Simulation of woven composite structures considering manufacturing effects

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1 Abstract

Keywords: composite materials, manufacturing effects, draping simulation, crash simulation

In recent years, advanced material models have emerged in finite-element codes for the simulation of composite materials reproducing realistic failure mechanisms. Through the increased reliability in simulation, less conservative designs of composite structures have been made possible. However, most of the current numerical solutions are considering the composite material independently of real manufacturing conditions, which can strongly affect the local material architecture and properties. To extend the potential of composite structures, it is therefore necessary to enhance the simulation models by including additional information from the production processes. To answer this problematic, many works have focused on the detailed simulation of these processes and on the transfer of information between the simulation steps [1, 2].

The present contribution presents the recent advances achieved in the field of numerical process chain for the simulation of woven composite parts within the project “Digital Fingerprint” in the research campus ARENA2036. In particular, it focuses on the simulation of the draping process using a stacked-shell approach coupled to the material model **`*MAT_249_REINFORCED_THERMOPLASTIC`** [3] and the transfer of resulting information such as the local fibre shearing to a simplified single-layered structural model using the software Envyo® [4]. An exemplary load case for the structural simulation is investigated and the lately available extension of the draping material card **`*MAT_249_CRASH`** is compared with **`*MAT_261`** [3]. Finally, a probabilistic simulation framework using the software LS-OPT [5] to account for manufacturing tolerances is presented.

2 Introduction

In the first phase of the research campus ARENA2036, the project DigitPro (for Digital Prototype) dealt with the development of a closed simulation chain for the simulation of braided structures under crash loading. The development of the software Envyo® allowed for the coupling of manufacturing simulations (draping, braiding and infiltration) and of structural simulations from different solvers in a neutral HDF5 format. The mapping of local data such as fibre orientation and thickness increased the prediction potential of the numerical simulations. The second-phase project “Digitaler Fingerabdruck” (“Digital Fingerprint”) benefits directly from the mapping methods and from the knowledge gained in DigitPro and aims at extending the possibilities of the process chain in view of sizing and computing of woven composite structures with integrated sensors. Through the comparison of simulation results and on-board data, the process chain shall adapt and modify the structure in an intelligent manner to optimize its potential.

Flexibility and cost-effective solutions of computer-aided engineering (CAE) are essential for all industrial approaches for many years. Predicting capabilities, model scales and the size of the manageable complexity have been improved day by day. Almost every individual step of the life cycle of a product can be modelled, simulated and evaluated before it is produced. This concept is called “Digital Twin”, or “*in plain English, this just means creating a highly complex virtual model that is the exact counterpart (or twin) of a physical thing”* [6]. Maximizing the potential of a digital twin concept is a challenging task and requires high collaboration of different industrial branches.

In this paper, LS-DYNA, LS-OPT and the mapping tool Envyo® are coupled to realize an integrated modelling scheme of a sensor embedded woven composite structure on a macroscopic scale. The process chain steps are discussed in detail, example solutions are demonstrated and a working prototype is introduced. Finally, some further steps and future improvements will be mentioned. The work in this paper has been carried out for the ongoing joint project “Digitaler Fingerabdruck” within the research campus ARENA2036 [7].

3 Materials and experimental test campaign

The project Digital Fingerprint focuses on a multi-material high voltage component consisting in a glass fibre reinforced plastic lid mounted on an aluminium housing (*Figure 1*). The different materials used in the component are documented in *Table 1*. The lid is manufactured by draping glass fibre woven layers in a preform and infiltrating them in a tooling for Resin Transfer Moulding (RTM). During the weaving process, MEMS sensors from Bosch [8] is automatically integrated within the ply by replacing one warp yarn and reinforcing locally the textile with additional yarns. The integrated MEMS sensors measure continuously the temperature and accelerations in x, y, and z directions at three positions in the part. The consolidated GFRP part is then prepared and trimmed into its final shape and bolted on the housing.

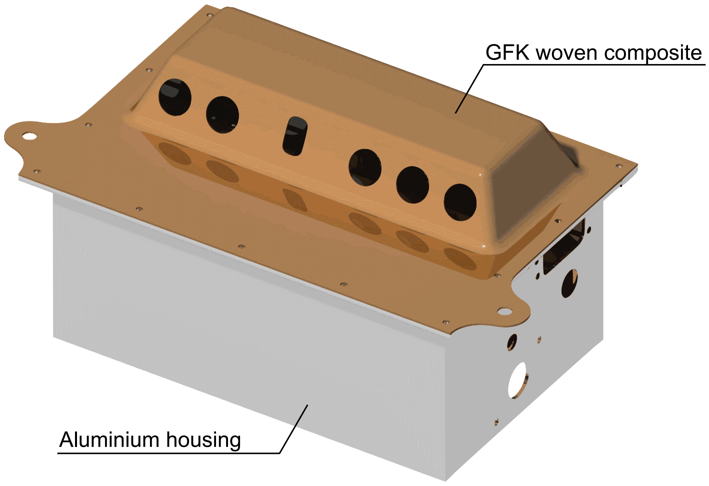

Figure 1: Component investigated in the project Digital Fingerprint within the ARENA2036 research campus

Table 1: Materials used in the sensor-integrated high voltage component

Glass fibre yarns	Johns Manville 086, 24k
Polymer resin	CR170
Woven ply	Diamond pattern 2x2
Aluminium	Al8082

In order to validate the simulation chains developed in the project, the materials listed in *Table 1* have first been investigated on the coupon specimen scale at the test facility of the Institute for Aircraft Design (University of Stuttgart), of the German Institutes of Textile and Fiber Research (DITF) and of the DLR Institute of Structures and Design. In particular, the behaviour of the dry preforms have been tested under tension and shear in order to calibrate the material card **`*MAT_249`** for a draping simulation.

4 The virtual simulation chains

The virtual process chains have for purpose to support the structure sizing and the manufacturing processes by providing information about the structural potential of the component based on partial or complete input from previous in-field observations. First, a virtual material characterization is performed on the multiscale to predict the mechanical properties of the woven composite material considering several potential scatter sources or manufacturing effects. The material properties are then further used in the process chain, which depicts many manufacturing steps and covers the in-service field. In this chapter, the two simulation chains are described and their potential in the Digital Fingerprint is highlighted.

4.1 Virtual material characterization

Virtual testing offers the promise of material, time and cost reduction in the characterization and investigation of composite materials. Within the multiscale approach, composite materials are represented via their main components at the microscopic, mesoscopic and macroscopic scales and the results at a lower scale are transferred to the higher scales for further computing (*Figure 2*).

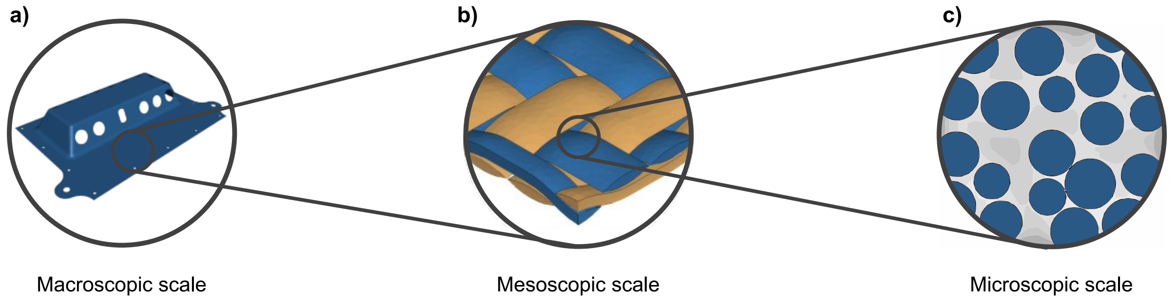

Figure 2: Multiscale chain for virtual characterization, from unidirectional ply to structure

In this work, the properties of a unidirectional, consolidated yarn are first computed on the microscale with a fibre/resin model (Figure 2c. The single fibres are modelled with an orthotropic material model **`*MAT_054`** and the resin with the **`*MAT_187_SAMP`** coupled to **`*MAT_ADD_GISSMO`** to represent the different fracture modes dependently to the triaxiality in the resin pockets. Fibre/resin interfaces are represented by a cohesive contact **`*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK`** with the option 9 considering a bilinear traction-separation law. The predicted material properties are fitted into a material card for **`*MAT_261`** and applied to the mesoscale model (Figure 2b), which generation has been documented in details in [9]. At this scale, the modelling at material card of the resin pockets remains unchanged compared to the microscopic scale. Finally, the properties of the consolidated woven laminate are transferred onto to the last scale for structure simulation using **`*MAT_054`** (Figure 2a). The present multiscale approach, by introducing the thermal properties of the various components through **`*MAT_ADD_THERMAL`** or the fatigue properties through **`*MAT_ADD_FATIGUE`**, allows furthermore detailed investigations of the composite material.

4.2 Virtual process chain

One of the main challenges in the development of a virtual process chain is the need for a common platform and compatible software formats to depict various process steps, which sometimes require specific simulation tools. In this project, LS-OPT is used to centralize and connect the process simulations such as draping, trimming or assembling and transfer information across the models by introducing the tool Envyo®. The following sections describe some of the main aspects of the developed process chain (*Figure 3*).

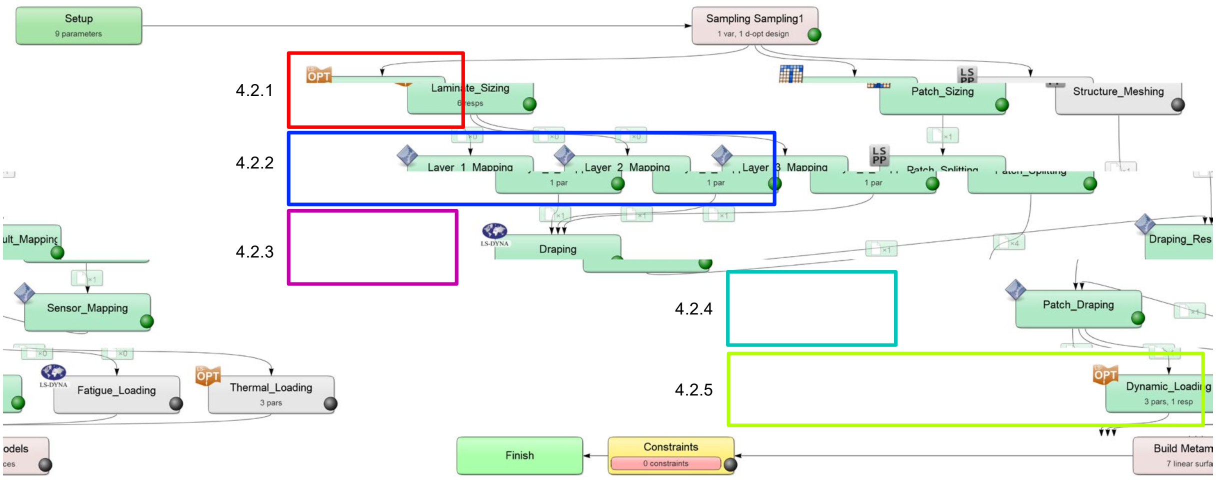

Figure 3: Numerical process chain in LS-OPT for the investigation of woven GFRP parts; section numbers are indicated near the corresponding process steps.

4.2.1 Automatic sizing

Prior any process steps, the stacking sequence of the woven layers is first optimized for a specific loading scenario (in this case a vertical choc through a sinusoidal acceleration in z-direction). The laminate is subdivided into three layers which thicknesses and angles are iteratively optimized using the space filling method to minimize the laminate weight and the maximal deformations between the bolts. The resulting set of parameters is fed forward the next step for mapping.

4.2.2 Beam-shell mapping

The starting point of this mapping step is a beam model of the woven ply, which was automatically generated based on the mesoscale model of section 4.1. In Envyo®, necessary modifications of the source mesh can be enabled through **TRANSFORMATION=YES**. For each layer, the beam model is first rotated by the optimized angle from section 4.2.1 using the option **ROTATESRC** and the source beam elements are mapped on the target shell mesh for draping simulation using the command **ENVYO=BEAM-SHELL** (Figure 4).

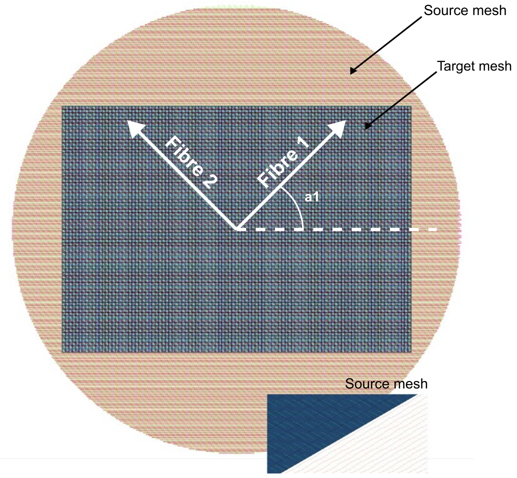

Figure 4: Visualisation of the rotated source mesh with beam elements and of the target mesh with shell elements

Since the woven fabric should be represented by a shell element mesh, it is beneficial to use **ALGORITHM=CONSIDERONDULATION**. This option is especially useful while modelling unidirectional shell layers to consider beam element positions in shell thickness directions combined with ***ELEMENT_SHELL_COMPOSITE(_LONG)**, which is activated in Envyo® by defining **SHELL_OPTION=COMPOSITE(_LONG)** in the mapping option file. The advantage of using ***ELEMENT_SHELL_COMPOSITE(_LONG)** is that each through thickness IP can have a different thickness and material ID. As a result, different stacking properties can be defined for each element. This flexibility helps to model discontinuity between elements and to consider the waviness in woven composites. Since fibre interactions and fibre shearing should also be considered, ***MAT_249** is selected as target material model. It is an anisotropic hyper-elastic material model that support up to three distinguished fibre directions per integration point (IP). The new *IHIS=1* feature of this material model provides the possibility to initiate fibre directions in global coordinate system using IP history variables [3]. These mapping options were declared as follows:

```
ALGORITHM=CONSIDERONDULATION
SHELL_OPTION=COMPOSITE
TARGETMATERIALMODEL=249
```

If required, the integrated sensor band was mapped on the target mesh using a clustering method. The respective material IDs of the target mesh element layer were modified to distinguish these elements. The mapping option **CLUSTERID#1=&PID3** was used to generate shear band element cluster. The option means that the target PID 1 (**CLUSTERID#1**) is modified using source PID 3 (**&PID3**) and that the clustered element material models are distinguished using the integer value *28*. Other options must be defined to satisfy the input variable requirements of the *equation parser* implementation in Envyo® but are not used for this specific application. It is assumed that the sensor band has an isotropic material behaviour. Thus, the ***MAT_249** properties were modified to handle the combination of the fibre fabric and the sensor band behaviours.

4.2.3 Draping simulation

After mapping the beam source mesh data on the shell mesh, a first simulation of the draping process is performed to predict the local directions in the composite part. The woven fabric is modelled as rectangular mesh and discretized using fully integrated quadrilateral shell elements with an element length of 4 mm. The textile mesh is positioned between an upper and a lower mould modelled with

***ELEMENT_TSHELL** and corresponding to the moulds from the RTM tooling (*Figure 5*). Depending on the real boundary conditions, a holder plate can be introduced in the FE-model to clamp or pretension the textile and therefore reduce potential manufacturing defects such as folds. Furthermore, the investigated structure possesses corners with low radius which require a high shearing of the textile, thus raising additional instability issues. Therefore, a ***DAMPING_GLOBAL** command has been added to improve the element stability.
The fabric fibre directions were stored as history variables according to ***MAT_249** IHIS=1 option. ***MAT_249** supports up to three distinguished fibre directions on a single IP where shearing between fibres is also considered [3]. By combining this feature with the keyword ***ELEMENT_SHELL_COMPOSITE**, discontinuous composite layouts can be represented accurately, since each element can have a different material model ID.

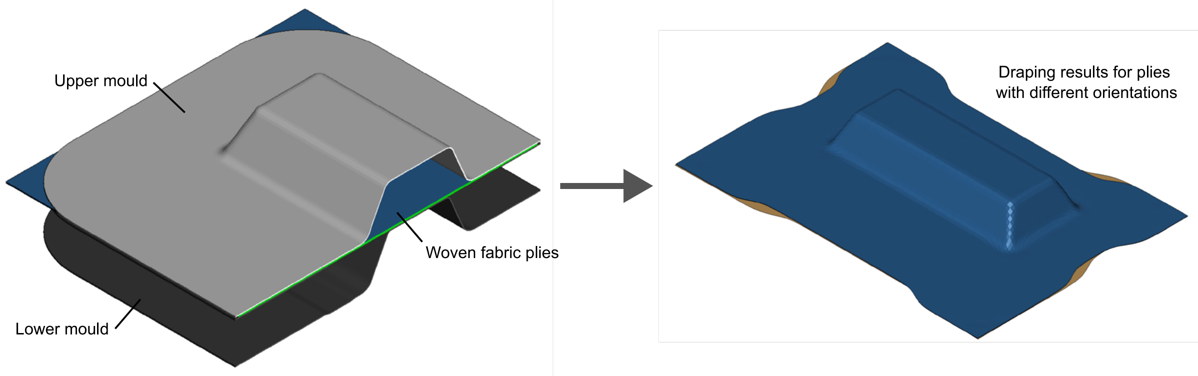

Figure 5: Model for draping simulation (left) and draping result at the example of three layers with various main rotation angle from the ply sizing

The draping simulation is necessary to estimate fibre directions of each element after the draping process in deformed configuration. Due to the nature of the displacement driven simulation, fibre directions will be distorted according to the element deformations. Since composite materials have an anisotropic material response, the element fibre directions in deformed configuration should be mapped onto the consecutive simulation mesh to increase accuracy.

4.2.4 Patch mapping

In a previous step, which will not be detailed in the present paper, an optimization of reinforcing TFP-patches in 0°, +45°, -45° and 90° direction has been performed using the software LS-Task®. To handle the reinforcement patches during the mapping step, following options are declared in mapping_info.in file:

```
ALGORITHM=POINTPROJECTION
REINFORCING_PATCH=YES
PATCHGLOBALZERODIRECTION=X
SHELLOPTION=COMPOSITE
OFFSET_OPTION=FLAT_LOWER
TARGETMATERIALMODEL=249

NUMPATCHES=4
REINFORCEPATCH#1=Reinforce_0.dyn;2001;<<patch_1_angle:0>>;<<patch_1_thick:0>>
REINFORCEPATCH#2=Reinforce_45.dyn;2002;<<patch_2_angle:0>>;<<patch_2_thick:0>>
REINFORCEPATCH#3=Reinforce_-45.dyn;2003;<<patch_3_angle:0>>;<<patch_3_thick:0>>
REINFORCEPATCH#4=Reinforce_90.dyn;2004;<<patch_4_angle:0>>;<<patch_4_thick:0>>
```

The option **SHELLOPTION=COMPOSITE** generates composite shell elements and **OFFSET_OPTION=FLAT_LOWER** shifts the shell elements in element normal direction so that all shell bottom surfaces are adjusted with each other as can be seen in *Figure 6*. Similarly **OFFSET_OPTION=FLAT_UPPER** option adjusts top surfaces. **TARGETMATERIALMODEL=249** activates functions to write the fibre directions as history variables for ***MAT_249** *IHIS=1* option.

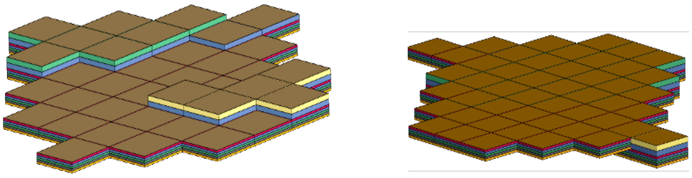

Figure 6: FLAT_LOWER option on the left and FLAT_UPPER option on the right

NUMPATCHES defines the total number of element-set files that should be considered in the patch handling routine. **REINFORCEPATCH#<INT>** option declares the reinforcement element-set files regarding material IDs, reinforcement angles and patch thicknesses. <<*patch_angle*>> and <<*patch_thickness*>> of all 4 reinforcement patches are parametrization of the respective. <<*patch_angle*>> describes a respective reinforcement patch fibre direction angle and <<*patch_thickness*>> describes a respective reinforcement patch thickness. These options will be used to create reinforcement patches top onto the existing data, since ***ELEMENT_SHELL_COMPOSITE** layers are defined from bottom to top with respect to the element normal to ensure the physicality of the stacking sequence. The overview of the patch handling process, effects of the reinforcement patches on element thicknesses and patch fibre directions in the reference configuration can be seen in Figure 7.

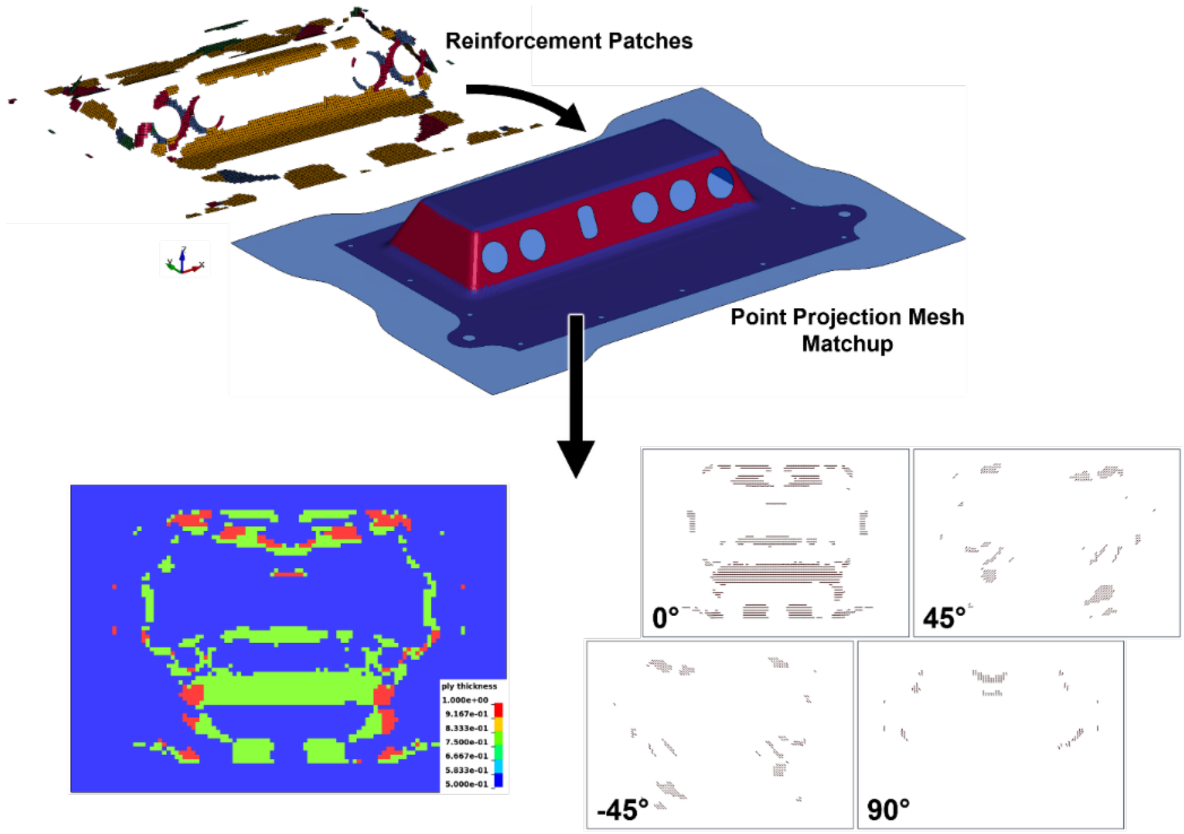

Figure 7: The overview of reinforcement patch handling. Reinforcement patches and mesh matchup in deformed configuration (top), element thicknesses after the patch handling (bottom left) and reinforcement patch fibre directions in the reference configuration (bottom right)

4.2.5 Probabilistic structure simulation and manufacturing effects

To show the potential of the present process chain, an elastic three-point bending simulation is exemplarily performed as shown in *Figure 8* and various parameters such as the reinforcement thickness, the reinforcement angle and the draping angle are analysed in a sequential meta-model-based Monte Carlo analysis, where the contact force between the moving bar and the structure is defined as response for the LS-OPT study. The accuracy of the meta-model and the effects of the nine variables on the final response can be documented by LS-OPT.

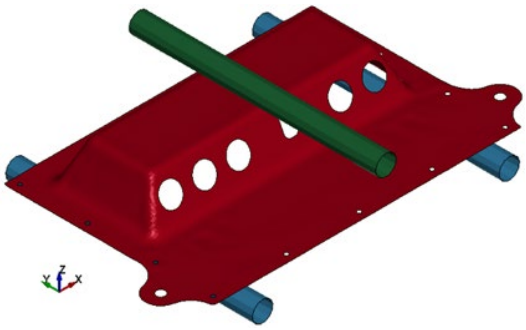

Figure 8: Three-Point bending simulation setup

The response value is used to evaluate the meta-model of the process chain for different parameter combinations. Therefore, the evaluation of this setup is more a statistical study rather than an optimization of a real-life process chain. Regarding to this assumption, selected evaluation plots of the study can be seen in *Figure 9*. The scattered data in the accuracy plot is generated using computed and calculated response values. It is desired that the computed response and the calculated response are equal, which is illustrated by the bold diagonal line. By neglecting some outliers of the scatter plot, the meta-model fulfils its purpose as a prototype. Since this model has nine parameters to investigate, the parameter correlation plot is more beneficial. The correlation plot can be used to assume some parameters as constant with respect to their contributions to the response value and a robust process chain with fewer parameters can be created. Thus, some computational effort can be saved. As can be seen in the *Figure 9*, the parameter *r1* has the most influence on the response value, which satisfies the expectations, since it changes the woven fabric alignment in draping simulation and influences the structure stiffness.

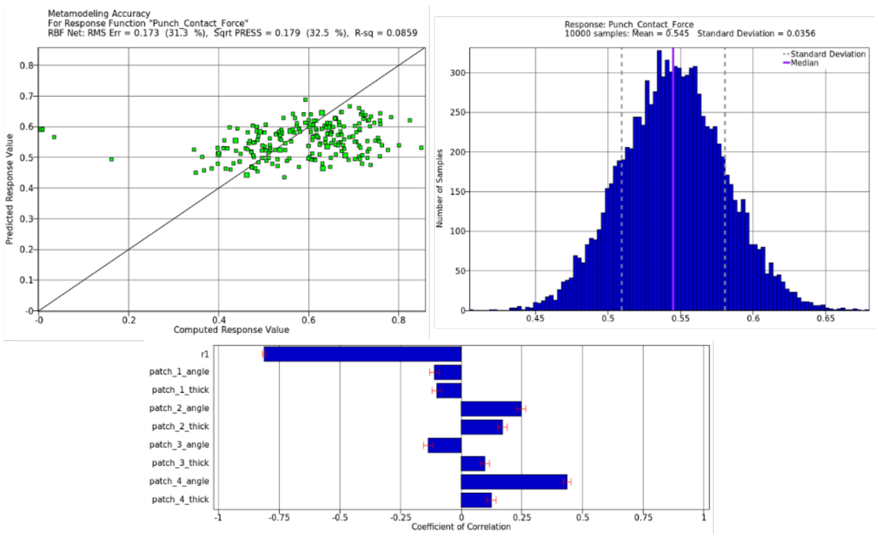

Figure 9: Meta-model accuracy plot (top left), the response value distribution (top right) and parameter correlation plot bottom

4.3 Structural simulation with *MAT249_CRASH

In this section, a structural simulation is performed using **`*MAT_261`** and **`*MAT249_CRASH`** with the optimised structure of the previously documented process chain. In the first model, the reference structure is modelled with **`*ELEMENT_SHELL_COMPOSITE`** and each woven layer is represented by alternating globally-oriented 0° and 90° layers. For this model, no draping information is considered. The second model is resulting from a draping simulation and each woven layer is modelled with one integration point using the **`*MAT249_CRASH`** (*Figure 10*).

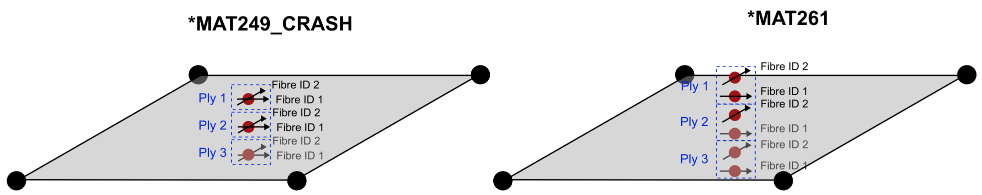

Figure 10: Modelling of the 3-layer woven composite with **`*MAT249_CRASH`** *and* **`*MAT261`**.

The newly developed extension for crash simulation of the material model **`*MAT249`** allows for a direct switch of the mechanical properties and damage mechanisms after the draping simulation and considers the real fibre orientation resulting from the draping process. It requires the knowledges of fibre and resin damage in dependency of the longitudinal fibre strain and the shear damage depending on. Since no experimental characterization of the material card was performed, the curves describing the damaging of fibre and resin components has been adapted to be comparable to the input in **`*MAT_261`**. The woven structure is impacted with a rigid sphere of 1 kg at a velocity of 1.4 m/s (energy of about 1 J). This load case represents the potential impact of a dropped tooling during the manufacturing and assembly steps. The force versus displacement curves are globally similar for the two material cards (*Figure 11*). The extension of the resin damage is similar in the two simulations (*Figure 12* left). However, the **`*MAT249_CRASH`** does not depict the stiffness drop after the complete matrix damage in the material. Furthermore, this material card overestimates the fibre failure during the impact. In comparison, the **`*MAT261`** only predicts a damage level of about 0.4. The damage mechanisms in **`*MAT249`** should be validated further on coupon specimens.

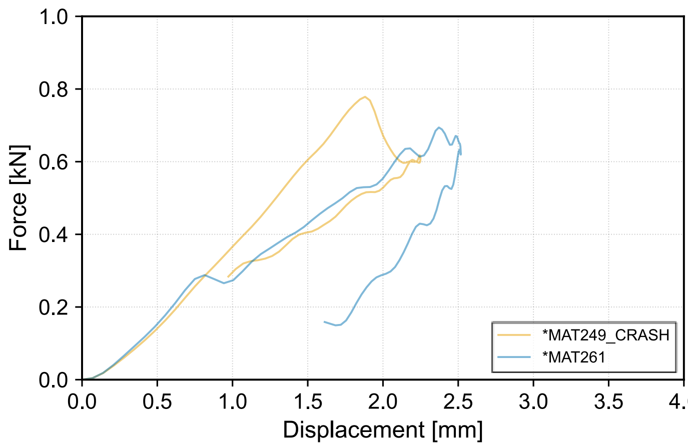

Figure 11: Reaction force during an impact with an energy of 1 J on the structure simulated with **`*MAT249_CRASH`** *and* **`*MAT261`**.

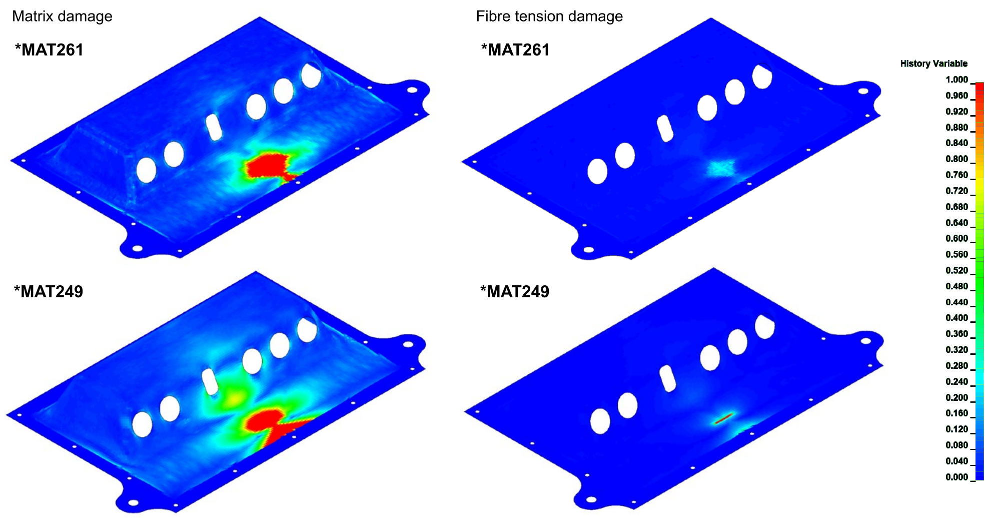

Figure 12: Matrix and fibre damage in the structure after a 1 J impact simulated with **`*MAT261`** *and* **`*MAT249_CRASH`**

5 Conclusion and outlook

A closed numerical chain has been developed in the project “Digitaler Fingerabdruck” for the simulation of the manufacturing and the structural testing of woven composite parts with a focus on stochastic effects. The implementation of the process chain within the LS-DYNA toolchain with help of LS-OPT and LS-Task allows for an advanced automation of the simulation steps. The use of Envyo® to transfer information (local orientation of the woven composite after draping etc.) between the various meshes completes the process chain by linking various disciplines of the product development.
For the structural analysis, the recently developed material model **`*MAT249_CRASH`** has been investigated in an impact simulation and compared to **`*MAT261`**. While the damage and failure mechanisms require some fitting and specific experimental testing on woven materials, their potential for a direct use on a draped model is particularly interesting. Moreover, the possibility to define up to three fibre orientation within a single integration point is promising for triaxially composites (i.e. triaxially braided composites). However, more validation on the specimen scale should take place.
Overall, the developed process chain offers several possibilities to support the product life cycle and can be extended to various additional engineering fields. A feedback loop still has to be integrated in order to adjust the input parameters depending on in-field data and improve further the product potential (thickness reduction, optimisation for specific load cases etc.). An extensive experimental validation of the performed steps, particularly the draping of sensor-embedded weaves, has to be carried on.

Acknowledgment

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