Finite element model for simulation of thermoforming process of composite materials.

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Abstract. Composite materials, due to their characteristics, are becoming increasingly used in the fabrication of primary structural elements. On the one hand, thermoplastic composites considerably increase the rate of production of parts; on the other hand, thermoplastic composites require higher processing temperatures; thermoplastic polymers, due to their high molecular weight, are more viscous than thermosets, leading to additional problems or even rendering unfeasible certain manufacturing processes used for thermoset matrices and the cost of acquiring this material is considerably high. Among the most used manufacturing processes for the manufacture of parts with composite material is the thermoforming process, where the thermoplastic composite is heated and shaped in the shape of the part by means of a press and heating system. In order to better understand this process, the present project intends to study the node sharing technique for the thermoforming process of composite materials.
Keywords: Thermoforming, Composite Materials, Finite Element Model

INTRODUCTION

Structural composite design strategies along with current production techniques should be planned together to achieve the best structural performance together with an adequate production cost. To reduce manufacturing costs in composite materials, simulation tools can be used to predict production problems in the early stages of the process, thus avoiding losses due to the disposal of defective parts. There are several manufacturing processes, such as manual lamination, filament winding, automatic fiber deposition, etc. Each of these processes has advantages and disadvantages depending on the part to be fabricated, structural criticality of the same and cost.

If on the one hand there are various types of manufacturing processes to produce a particular structural component, on the other hand, there are also various types of mats as well as reinforcements which combine to form the composite material. Considering only the polymer matrices, these may be thermo-fixed or thermoplastic. The thermoplastic matrices undergo a curing process since the thermoplastics undergo a consolidation process, and these polymers can be molded again when subjected to a heating, which is not possible for the thermo-fixed matrices. Among the various advantages of thermoplastics, it has been found that the processing time of these materials is considerably lower when compared with thermosets, which increases the industrial production of pieces of composite material using this type of matrix, moreover, these materials can be reused. However, the cost of thermoplastics is still higher than thermosets, and also the processing temperatures are higher. Within the various manufacturing processes of parts in composite, the thermoforming process appears to be one of the most promising for the manufacture of parts in thermoplastic composite materials. This process can lead to a very attractive production rate for the industry and also the parts manufactured by this process have a good quality.

On the other hand, several problems can occur during the thermoforming process, significantly affecting the final quality of the part. Defects induced by processes such as local buckling of fibers, wrinkling of layers, relative slip between layers, and shape distortions (Wolthuizen et al., 2014) are frequently observed during the prepregs formation, and the correction of these problems almost always require costly modifications of tooling, as well as the accomplishment of several tests in order to discover the best configuration thus minimizing the failures.

During the thermoforming process using unidirectional materials (UD), various failure modes are activated which can be categorized as inter-laminar and intra-laminar mechanisms. Intra-laminar mechanisms involve the modes of deformation of a set of parallel rigid fibers incorporated in a polymer matrix. The fibers are capable of sustaining a high-stress level when subjected to an axial load in the plane and tend to slide due to shear stresses in the plane resulting in considerable defects in the fabricated part (figure 1).

Other important intra-laminar mechanisms are the transverse distortion due to shear between layers and bending of the layers. Both mechanisms lead to considerable distortions off the plane. The interlayer mechanisms associated with the friction between layers and layers with the mold play an important role in the relative displacement between the layers of the laminate.

Figure 1 – Wrinkling from the process of thermoforming (Wolthuizen, 2014).

Furthermore, polymers exhibit viscoelastic behavior in the sense that their properties are time-dependent and also their properties are temperature dependent. The thermo-viscoelastic properties of the thermoplastic composites are due to the matrix, which can be considered as an isotropic material, but when combined with the reinforcement to form a composite, the elastic thermal viscoelastic behavior becomes anisotropic.

Finally, numerical simulation tools can be used to simulate the thermoforming process in order to determine the formability of a pre-impregnated laminate with respect to a given tool geometry as well as the defects that may occur and, distortions of that part. The standard procedure is based on problem-solving using the finite element method, where complex geometries, nonlinear materials behavior, advanced contact interactions, and manufacturing constraints can be assembled.

Therefore the understanding of this process and the possible deviations that may occur is of the utmost importance in order to apply it effectively. At this point numerical methods, in particular, the finite element method, constitute a powerful tool to predict possible deviations, reducing production costs.

MATERIALS AND METHODS

In order to achieve the proposed objectives, a methodology based on simulations and results verification is proposed, comparing them with those available in the literature.

The approach required to perform the work will make use of the fact that laminated materials are made up of stacked blades with different orientations for the fibers, and therefore, this being an important parameter to be studied, as well as temperature, time and pressure used in the process.

Experiments

The necessary experiments will be carried out to simulate the process of thermoforming of composite materials using molds with simple geometry, such as the top layer (omega) profile. The parameters of the materials to be used, especially those related to the viscous parameters of the material, will be those available in the literature.

In order to carry out the experiments, which were necessary for the validation and verification of the developed model, it was first made the thermoforming apparatus, such as the heated press (hot plates) and the forms of conformation, shown in figure 2. Subsequently, the performance of the step described above and the manufacture of the samples will be carried out, where they will be compared with the desired CAD model so that possible distortions of shapes and other possible faults can be verified.

Figure 2 – Thermoforming apparatus

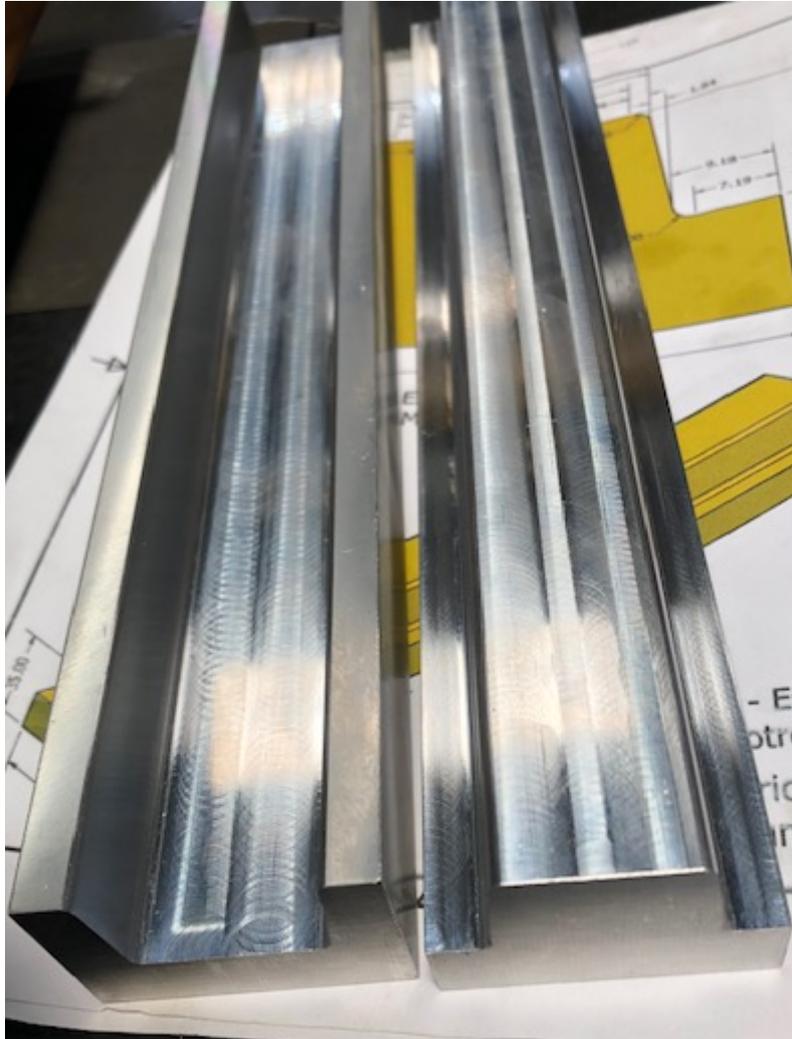An aluminum mold, as show in Figure 3, was used to manufacture a omega profile part.

Figure 3 – Aluminun mold.

Finite element model

In order to execute this research project, the numerical part has an important role, since it will be essential for a better understanding of the process of thermoforming.

In process modeling, there are basically two approaches, the discrete and the continuous approach. In the discrete approach, all components of the composite lamina are modeled (Vahid et al., 2017 and Boubaker et al., 2005), where friction between laminate layers is considered. These complex interactions result in a great computational cost. This approach is widely used to analyze the composite's formability, to understand the deformation mechanisms of the reinforcements during the process and also to study the tensions in the different directions of the laminate.

On the other hand, the continuous approach is widely used in the macroscopic simulation of laminates. In this approach, the laminate is discretized using shell or solid elements. This approach results in less computational time and is more suitable for studying the residual stresses and shape deviations of the laminate due to the process (Vahid et al, 2017).

The mechanics of fiber fabrics constitute a three-dimensional problem due to how the fabric are made (Boubaker et al, 2005). Boubaker et al. (2005) proposed a discrete model using massless rod elements interconnected by springs at nodal points where point masses are also located to form a unit cell to model static and dynamic tissue behavior. These models are called discrete models. In these models, they take into account the difficulties of modeling the interactions among the

fibers due to the weft of the tissue, however, the layers are not considered as continuous means (Wang et al, 2013).

The discrete models are designed for use on both the meso and macroscopic scale. This approach is used to verify the formability of the laminate as well as strain-strain relationships in different directions and also to better understand the reinforcement deformation process (Vahid et al., 2017).

Another computational approach to simulate the process of thermoforming is done through continuous models, usually using shell elements for each layer of the laminate (Wang et al, 2013). This approach is widely used on the macroscopic scale, in which, regardless of the type of fabric, the layers of the laminate are considered homogeneous (Vahid et al, 2017).

Each homogenized layer can undergo large deformations in both shear and bending (Vahid et al, 2017). As expected, the mechanical properties of the layers are determinant for the formability of the material in question (Wang et al, 2013).

The modeling of the polymer material used in the thermoforming process constitutes a critical point for the simulation, since the slip mechanisms between the sheets, as well as the shearing occurring within the composite material layer, which is one of the The main factors for this process depend on the mechanical properties of the polymer at the temperature at which the process will occur (Vahid et al, 2017). The composite material layers are modeled as being composed of an anisotropic material with hyperelastic thermo-viscoelastic behavior.

To perform the simulation of the thermoforming process, this work uses membrane elements (without flexural stiffness) together with shell elements, and these elements share the same nodes (Figure 4). In this approach the membrane element is used to represent the fibers of the fabric, whereas the shell elements are used to represent the matrix of the composite. For both elements, a ortotropic constitutive law are addopted, but for the shell elements, to improve the model accuracy, it is regarded the bending stiffness idealization. In this sense, a qualitative simulation of a thermoforming process of a laminate composed of pre-impregnated carbon fiber sheets with epoxy resin was carried out.
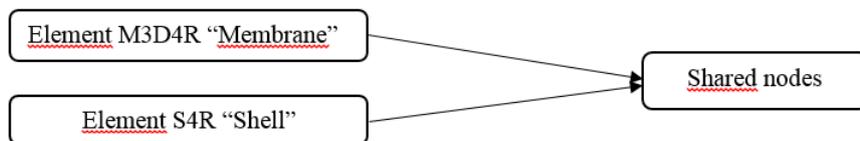

Figure 4 – Shared nodes schema

In this model the molds used rigid elements of 4 nodes. Already the laminate used 4-node membrane elements, together with bark elements, with 4 nodes and reduced integration.

The simulation was performed using finite element explicit algorithm, thus the increment time can increase the simulation time, on the other hand, the model is rather simple, thus the overall simulation time are about 1 hour in a 4 cores computer.

As a boundary condition, the lower mold had all the restricted degrees of freedom (condition applied at its reference point), while the upper mold had all its degrees of freedom restricted, but a prescribed downward displacement (y-direction) was imposed at the reference point.

To model, the friction and the contact between layers were considered a coefficient of friction of 0.3 for the tangential behavior and the hard contact model for normal behavior.

The laminate had its right border with all restricted degrees of freedom, simulating a condition of fixing the fabric in the mold. Figure 5(a) and 5(b) presents the proposed model together with the boundary conditions applied.

RESULTS

In this first simulation were used the constitutive models of material native to *Abaqus^{TM}*. The properties of the simulated material are shown in tab 1. It is important to notice that for unconsolidated fabric, the properties used for an orthotropic material is less than 5% of the table 1 values.

Fig. 6(a) shows the simulation results for unidirectional four layers carbon fiber laminate ($[0/90/0/90]$) and Fig. 6(b) shows the thermoforming results. As expected the finite element model was capable to model the wrinkles in the fiber direction as for the experiment.

The final results are show in Figure 7(a) and 7(b). It is possible to see the laminate wrinkles for this simulation, which corroborate the forming process as are shown in Figure 8.
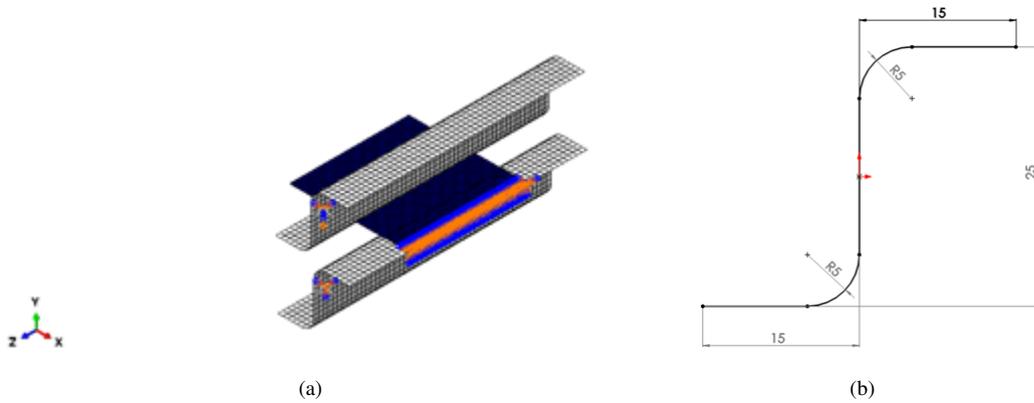
(a)   (b)

Figure 5 – (a) Finite element model boundary conditions; (b) Punch dimensions

Table 1 – Carbon fiber epoxi Prepreg properties.

property	Value
Density $[g/m^3]$	1.39
E_{11} [GPa]	140.0
E_{22} [GPa]	10.0
G_{12} [GPa]	5.4
v_{12} [GPa]	0.3

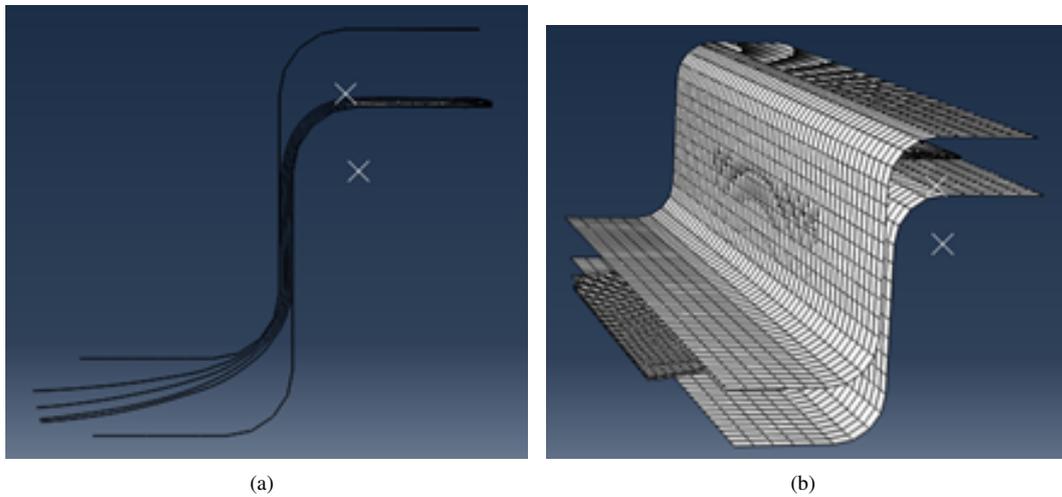(a)   (b)

Figure 6 – (a)View of the composite forming during the simulation; (b)Lateral view of the conformation process simulation

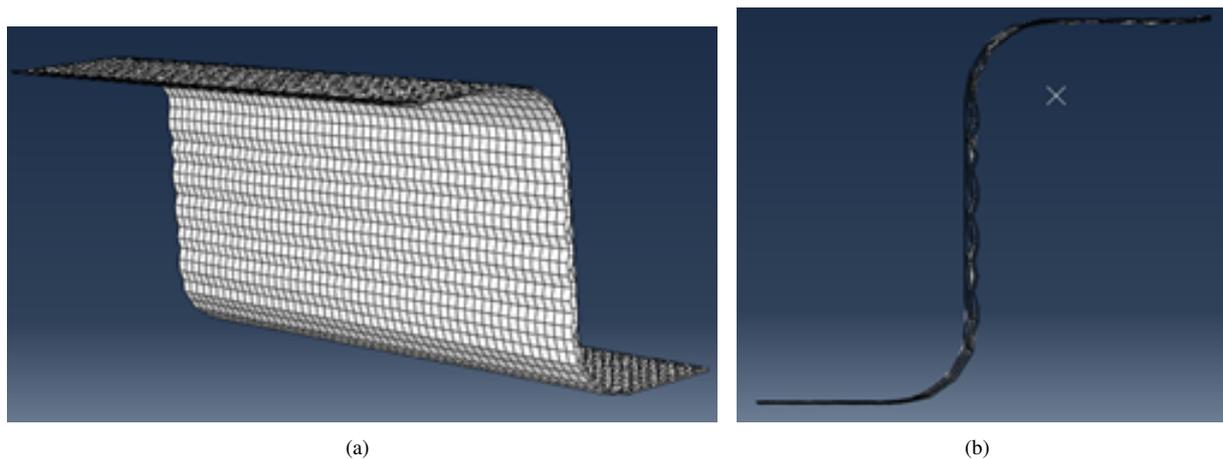(a)   (b)

Figure 7 – (a)Finite element model during conformation process; (b)Another view of the finite element model during conformation process

Figure 8 – Thermoforming Composite experimental results

CONCLUSIONS

To date, a qualitative test of a forming process, using the node-sharing technique, was performed. The computational results showed to be coherent with the experiments, with wrinkles with similar configuration.

REFERENCES

Abadi, M.T., Viscoelastic model for thermoforming process of thermoplastic composit sheets, The 9th International Conference on Flow Processes in Composite Materials, Quebec, 2008.

Araújo, A.L., Mota Soares, C.M., Mota Soares, C.A. A Viscoelastic Sandwich Finite Element Model for the Analysis of Passive, Active and Hybrid Structures. Applied Composite Materials. 17, 529-542 (2010).

A. Ridruejo, C. González, J. Lorca, A constitutive model for the in-plane mechanical behavior of nonwoven fabrics, International Journal of Solids and Structures 49, 2012.

Bakhalov N and Panasenko G. Homogenization: Averaging Processes in Periodic Media. Kluwer: Dordrecht, 1989.

Bensoussan A, Papanicolaou G and Lions J L. Asymptotic analysis for periodic structure. North Holland: Amsterdam, 1978.

B.B. Boubaker, B. Haussy, J.F. Ganghoffer, Discrete models of fabrics accounting for yarn interactions, Eur J Comput Mech, 14 (2005), p. 653.

P. Wang, N. Hamila, P. Boisse, Thermoforming simulation of multilayer composites with continuous fibers and thermoplastic matrix, Composites Part B: Engineering, Volume 52, September 2013, Pages 127-136.

Vahid Z., Hassan M. N., Jos S., Ahmad R. B., Morteza A., Rinze B., A new procedure for Finite Element simulation of forming process of non-homogeneous composite laminates and FMLs, Composite Structures, Volume 163, 1 March 2017, Pages 444-453.

Vahid Zal, Hassan Moslemi Naeini, Jos Sinke, Ahmad Reza Bahramian, Morteza Abouhamzeh, Rinze Benedictus, A new procedure for Finite Element simulation of forming process of non-homogeneous composite laminates and FMLs, Composite Structures, Volume 163, 2017, Pages 444-453.

Vanclooster, K., Forming of multilayered fabric reinforced thermoplastic composites, Doctoral Thesis, Katholieke Universiteit Leuven, Leuven, 2009.

Wei Tan, Brian G. Falzon, Modelling the crush behavior of thermoplastic composites, Composites Science and Technology, Volume 134, 2016, Pages 57-71.

Wolthuizen, D.J.; Schuurman, J.; Akkerman, R; Forming limits of thermoplastic composites; Key Engineering Materials, v 611-612, p 407-414, 2014.

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