THERMOPLASTIC FIBER REINFORCED PLASTICS: MATERIAL CHARACTERIZATION AND DRAPING SIMULATION

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Abstract
Thermoplastic fiber reinforced plastics, due to their property, are widely used in engineering in order to reduce the weight of car components. Their application is becoming particularly important in the design of lightweight structures, especially, in the framework of electro-mobility. Therefore, it is a challenging task to develop and improve an industrial technology that can meet the requirements in terms of material costs and component quality. However, the simulation and optimization of the process-chain, which leads to the production of lightweight constructions, is a very demanding effort.
In the present work, an example of the preforming procedure as part of the process-chain related to a car door production is described and simulated using the Finite Element (FE) software LS-DYNA®.

1 Introduction

In the present paper, a description of the process-chain simulation developed in the framework of the project 3DProCar is given. The development activities of the aforementioned project include theoretical, analytical and experimental work related to the entire process-chain in order to produce a light weight car door and in more general case automotive components with complex geometry. Particularly, each individual process is analyzed and simulated in order to assure the application of the project results to other car structures and lightweight components.
A thorough understanding and reproduction of the manufacturing process is very important to correctly evaluate the orientation of the fiber and the related structural stiffness at the end of the process chain. In the specific case, the use of finite element analysis can be considered particularly relevant in the prediction of the preforming process, helping to detect the critical forming regions and to minimize the presence of wrinkles.
A correct interpretation of the material behaviour is not a simple task, especially in terms of modeling and computation time in case of complex simulations. Woven fabric can be described, depending on the application, by detailed multi-scale models or by models formulated in the framework of continuum mechanics. However, at large scale, as in draping simulations, employment of highly detailed models leads to high costs in terms of computation time and especially shows an increased complexity with regard to the parameters identification and validation.
In the first part of this work, a description and application of the recently developed material model **`*MAT_249`** is given. In the specific case, characterization of the material model is performed by comparison of experimental and numerical results based on tensile, bending and shear tests. In the second part of the paper, a short overview of the industrial process is given and the related simulation steps are described. Subsequently, results of the draping simulation are illustrated and conclusions are drawn out.

2 Description of the material model – MAT_249

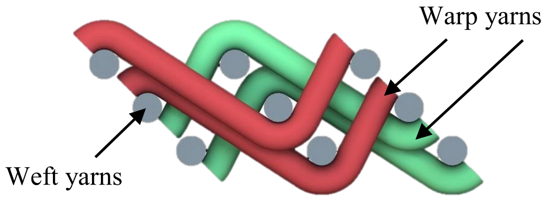
The material model employed to describe the behaviour of the woven fabric is **`*MAT_249`** for thermoplastic pre-pregs and dry fabric. **`*MAT_249`** is particularly suited for draping simulations due to several reasons: homogenized macroscopic approach, matrix and fibers are directly accounted for by the constitutive model and especially it can be used with shells [1]. In the specific, it is assumed that the material is characterized by two contributions which describes the structural behaviour of fibers and matrix. The latter is modeled with an elasto-plastic constitutive law based on Von-Mises plasticity theory which can be combined with the influence of temperature. On the other hand, fibers are represented by vectors stored at the integration point level and described by a hyperelastic material. Their behaviour under compression/tension is defined by means of stress-strain curves and the shear response, which takes into account the angle between neighbouring fibers, can be specified in terms of shear stress as a function of a given angle. The combined stress response is computed as the sum of the matrix and fiber stresses.

As additional feature, results obtained after the draping simulation, using **`*MAT_249`**, can be mapped employing the mapping tool ENVYO® and later on adopted to perform crash analysis [2].

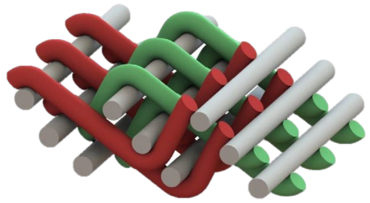
3 Material characterization

3.1 Experimental tests

The woven fabric, object of this work, is composed by four warp yarns per cm of width and by 3 weft yarns per cm of length (see Fig. 1). In both directions, the fineness of the textile is 1600 tex.



(a)



(b)

Fig.1: Fabric structure: (a) plane view and (b) tridimensional view

The deformation state involved in the draping process of a fabric is highly heterogeneous and can be considered rather complex. In particular, depending on the complexity of the geometry, which characterize the final shape of the component, different kind of deformation mechanism takes place during the preforming. In Fig. 2, description of the possible deformations for a typical geometry is given. As can be seen, three basic responses can be recognized: tension, bending and shear. In regard to the previous observations, the material characterization is performed on the base of tensile, bending and shear tests.

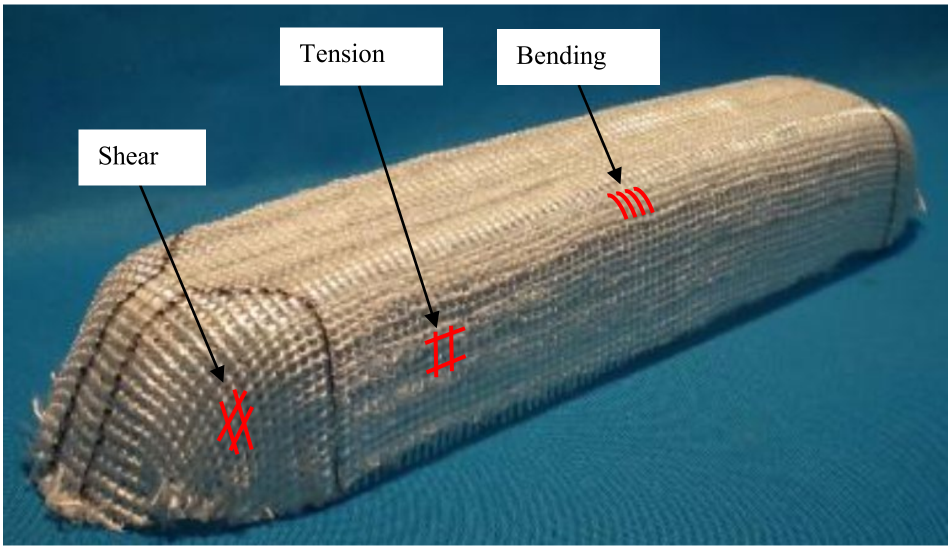
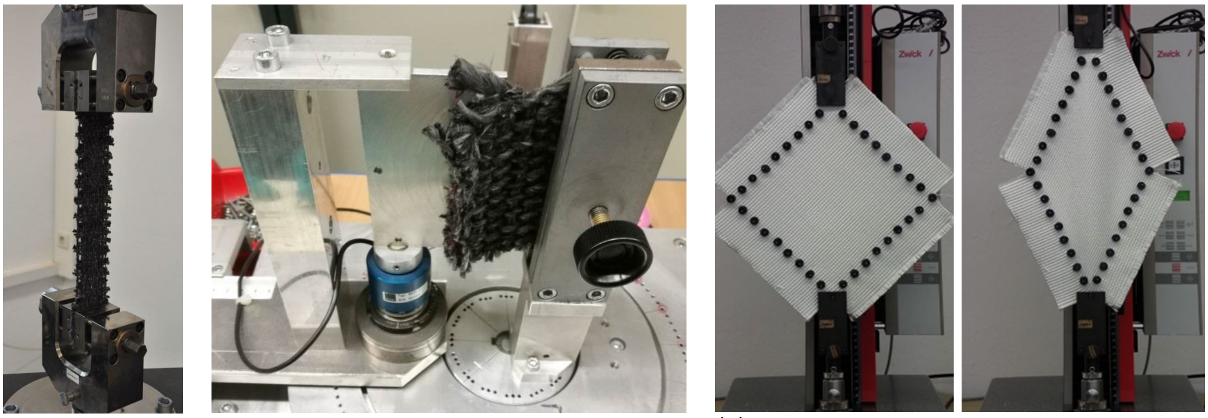


Fig.2: Observed deformations after draping for a typical geometry taken as example from the literature [3]

The tensile test is carried out on a sample of 200x55 mm², clamped by grips using jaws (see Fig. 3a). The bending behaviour is estimated by impacting the fabric against a rigid plate and measuring the reaction moment on the support throughout the test at different rotation angles (see Fig. 3b). Furthermore, in order to evaluate the drapability of the material, picture frame test on a sample of 200x200 mm² is performed. The specimen is hold by 4 clamping plates on the four sides and loaded on the crosshead (see Fig. 3c). During the experimental test, the load required to pull the crosshead is continuously recorded in order to evaluate the shear force as a function of the displacement or shear angle. It has to be noted that the thickness of the fabric has been estimated as 9.62 mm under a pressure of 0.025 N/mm².



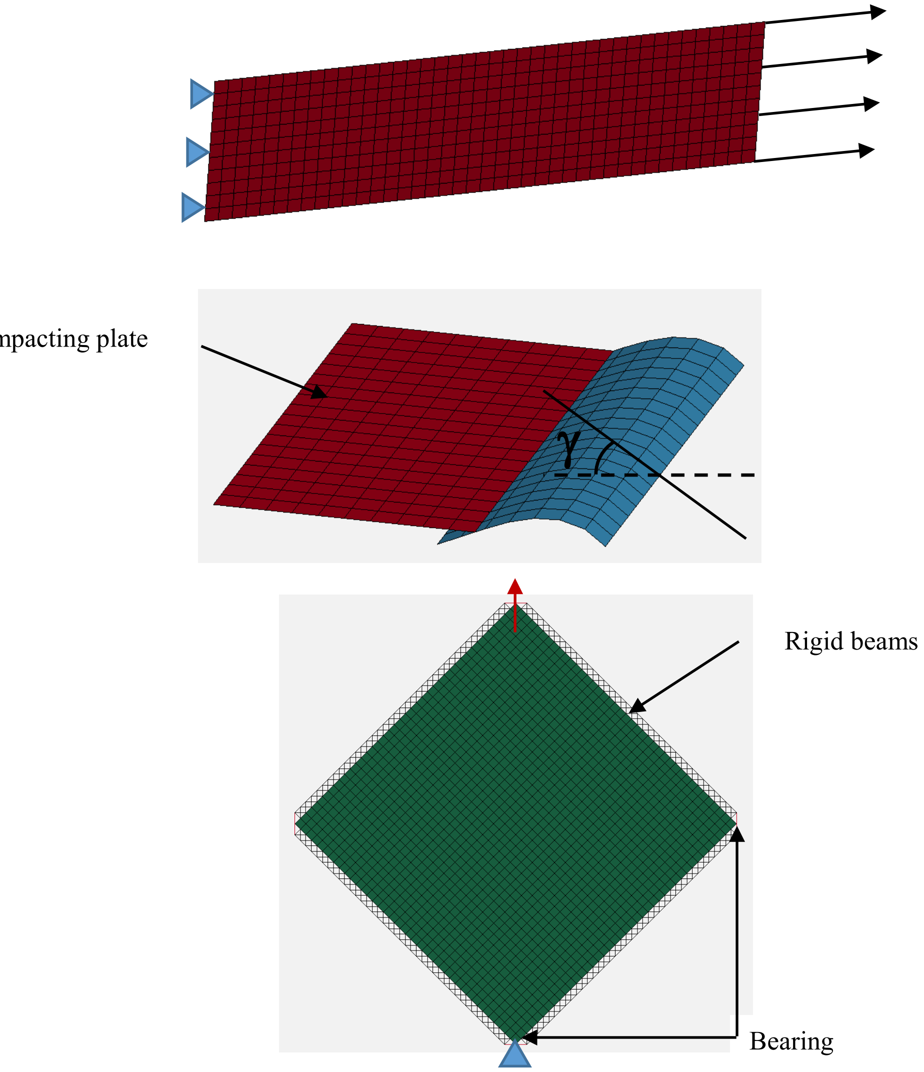
(a) (b) (c)

Fig.3: Experimental test set-up: (a) tensile test (b) Bending test and (c) picture frame test

3.2 Characterization of the material parameters

Quasi-static Finite Element Analyses (FEA), using the material model **`*MAT_249`** and the explicit solver LS-DYNA® version R10.0, were carried out for each proposed load case. Purpose of the numerical simulations was the calibration of the parameters related to the material model and later on evaluate the response under the entire component forming process.

(a)



(b)

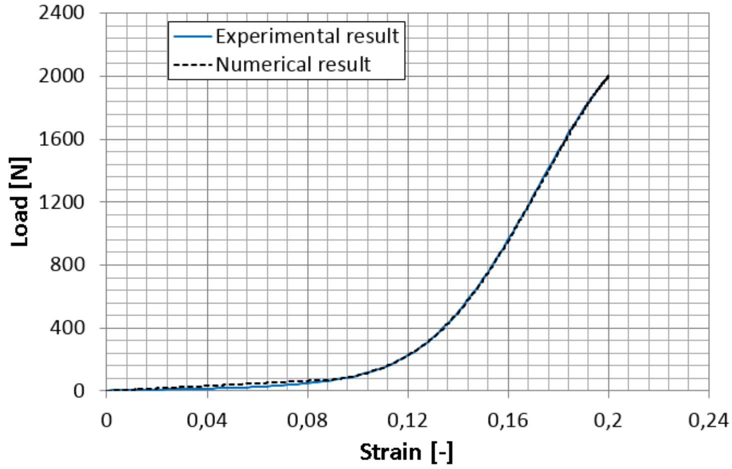
(c)

Fig.4: Employed FE model: (a) tensile test (b) Bending test and (c) picture frame test

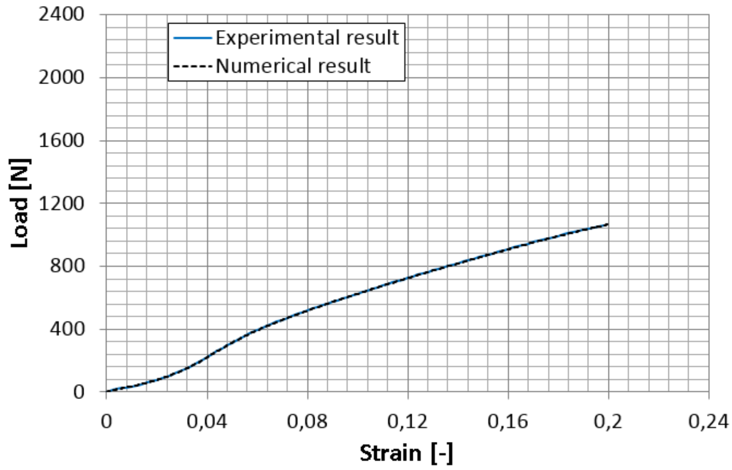
The employed FE-model take into account the same material card and element formulation. However, it has to be noted that the direction of the fibers is chosen according to the relative tests (tension and bending). In the picture frame test, the yarns are oriented at 45° with respect to the load direction and the clamping plates are modelled with rigid beam elements. Illustration of the described models can be found in Fig. 4.

In order to correctly represent the behaviour of woven fabric, shell elements with formulation equal to 16 (ELFORM=16) and modified integration rule to capture the bending behaviour, are employed. Furthermore, the interaction between the neighboring fiber families is accounted such that the resulting tensor is represented as pure shear stress state using the option METHxy=10 tailored for woven fabric, which represent an elastic shear response [4].

In Figs. 5, 6 and 7 the comparison between experimental [5] and numerical results are shown for tensile, bending and shear test, respectively. As can be seen, the material model is able to realistically predict the behaviour of woven fabric under the three planned load cases, both in warp and weft directions. The proposed material model can even correctly reproduce the strong non-linear trend that describes the bending moment as a function of the rotation angle, for each fiber direction. It has to be noted that the bending behaviour plays an important role in determining the wrinkling after draping of the fabric. Therefore, a wrong estimation of the bending behaviour can lead to unrealistic wrinkles, especially in terms of shape [6].

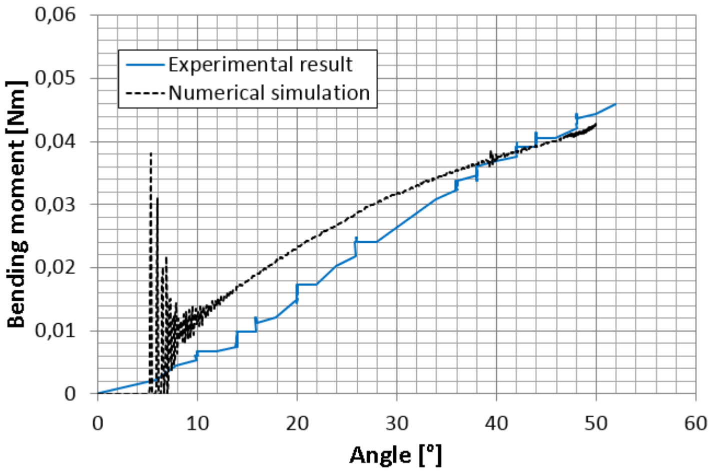


(a)



(b)

Fig.5: Experimental and numerical results of the tensile test: (a) warp yarns direction and (b) weft yarns direction



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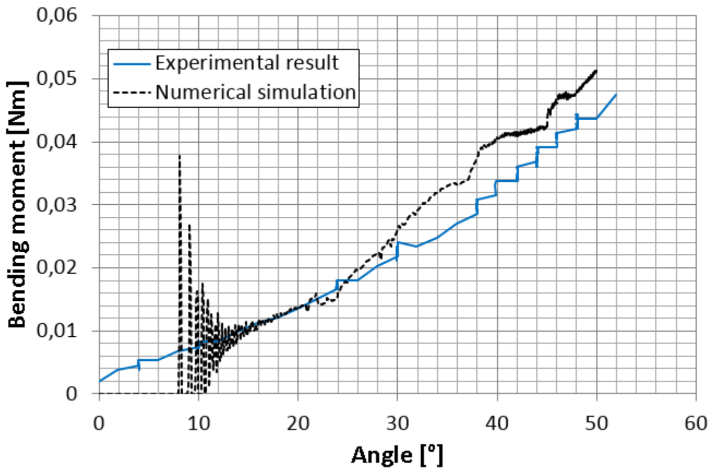


(b)

Fig.6: Experimental and numerical results of the bending test: (a) warp yarns direction and (b) weft yarns direction

Furthermore, the predicted load-displacement curve of the picture frame test nicely agree with the experimental trend, showing a changing of stiffness after the locking angle evaluated at approximately 28.5°.

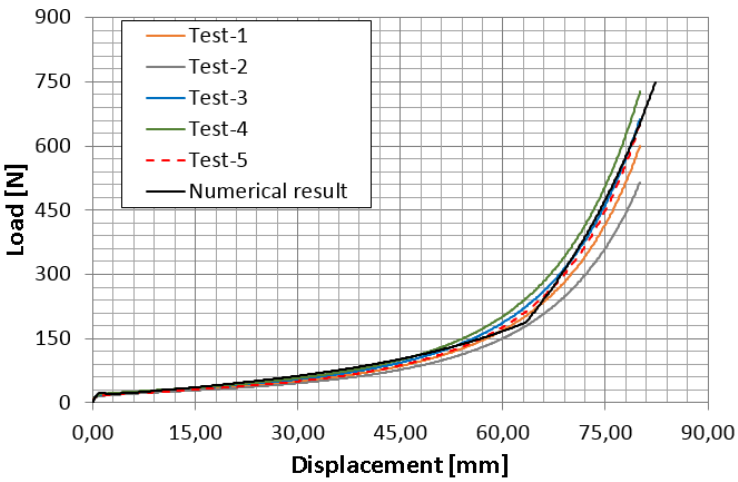
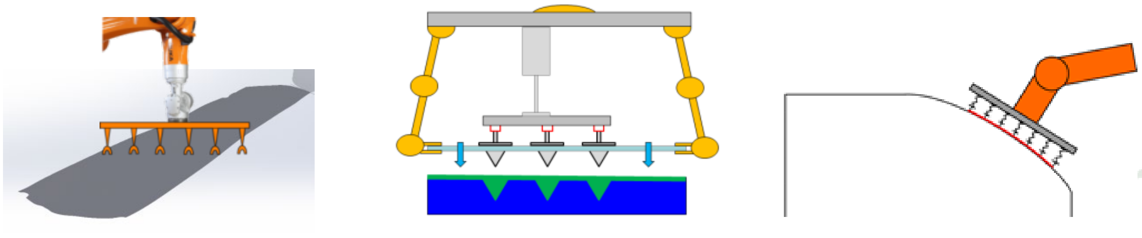


Fig.7: Experimental and numerical results of the picture frame test

4 Preforming process: draping simulation

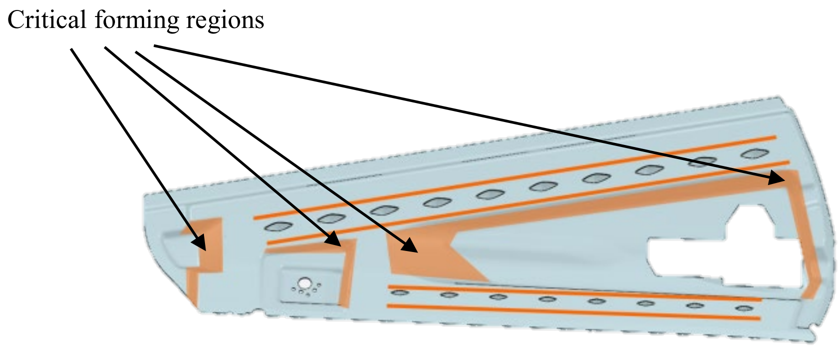
The draping process can be described by three different phases, which correspond to the lay-up of the fabric on the preforming table, the positioning of the textile according to the planned fixtures and the draping by means of the designed tools. It has to be noted that the industrial process is completely automated (see Fig. 8) and that the simulation of each single step represents the programmed manufacturing procedure.



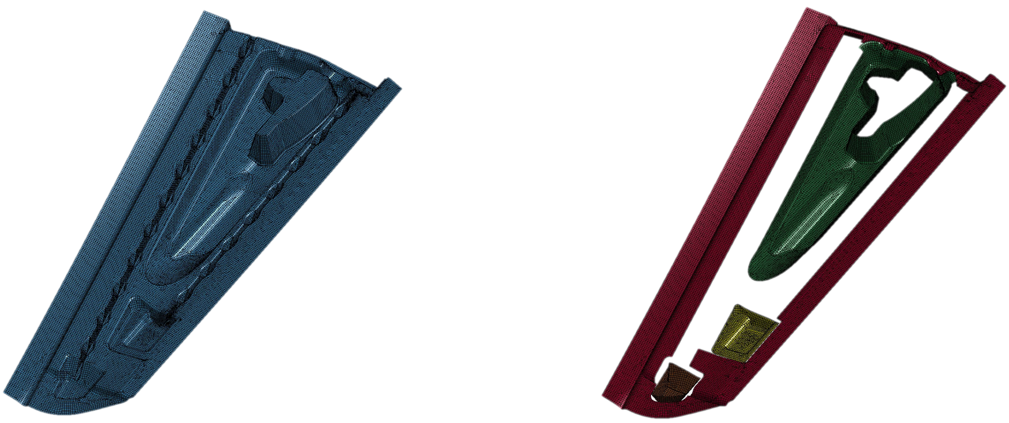
(a) (b) (c)

Fig.8: Automated industrial process: (a) Transport and lay-up of the fabric, (b) positioning on the forming table and (c) draping

In Fig. 9, the critical forming regions, the FE-model of the preforming table and the related tools are depicted.



(a)



(b) (c)

Fig.9: Employed FE model for draping simulation: (a) Critical forming regions, (b) forming table and (c) designed forming tools

As can be seen, a total number of three tools are modelled, with an additional blank holder to keep fixed the fabric during the draping. Moreover, the three tools are shaped in order to cover the most critical forming regions in terms of drapability.

Furthermore, it has to be noted that the initial orientation of the fibers is considered at 45° with respect to the reference system described in Fig. 10.

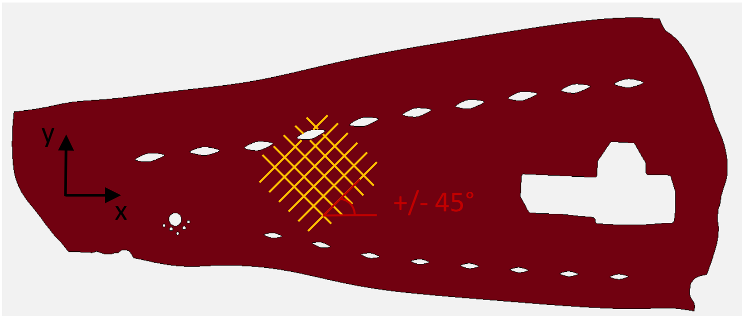
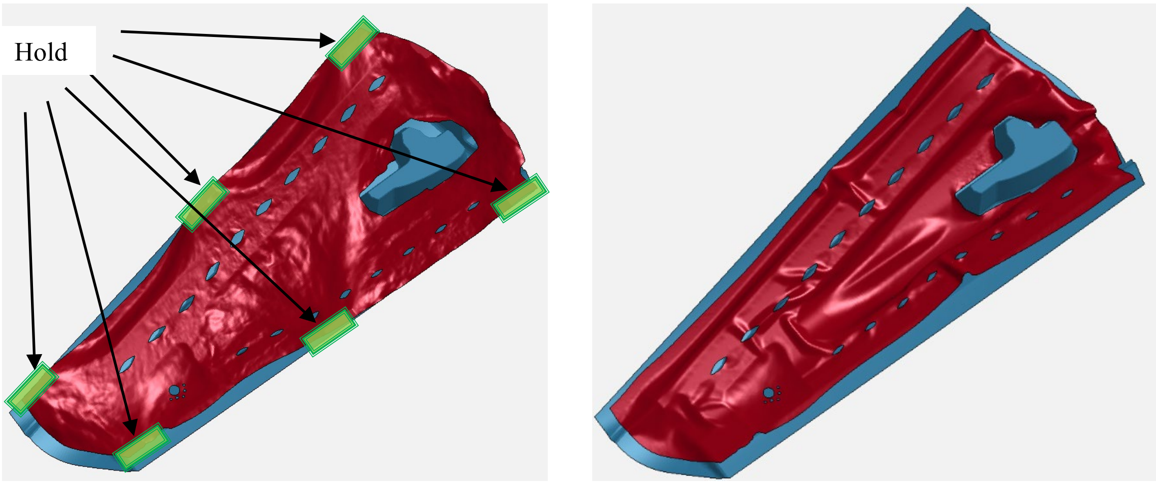


Fig.10: Assumed initial fiber orientation in the performed draping simulation

5 Numerical simulation: gravity

At the first step of the numerical simulation, the fabric is considered hold by a robot in certain regions and subjected only to the action of the self-weight. As second step, the textile is considered free to lay-up on the preforming table under the effect of the gravity acceleration. Both final configurations of the aforementioned steps are illustrated in Fig. 11.



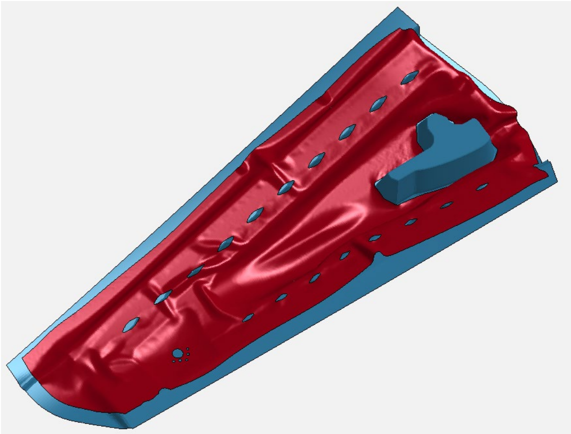
(a) (b)

Fig.11: Final configuration of the fabric subjected to self weight loading: (a) hold by robot and (b) after lay-up on the preforming table

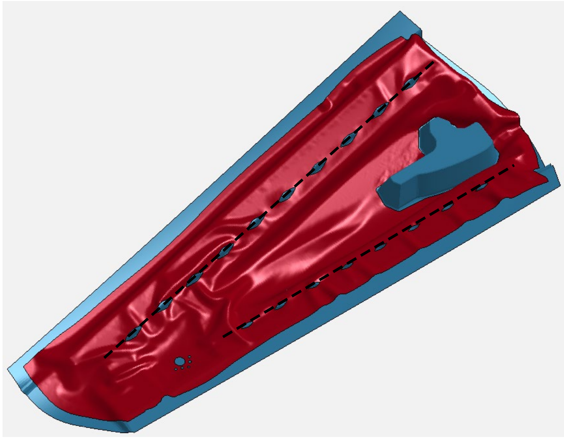
It can be seen that a significant amount of wrinkles are present in the central region of the preforming area. However, their distribution and entity are strongly dependent on the initial fiber orientation and on the proposed initial shape of the fabric.

6 Numerical simulation: positioning

In order to correctly position the oval necks of the textile on the appropriate locations of the preforming table, a third step of numerical simulation is performed. The resulting configuration, shown in Fig. 12, clearly brings to light the appearance of several wrinkles due to the fabric arrangement on the closest zones around the oval necks.



(a)



(b)

Fig.12: Final configuration of the fabric due to the positioning on the preforming table: (a) before positioning and (b) after positioning

7 Numerical simulation: draping

As last step of the process simulation, draping of the textile is performed according to the manufacturing procedure. As mentioned before, the first tool activated is the blank holder and later all the other tools are set in motion in order to drape the critical forming regions. It has to be noted, that the order in which the draping is carried out, in terms of chronological activation of each single tool, is totally arbitrary. Therefore, with a view to optimization, different temporal combinations should be tested. However, purpose of the present work is to evaluate the applicability of the numerical tool and the development of methods to carry out draping simulations of complex geometries.
In Fig. 13, the result of the numerical simulation is shown. It has to be noted that, currently, no experimental tests are available. However, validation of the simulated process is underway in the framework of the aforementioned project.
It can be concluded that the final deformed shape for the industrial process, object of the current work, shows a very nice draping behaviour even for very challenging geometry. Furthermore, it can be pointed out that the employment of the material model **`*MAT_249`** has shown no numerical instabilities in terms of unrealistic wrinkles confirming the results obtained by Scarlat et al. [7].

(a)

(b)

Fig.13: Final configuration of the fabric due to the draping on the preforming table: (a) before draping and (b) after draping

8 Summary and conclusions

In the present article the simulation of a draping process of a woven fabric is numerically studied. The draping simulation is carried out in order to develop a method to reproduce the manufacturing procedure, planned and organized in the framework of the project 3DProCar. Based on the evaluation of experimental and numerical results, the following can be concluded.
(1) Characterization of the material model **`*MAT_249`**, based on experiments and analysis, show the potentiality of a macroscale approach to simulate the behaviour of woven fabric by means of three basic types of test: tension, bending and shear tests.
(2) Comparison between numerical and experimental results, carried out on samples subjected to bending, brings to light the ability of the model to capture highly non-linear behaviour with a relatively simple numerical approach.
(3) The evaluation of the numerical results, in terms of draping, confirms the suitability of the proposed macro-scale approach to simulate the whole forming process to produce lightweight components of complex geometry.
(4) Based on the proposed results, additional numerical analyses can be performed, with a view to optimization, to reduce the wrinkles and improve the shape and size of the initial fabric. In particular case, the numerical simulation can be considered as a powerful tool to support the planning of automated manufacturing processes.

9 Acknowledgement

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10 Literature

[1] Klöppel T.: "Recent Developments and Application of *MAT_REINFORCED_THERMOPLASTIC", 11th European LS-DYNA Conference, Salzburg, Austria.
[2] Liebold C., Haufe A., Vinot M., Dittman J., Böhler P., Finckh H. and Fritz F.: "The Digital Prototype as Part of Envyo® - Development History and Applications within the ARENA2036 Environment", 11th European LS-DYNA Conference, 2017, Salzburg, Austria.
[3] Pierce R., Falzon B. G., and Thompson M.C.: "Combining draping and infusion models into a complete process model for complex composite structures", ICC M20 20th International Conference on Composite Materials, 2015, Copenhagen, Denmark.
[4] LS-DYNA Keyword User's Manual, Volume II, LS-DYNA R10.0, Lawrence Livemore Software Technology Corp (LSTC), 2017.
[5] Maron B.: "Beitrag zur Modellierung und Simulation des Thermoformprozesses von Textilverstärkten Thermoplasten", Dissertation Technische Universität Dresden, 2016, Dresden.
[6] Boisse, P., Hamila N., and Madeo A.: "Modelling the development of defects during composite reinforcements and prepreg forming." Phil. Trans. R. Soc. A 374.2071, 2016: 20150269.
[7] Scarlat G., Ramgulam R., Martinsson P., Kasper K. and Bayraktar H.: "Material Characterization of a 3D-Woven Carbon Fiber Preform at Macro-Scale Level for Manufacturing Process Modelling", 11th European LS-DYNA Conference, 2017, Salzburg, Austria.