (simulation)

The numerical solution for the simulation of this process is built with the SAMCEF finite element code. The draping is first simulated, either with a kinematic approach or with the finite element method. In the first case, an original method based on the fast Marching Method is used. Then, the history of the temperatures during the cooling of the composite part is obtained with a thermal analysis. For this stage, a model is built assuming an isotropic material for the matrix. The fibers are not included in this model, and their influence on the heat transfer is neglected. This temperature history is then used for the modeling of the crystallization. At this step, specific material laws are used to determine the crystallization rate depending on the temperature and the cooling rate. This provides locally the mechanical properties of the matrix, which are then combined in an homogenization approach to the mechanical properties of the fibers in order to obtain the equivalent orthotropic properties of the fiber/matrix material. The paper discusses the assumptions made in the analysis chain, the relevance of the different draping methods and of the material parameters of the crystallization laws. Finally, an application demonstrates the ability of the SAMCEF finite element software to simulate such a manufacturing process. This research is a first step, and a comparison with experimental results, or with results obtained with other commercial software, is planned in order to validate the approach.

2. THE DRAPING PROCESS

2.1 FEM approach

The draping process can be addressed in two ways. The first one is based on the solution of the elastic problem with the finite element method [6]. In that case, not only the mold on which the fabric is to be draped must be modeled, but also the full punch system, with the correct boundary conditions (Figure 2).

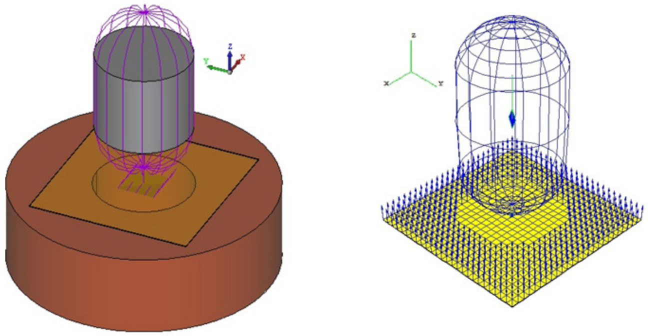


Figure 2. Finite element model of the draping process

A solution obtained with the SAMCEF finite element code is illustrated in Figure 2, and is compared to a solution from the literature [6].

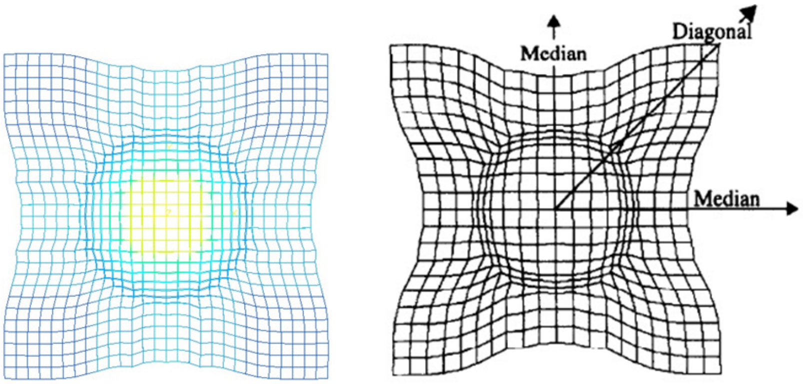
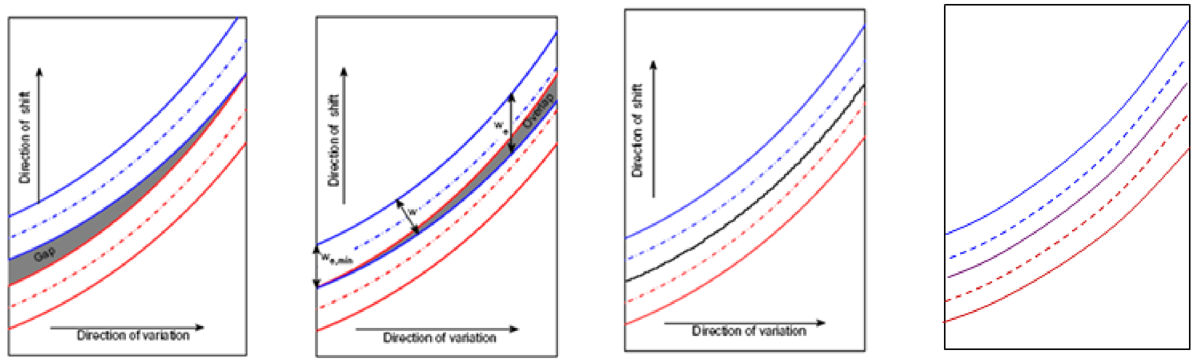


Figure 3. FEM solution of the draping simulation

2.2 FMM kinematic approach

The second way to address the draping simulation is to use a kinematic approach [7]. Here the method developed in [8] for the definition of the course trajectories in the Automated Fiber Placement (AFP) process is used. Even if methods are available today, they present some drawbacks, as illustrated in Figure 4. In the pictures, the successive courses of an AFP path planning system are represented, with the dashed curves corresponding to the course centerline. In the first picture [9], the successive courses are defined in such a way that gaps will occur, while in the second picture, the second course is translated and overlaps appear. In order to avoid these undesired situations, the cut and restart capabilities of the machine can be used, as illustrated in the third picture. However, doing so, the full capacity of the machine is not used. The new method described in [10] allows the definition of courses with constant width, avoiding gaps and overlaps, while using the full layup capacity of the machine. This method is based on a mesh of the structure, and can therefore address complicated geometries. A reference fiber is defined on the mesh of the structure. This reference fiber is then propagated to the whole structure, as the initial front in the Fast Marching Method (FMM) which is commonly used in several fields of the Physics [10]. Since the travel time of each point on the front is the same, the method provides a network of equidistant curves (defined on the mesh, in a level-set way). This network can be seen as courses of an AFP process. Since the curves are equidistant, the method avoids the presence of gaps and overlaps, as illustrated in the picture 4 of Figure 4. The idea is also presented in Figure 5.



(a) Gap between two courses (b) Overlapping courses (c) Constant thickness

Figure 4. Definition of the courses in an AFP pocess simulation

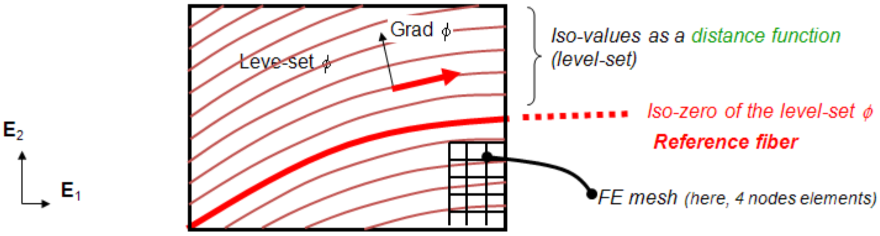


Figure 5. The principle of the FMM method for AFP simulation

Even if it was initially developed for unidirectional plies, this approach can be extended to the fabrics. When two reference fibers, perpendicular at the seed point, are used, the method can be seen as a way to define the draping of fabrics, as illustrated in Figure 6. In that case, when the surface is non-developable, the shearing occurring between the fabric tows can be identified.

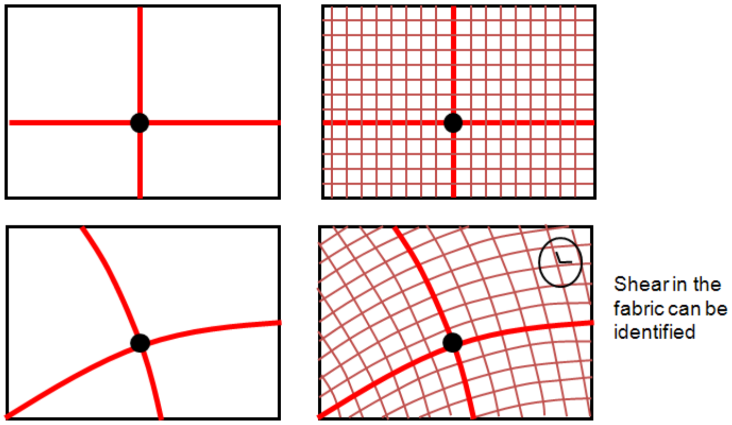
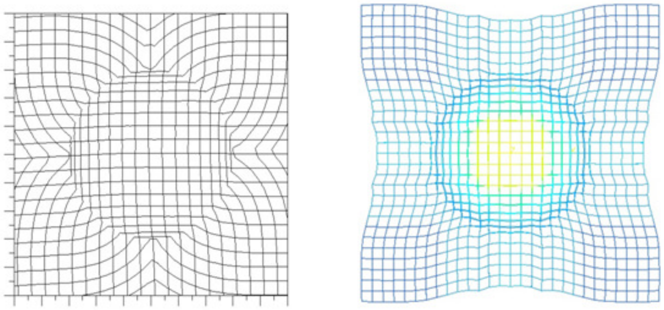


Figure 6. The FMM method applied to fabric draping simulation

2.3 Comparison of the two methods

FEM and FMM solutions are compared in Figure 7. The advantage of the FMM is that it provides a very quick solution, because the computational effort is much less demanding. The inconvenience is that this scheme is independent of any fabric pattern. However, even if approximated, a solution is always obtained, which is not the case with the FEM approach as convergence problems in the non-linear solution may appear.



FMM solution

FE solution

Figure 7. Kinematic approach based on FMM for the draping simulation

3. THERMAL ANALYSIS AND CRYSTALLIZATION

The goal of the thermal analysis is to obtain the temperature history over time through the structure when the composite is cooled down. The inputs are some surface temperatures or a heat flux, as well as the thermal properties of the matrix depending on the temperature.

While the thermoplastic material is cooling down, its structure changes from a liquid state to the solid state. With the crystallization kinetic model developed in [11,12], it is possible to determine the relative degree of crystallization θ(T), which is a function of the temperature T and of the cooling rate (see Figure 8), as given in (1).

$$\theta(T) = 1 - \exp\left[-\Psi(T)\left(\frac{T_s - T}{\dot{T}}\right)^n\right]$$

$$\Psi(T) = C_1 \exp\left[\frac{-3U^*}{R(T - T_\infty)}\right] \exp\left[\frac{-3C_2}{\frac{2T}{T + T_m^0} T (T_m^0 - T)}\right] \qquad (1)$$

It is assumed that as long as the relative degree of crystallization is lower than 50%, the stiffness of the matrix is very close to zero. Above this rate, the mechanical stiffness progressively appears, and thermal loads can generate a non-uniform strain field and consequent residual stresses, sometimes relevant in the problem.

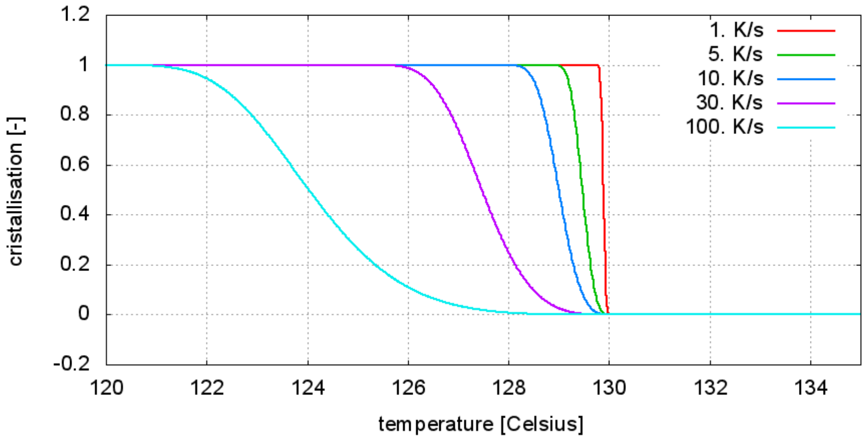


Figure 8. Relative crystallization degree with respect to temperature and cooling rates

4. ILLUSTRATION

We consider the corner beam problem subjected to a uniform cooling heat flux applied on both inside and outside surfaces. The reader will understand that some data and results are omitted here for confidentiality reasons. In the Figure 9, the temperature distributions are provided at two different times. We can see that, since the heat exchange surfaces are not identical, a gradient of temperature appears in the corner. Here, the model includes an isotropic material with the thermal properties depending on the temperature.

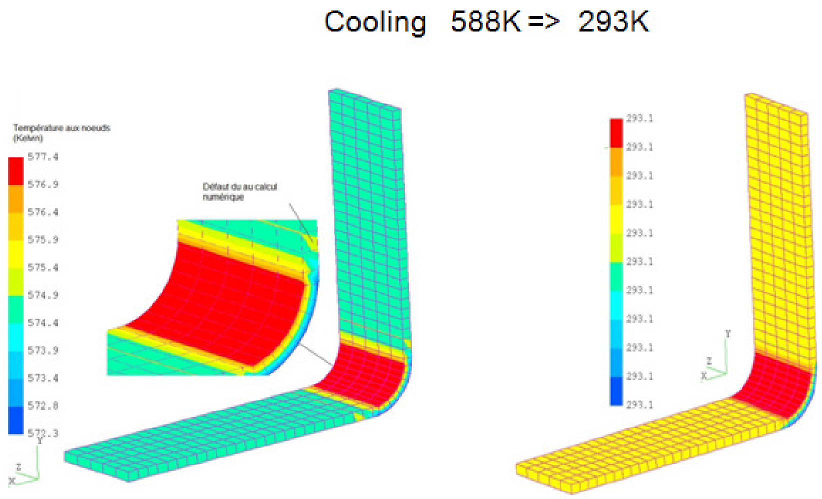


Figure 9. Temperature distributons at two different times during the cooling

Then, the crystallization is simulated. A new and more accurate mechanical model including the fibers is now used. The locally prescribed temperature history is the one computed in the thermal model. The crystallization rate is obtained based on the temperatures and the cooling rate, as illustrated in Figure 10. In our case, the crystallization occurs during a small range of temperature variation. This simulation provides the mechanical properties of the matrix. Homogenization (based on a mixture rule) is then used to obtain the corresponding equivalent mechanical properties of the fiber/matrix material: a homogenized orthotropic constitutive law generally used for unidirectional plies is considered. Then, two such orthogonal UD plies are superposed to model one fabric ply. In order to take into account possible shear locking effect, the value of the shear modulus can be adapted, depending on the resulting draping simulation.

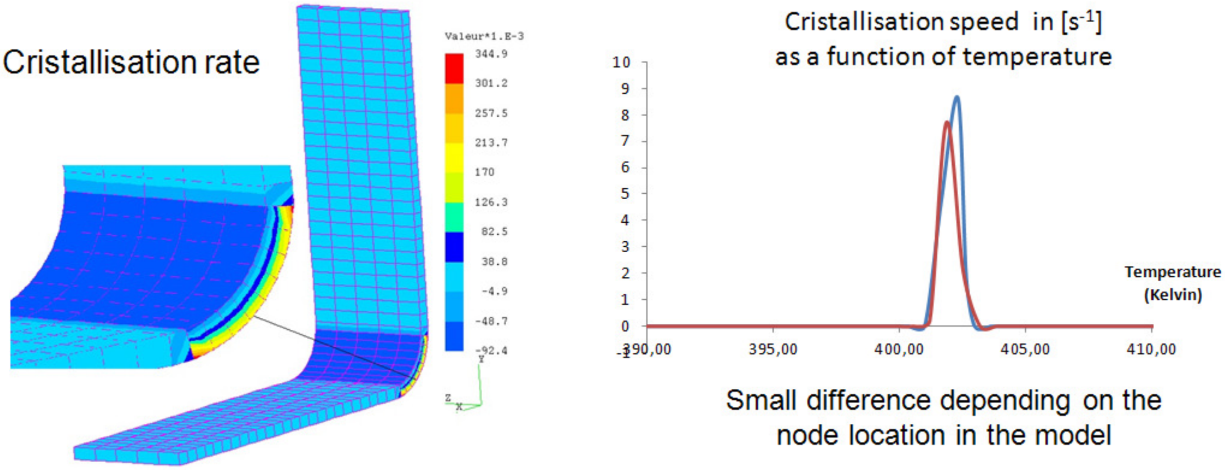


Figure 10. Computed crystallization rate and crystallization speed

Based on this analysis, the residual stresses can be determined. The total strains are the sum of the mechanical strains and the thermal strains. Knowing that the mold is closed, the total strains are therefore equal to zero, and the mechanical strains are then the opposite of the thermal strains. These are the inputs to compute the residual stresses, which lead to a geometric distortion of the composite part during the manufacturing process. We assume that the residual stresses are purely elastic. In that case, the distortion of a free structure is equal to the distortion of a freed structure initially locked by the walls of the mold. In our simulations, the locking of the structure representing the constraining action of the mold is therefore not taken into account in the model, and the component is free to distort during the simulation of the crystallization. The distortion obtained on the corner beam is illustrated in Figure 11. It is observed that a spring-in effect appears.

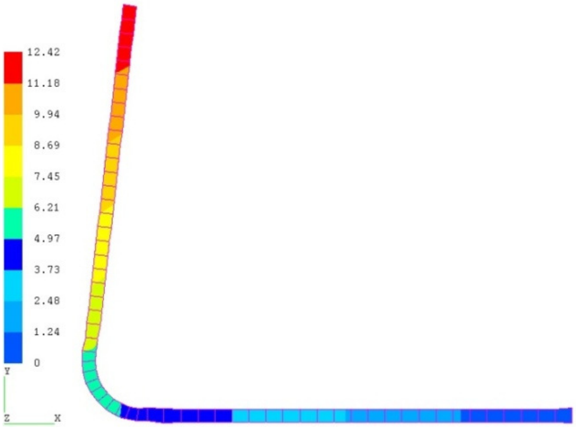


Figure 11. Distortion after the crystallization

5. CONCLUSION

A first solution obtained with the SAMCEF finite element code for the simulation of the thermoforming of thermoplastic composites was presented. The draping simulation was studied with the finite element method and with a new kinematic approach. The process simulation, including the crystallization of the matrix, was able to identify the distortion resulting from the manufacturing process. A comparison with experimental results is planned in order to validate the approach.

6. ACKNOWLEDGEMENT

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