Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 99 (2021) 437–442

www.elsevier.com/locate/procedia

14th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '20

Production of hybrid tubular metal-fibre preforms: development of a digital twin for the draping process

Paul Ruhland[a,*], Yizhou Li[a], Sven Coutandin[a], Jürgen Fleischer[a]

[a]*Karlsruhe Institute of Technology, wbk Institute of Production Science, Kaiserstr. 12, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +49 1523-9502608; fax: +49 721 608-45005. *E-mail address:* paul.ruhland@kit.edu

Abstract

Hybrid shafts or rods with a metallic end fitting and a load transmitting area made of fibre reinforced plastics possess a great potential in terms of lightweight design, e.g. in automotive industry or aviation. One essential and quality-defining process step in the manufacturing of such parts is the draping of dry braided fibre fabrics onto the shape of the metallic end fitting. To explore the immature draping process and to derive the draping tool geometry a digital twin based on finite element simulation has been developed and validated by first experiments.

Keywords: Fiber reinforced plastic; Preform; FE-Simulation

1. Introduction

In the field of lightweight design fibre reinforced plastics (FRP) are a widely used material due to their good density-related mechanical properties such as high stiffness and strength.
Since the resistance of FRP under multi-axial or tribological stresses is insufficient in many cases, the load introduction area of a part is often made of metallic materials. This leads to FRP metal hybrid parts.
Manufacturing processes for such hybrid parts can be divided into intrinsic and extrinsic hybridization processes. In intrinsic hybridization processes the joining of both components occurs while one of the components is casted or formed. This leads to an easy process route, low hybridization costs and high performance parts [1]. In extrinsic processes, however, components are joined after both have reached their final geometry. Joining methods are e.g. adhesive bonding, bolting and screwing.
For the production of longitudinal parts, such as shafts, rods, profiles or axles, extrinsic and intrinsic manufacturing processes for hybrid parts exist. FRP profiles can be manufactured in wet fibre winding, pultrusion or resin transfer moulding process [2, 3]. These profiles are then extrinsically joined with metal end fittings by bolting, adhesive bonding, pressing, riveting or screwing [4, 5]. An example for the intrinsic hybridization is the integral blow moulding process. In this process, a thermoplastic pre-impregnated braided hose which is heated above the melting point is formed by pressure from the inside against metallic end fittings [6]. Short process times are advantageous. However, the thermoplastic semi-finished products used are comparatively expensive
Another process with great potential in terms of cost, cycle time and component performance is the rotational moulding (RM) process [7, 8]. In this process a hybrid preform, consisting of metallic end fittings and a dry braided fibre area as shown in Fig. 1a, is infiltrated with a resin by centrifugal forces due the rotation of a mould. The overall production process of such a hybrid preform has been described in previous papers [9]. The focus of this paper is the draping process in which the monolithic preform is formed onto the shape of the metallic end fittings (as shown in Fig. 1b. The draping is performed by a forming unit with silicone membranes inside. After the monolithic preform is heated up by infrared radiators which leads to the melting of a binder inside the preform, the draping process starts. The membranes are pressurized one by one and therefore pressed against the braided sleeves.

10.1016/j.procir.2021.03.062

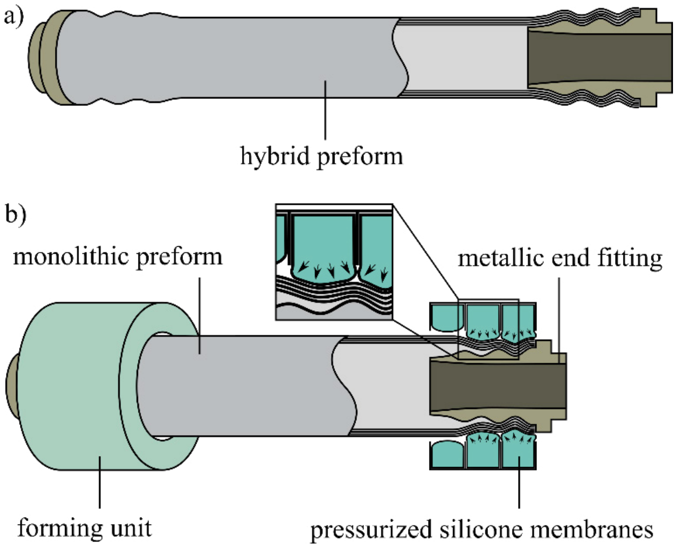

Fig. 1: For the rotational moulding process used hybrid preform (a) and draping process (b).

The braided preform is thus formed onto the metallic end fitting on the inside. Since the main deformation mechanism during the draping process is shearing of the textile, an additional axial movement of the forming unit is necessary to compensate the radial deformation due to the membranes.

So far, the described process and prototypic production machinery have been developed at the wbk Institute of Production Science. To gain a better process understanding of the immature draping process and to optimize the draping process and draping tool geometry, a digital twin using a finite element (FE) simulation model is presented in this paper.

2. FE model of textile draping processes: state of the art

Fibre reinforced plastics are so-called multi-scale materials: Due to the fibrous reinforcement structure, architecture and properties on the smallest scale influence the behaviour of the overall component. FRP in the using phase, but especially the textile products during forming, are usually modelled on three scales: micro, meso and macro.

On the lowest scale, the microscopic scale, individual filaments are modelled as such in their interaction with the surrounding filaments. Due to the high level of detail of simulations on the microscopic scale, they are usually only used for the calculation of material properties or, for example, for the investigation of pore formation or microparticles on the draping. [10–13]

On the mesoscopic scale, single filaments are joined into bundles of fibers or yarns. The textile architecture of the yarns, e.g. the woven or braided structure, is shown. So-called unit cells are often observed at this level which – in the case of fabrics, for example – consist of one woven fabric cell. [14, 15]

On the macro level, the complete component is considered. The properties of yarns are homogenized in layers to form curved shells or membranes. Several layers can be in contact with each other or with the environment, e.g. tools. Typically, the component-specific design of the process is considered on this level, since the simulation area covers the complete component. [14, 15]

Nishi describes a macroscopic approach for simulating dry fabrics in which the membrane and bending properties of the textile are decoupled. For this purpose, the membrane elements which map the in-plane anisotropic, non-linear material properties are duplicated as shell elements and offset so that the elements cannot influence each other. The macroscopic model is compared with a mesoscopic model and shows good agreement depending on the bending stiffness of the shell elements. [16]

Similar to [16], Kärger et al. predict the draping behaviour of fabrics by decoupling membrane and shell elements. The authors additionally reflect the results of the draping simulation in the design of the component so that process and component can be optimized simultaneously in a closed simulation chain with the help of an evolutionary algorithm. [17]

Coutandin et al., too, use the decoupling of membrane and shell elements for predicting fibre orientation and wrinkling in stamp preforming successfully. [18]

So far, no approach has been shown using the above mentioned FE method to simulate the draping of hollow textile structures such as braided sleeves in a multiple layer stack.

3. Approach: Digital Twin for the Draping Process

As described in Chapter 1, a digital twin using an FE simulation, will be beneficial to understand the draping process and optimize process parameters and tools. Therefore, an FE model in the commercial software ABAQUS has been developed that usesusing the decoupling of membrane and shell elements to build a macroscopic copy for the draping process.

The simulation model, especially the geometry modelling and process parameters such as pressure and movements, shall be parametric in a way that these parameters can be optimized in an automated loop later.

4. Simulation Model for the Draping Process

A simulation area as shown in Fig. 2 has been chosen to develop the digital twin. Since the forming units are symmetric and identic at both ends of the machine, the simulation area covers half of one forming unit.

The simulation model is built by parametric modelling using ABAQUS and Python. The necessary modelling steps are described below.

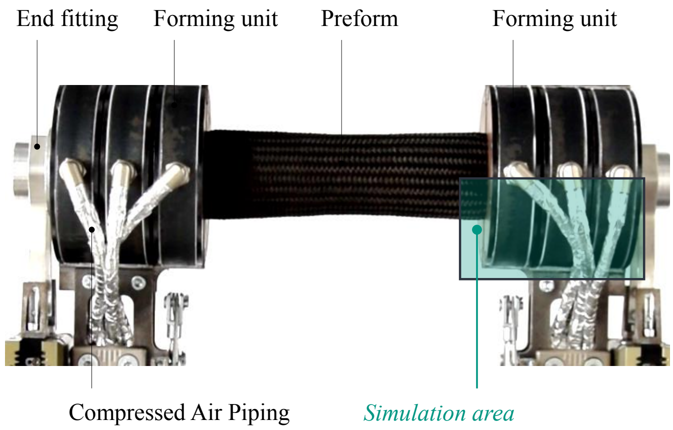

Fig. 2: Prototypic draping machine with two symmetric forming units.

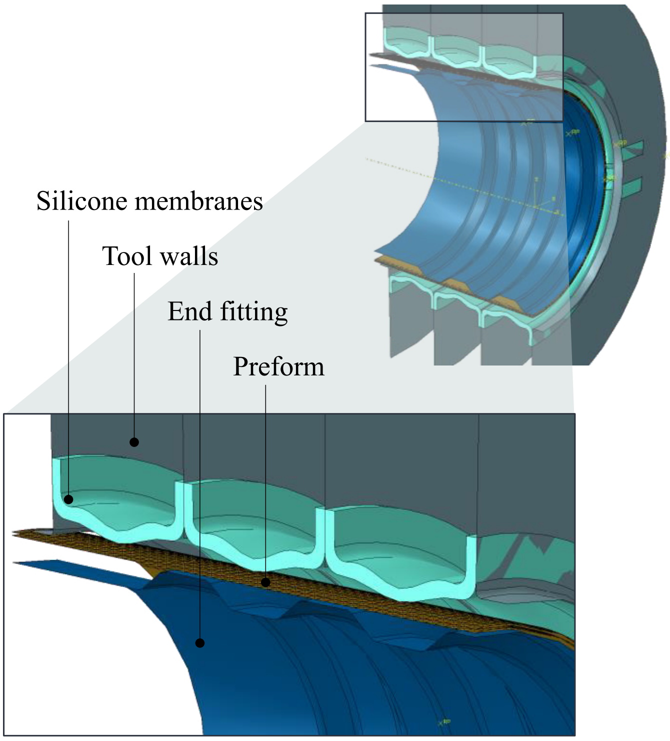

Fig. 3: Geometry modelling of the draping tool, end fitting and the preform.

Geometry Modelling

Using existing symmetries of the draping process, the simulation area consists of the one half of one forming unit, cutting the six necessary draping membranes of each forming unit in half. Including the preform and end fitting, the simulation area consists of four groups of parts which are shown in Fig. 3 and described below:

- The (steel) walls of the draping tool and the (aluminium or steel) end fitting are modelled as non-deformable rigid body parts since their deformation is very small compared to the very flexible silicone membranes and the textile
- The silicone membranes are one of the central elements in the draping process. Their real shape (assembled in the prototypic forming tool) is shown in Fig. 4a. Since their optimal shape is unknown, their geometry is modelled parametrically as deformable bodies. ABAQUS geometry creation methods such as Revolution, Extrusion, Loft and Sweep have been tested to find the best way creating the shape. It has been found that the Sweep method fits the possible shape of the membranes best. The geometry, which is shown in Fig. 4b, is completely changeable by 8 key parameters.
- The monolithic preform, consisting of two layers of braided fabrics, is modelled as coupled shell and membrane elements (as described in chapter 2 [16]) in a cylindrical shape.

Material Modelling

Draping Membranes are modelled as hyper elastic materials. The material of the membranes is a silicone type "Wacker Elastosil M 4630". In [19], the Ogden and Neo-Hooke model show good match between simulation and reality for rubber materials as used for the draping membranes. Tensile tests have been performed to evaluate the material data for the silicone.

The material parameters of the preform have been evaluated using of picture-frame test and cantilever test. Tensile properties of the fibres have been taken from literature. The results of the experimental data are described in [9]. The textile material properties are integrated into the model by using the ABAQUS *FABRIC material model.

Meshing

For the textile preform, shell and membrane sections are meshed separately. The shell is meshed using S4R elements as described in the work of [20] and [21]. The Membrane is meshed with M3D4R elements. It has been found that for modelling textiles the element edges should ideally follow the fibre directions. Therefore all element cells are diagonally divided. The final meshed part is shown in Fig. 5a.

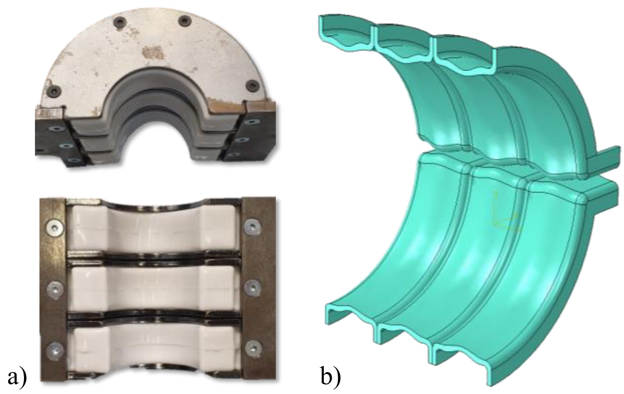

Fig. 4: Draping tool (a) and parametric geometry model for the draping membranes (b).

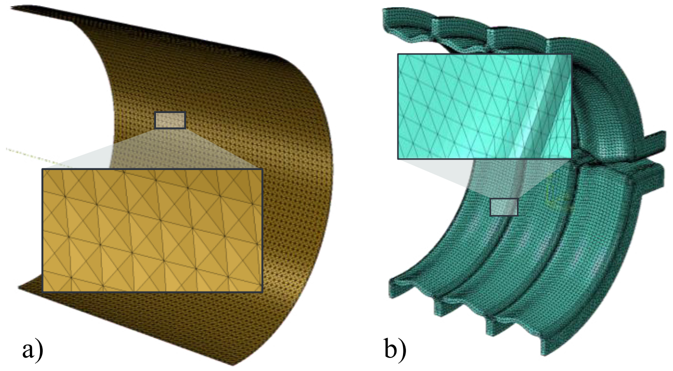

Fig. 5: Meshed geometry of the preform (a) and the draping membranes (b).

The silicone membrane is meshed using a bottom-up approach. Similar practices have been found e.g. in [22] modelling a car tire. The element type for the membranes is C3D8R. The meshed part is shown in Fig. 5b.

Contact Modelling

The following contacts exist in this simulation model:

- *Ply-Ply contact* between textile layers
- *Ply-membrane contact* between textile and draping membrane
- *Ply-fitting contact* between the textile and the end fitting on the inside
- *Membrane-membrane contact* between the draping membranes at certain positions

A VFRIC user subroutine for using more complex friction models in future works, especially for the ply-ply contact, has been integrated. For the results shown here, a basic coulombs friction law with μ = 0.3 has been used.

Loads and Boundary Conditions

The model uses the symmetry of the draping tool to save simulation time (c.f. Figure 1).
The membranes are loaded with a uniform pressure from the inner surface area, following a linear amplitude. This pressure occurs subsequently for the three membrane rings.

Results

The results of a first simulation using the above described simulation model described above is shown in Figure 6.

The results show the deformation of both the draping membranes under pressure and of the two-layer preform.
In Figure 6a shows the situation before pressure is applied is presented. The shown nominal fabric strain EFABRIC12 represents the shearing of the textile material. In this case, a value of zero corresponds in this case to the fibre direction of +/- 45 degree of the undeformed preform.
In Fig. 6b, the first draping membrane is pressurized. Subsequently, the other membranes are pressurized in Fig. 6c and d. The draping of the preform onto the metallic end fitting leads to a shearing of the preform. Especially at the contact point of two membranes (shown in Fig. 6e) high shearing angles occur. In real preforming this might lead to wrinkles.
First experiments show that these wrinkles also occur in reality (see Figure 7). In future works the simulation model needs to be validated with more experiments to compare geometry, fibre orientation and material flow.

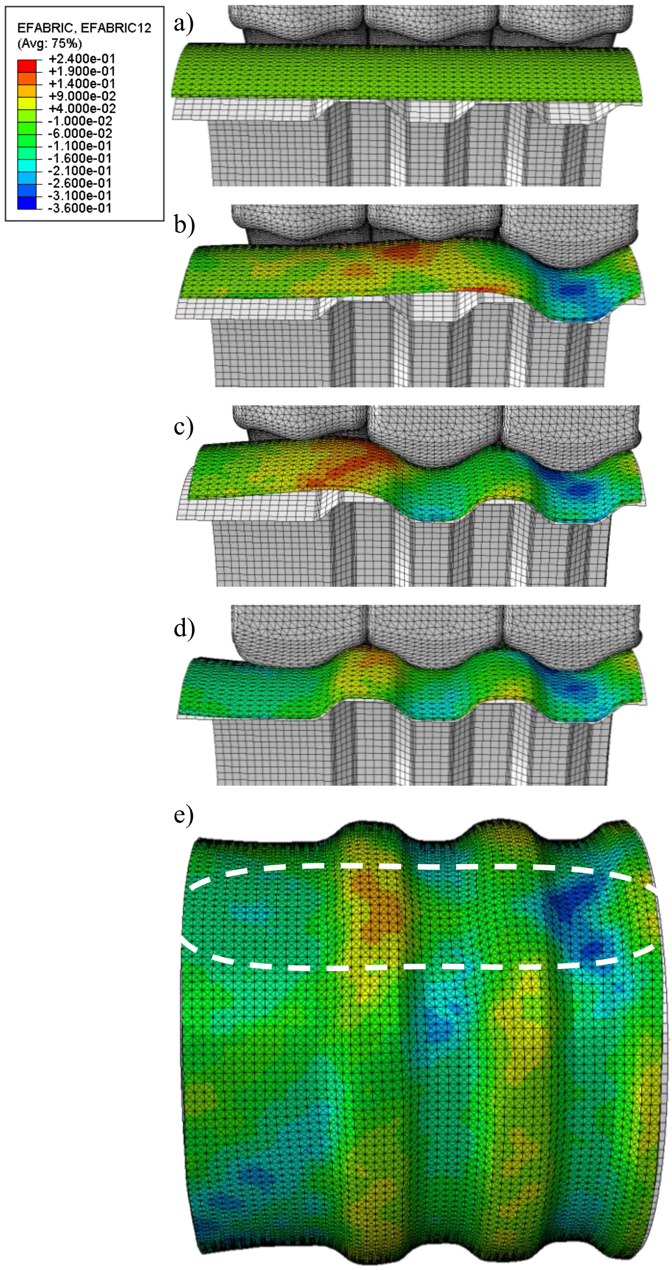

Fig. 6: Simulation results of the draping process with the state before the draping starts (a), three draping steps (b, c, d) and shear deformation of the preform showing the tendency to wrinkles. In a - d three membranes are hidden.

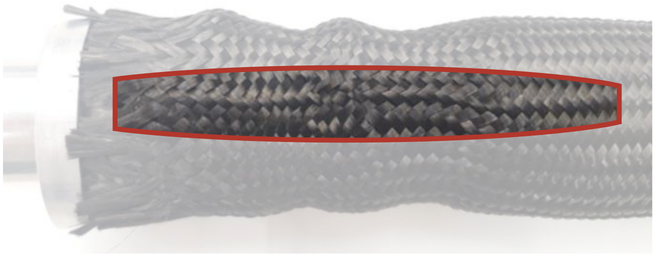

Fig. 7: Formation of Wrinkles in first draping experiments.

5. Conclusion and Outlook

The rotational moulding is a process to manufacture high performance hybrid FRP metal parts. One key process step in this process route is the draping of the preform onto the metallic end fittings. This is done by a draping tool consisting of silicone membranes that get pressed by the use of pressured air against the preform, thus forming the textile.

For a better understanding of the draping and in order to optimize the draping process and the draping tool, a digital twin has been developed. The digital twin is built in the commercial FE software ABAQUS.

The simulation area for this digital twin covers, due to symmetries in the process, one half of one forming unit. In this simulation area, a parametric model has been built to represent the draping process. The textile preform has been modelled using coupled membrane and shell elements, while the silicone draping membranes are built as hyper elastic rubber materials. First results show the shearing of the preform while getting draped by the silicone membranes. The results of the simulation are in good accordance with first experiments but must be validated by further experimental data.

In addition to the validation, the python based parametric model will in future works be used for automated optimization loops. These optimization aims for the perfect shape of the draping membranes to avoid the shown wrinkling of the textile.

Acknowledgements

Prototypic machines for hybrid preforming were developed within the project “FaMeZug”. This project was funded by the Federal Ministry of Economic Affairs and Energy. The simulation model is based on investigations of the project “Beanspruchungsgerechte Gestaltung von Lasteinleitungen für im Schleuderverfahren hergestellte hybride Leichtbauwellen” which is kindly supported by the German Research Foundation (DFG - Deutsche Forschungsgemeinschaft). This project is part of the collaborative research program ‘‘Schwerpunktprogramm 1712’’ of the DFG. The authors would like to thank all funding authorities.

References

[1] Fleischer J, Ochs A, Dosch S. The future of lightweight manufacturing: production-related challenges when hybridizing metals and continuous fiber-reinforced plastics, 2012, p. 51.
[2] Neitzel M, Mitschang P, Breuer U. Handbuch Verbundwerkstoffe: Werkstoffe, Verarbeitung, Anwendung, 2014, 1st edn. Carl Hanser Fachbuchverlag, s.l.
[3] Fleischer J, Teti R, Lanza G, Mativenga P *et al.* Composite materials parts manufacturing, 2018. CIRP Annals *67*, p. 603.
[4] Eksi S, Kapti AO, Genel K. Buckling behavior of fiber reinforced plastic–metal hybrid-composite beam, 2013. Materials & Design *49*, p. 130.
[5] Parashar A, Mertiny P. Adhesively bonded composite tubular joints: Review, 2012. International Journal of Adhesion and Adhesives *38*, p. 58.
[6] Barfuss D, Grützner R, Hirsch F, Gude M *et al.* Multi-scale structuring for thermoplastic-metal contour joints of hollow profiles, 2018. Production Engineering *12*, p. 229.
[7] Koch S-F. Fügen von Metall-Faserverbund-Hybridwellen im Schleuderverfahren: Ein Beitrag zur fertigungsgerechten intrinsischen Hybridisierung, 2017, 1st edn. Shaker, Aachen.
[8] Fleischer J, Koch S-F, Coutandin S. Manufacturing of polygon fiber reinforced plastic profiles by rotational molding and intrinsic hybridization, 2015. Production Engineering *9*, p. 317.
[9] Ruhland P. Production of Hybrid Tubular Metal-Fiber-Prefroms: Material Characterization of Braided Hoses with a Binder, 2019.
[10] DYNAmore GmbH, Editor, 2015. Proceedings of the 10th European LS-DYNA Conference, Würzburg, Germany.
[11] Pham MQ, Döbrich O, Trümper W, Gereke T *et al.* Numerical Modelling of the Mechanical Behaviour of Biaxial Weft-Knitted Fabrics on Different Length Scales, 2019. Materials (Basel, Switzerland) *12*.
[12] T Gereke, O. Döbrich, S. A Malik, R. T Kocaman *et al.* Numerical micro-scale modelling of the mechanical loading of woven fabrics equipped with particles, 2018. IOP Conference series: Materials Science and Engineering *460*, p. 12006.
[13] Vorobiov O, Bischoff T, Tulke A, 2015. Micro-meso draping modelling of non-crimp fabrics, in Proceedings of the 10th European LS-DYNA Conference, Würzburg, Germany, p. 15.
[14] Cherif C. Textile Werkstoffe für den Leichtbau, 2011. Springer Berlin Heidelberg, Berlin, Heidelberg.
[15] Long, A.C., Editor, 2007. Composites forming technologies. Woodhead.
[16] Nishi M, Hirashima T. Approach for dry textile composite forming simulation, 2013. Proceedings of 19th International Conference on Composite materials (ICCM-19), p. 7486.
[17] Kärger L, Galkin S, Zimmerling C, Dörr D *et al.*

Forming optimisation embedded in a CAE chain to assess and enhance the structural performance of composite components, 2018. Composite Structures *192*, p. 143.

[18] Coutandin S, Brandt D, Heinemann P, Ruhland P *et al.* Influence of punch sequence and prediction of wrinkling in textile forming with a multi-punch tool, 2018. Production Engineering *12*, p. 779.

[19] Korochkina TV, Jewell EH, Claypole TC, Gethin DT. Experimental and numerical investigation into nonlinear deformation of silicone rubber pads during ink transfer process, 2008. Polymer Testing *27*, p. 778.

[20] Jauffrès D, Sherwood JA, Morris CD, Chen J. Discrete mesoscopic modeling for the simulation of woven-fabric reinforcement forming, 2010. International Journal of Material Forming *3*, p. 1205.

[21] Gatouillat S, Bareggi A, Vidal-Sallé E, Boisse P. Meso modelling for composite preform shaping – Simulation of the loss of cohesion of the woven fibre network, 2013. Composites Part A: Applied Science and Manufacturing *54*, p. 135.

[22] Cho JR, Kim KW, Yoo WS, Hong SI. Mesh generation considering detailed tread blocks for reliable 3D tire analysis, 2004. Advances in Engineering Software *35*, p. 105.